Volume 1

DRYING OF FOODS, VEGETABLES AND FRUITS

Editors
S.V. Jangam, C.L. Law, A.S. Mujumdar

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Editors: Sachin V. Jangam, Chung Lim Law and Arun S. Mujumdar

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PREFACE

Drying is an important unit operation used in numerous industries and well known as a dominant industrial consumer of fossil fuel-derived energy in developed countries. As standard of living rises in the developing world energy usage for drying operations will rise along with the demand for energy-efficient, faster, environmentally friendly (minimal carbon foot print) and cost-effective drying technologies will continue to increase worldwide. Indeed, the growth in energy consumption for drying will increase at a higher pace in the rapidly developing world, in particular the rapidly developing as well as very large economies of China, Brazil and India. As the fuel prices rise, it is necessary to develop sustainable drying technologies using renewable sources using innovative ideas. Drying of food products has been a very important industrial sector for many years. This is also reflected in the continuing success of the International Drying Symposium (IDS) series and numerous sister conferences as a well as a premier archival journal devoted exclusively to drying science, technology and engineering. Drying R&D seems to have reached a sustainable level of activity around the globe, still there is tremendous scope to carry out R&D in this complex process.

Although a large volume of highly recognized technical literature is available on drying of foods, it is still a daunting task to access and assimilate the essence of this voluminous literature for researchers in developing and under-developed countries. To alleviate this problem, Professor Arun S. Mujumdar has initiated a series of e-books which can be made available freely or at minimal affordable cost even in the poorer countries with access to the internet. Indeed, the internet has 'flattened' the world in providing access regardless of the state of the economic development. The first e-book of this type is entitled Mathematical Modeling of Industrial Transport Processes, which is available for free download at http://serve.me.nus.edu.sg/arun/. This e-book is also a part of this activity and provides a simple convenient introduction to the basic principles, terminology, selection and classification of dryers, details on commonly used dryers and new developments in drying of foods, vegetables and fruits. Our main goal is to make useful technical literature available for particularly those who have little access to expensive books and journals. Students and faculty members can use these books for teaching purposes as well as for research and industrial needs. Contributors of this book have tried to put their ideas in simple terms without sacrificing quality. All chapters are reviewed by the editors at the same standards as those used by well known international publishers. Indeed all authors are writing by invitation and have a strong publication record themselves. This is a professional service on their part. We all must be grateful for this thankless service they are providing in the name of humanity and sustainability of global resources.

It is important to note that authors and editors have made special efforts to ensure that this book and its companion books properly credit relevant early work but the chapters do not include any copyrighted material. This e-book is carried out as professional service by members of our international network of researchers and educators in the hope of making the knowledge contained herein available freely without geographical or economic barriers. The internet has made the world "flat"; yet access to knowledge is generally restricted. We hope that this effort will provide rapid and free access to relevant knowledge freely to those who can most benefit from it. We are truly grateful for the outstanding effort of our authors and referees for their truly thankless contribution in the interest of global dissemination of useful information. We believe the e-books we are planning can be used for teaching as well as R&D purposes.

This book is divided in three volumes; the first volume is dedicated to fundamentals of drying FVF, second volume has detailed discussion on drying of various types of food, while the third volume covers special topics of wide interest. The first volume starts with basic discussion of relevant principles, terminologies and introduction to advances in drying of food products followed by a chapter on hygrothermal data for various FVFs. This is followed by a comprehensive discussion on selection and classification of dryers for food products. This is followed by chapters on osmotic pretreatments, quality and safety in food drying, energy optimization and use of renewable sources of energy for drying of foods. The second volume will cover drying of most of the food variety such as drying of grains, rice, medical plants, roots, meat products, marine products, exotic tropical fruits, probiotics and recently popularized functional food and snack food. The third volume will cover special topics such as Foam mat drying, low temperature drying, spray drying, microwave drying, vacuum frying and baking of bread. For the time being we are happy to bring out the first volume of this effort, however, remaining two volumes will be published soon.

We believe this book is suitable for self-study by engineers and scientists trained in any discipline and so as for the readers who have some technical background. It should also be helpful to industrial users of dryers, dryer manufacturers as well as entrepreneurs. The topics chosen are designed to give readers a quick practical overview of the subject without going into deep mathematical or theoretical considerations. It could serve as a text or supplementary text for professional development short courses as well.

We are grateful to a large number of individuals, mainly the contributors of individual chapters which are listed following the preface. We are very grateful for their support in making this e-book available freely. We hope that this book will be useful to researchers working in food dehydration. We hope that the authors of this book have succeeded at least partially in achieving goals behind this e-book. We plan to put up enhanced editions of these books in due time. Response from readers is always welcome along with ideas for new e-books and offers of chapters.

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Chapter 1
Basic Concepts and Definitions

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Contents

1.1. INTRODUCTION

There are two main sources of food; plants and animals. Although various researchers have classified foods in different ways, generally they are categorized as perishable (which spoils very fast), non-perishable (relatively slower spoilage), harvested food, raw food, fresh food, formulated food, synthetic food and recently popularized functional food (Rahman, 1999; Passos and Ribeiro, 2009). All variety of foods in our day to day life needs some way of preservation mainly to reduce or stop spoilage, to make it available throughout a year, to maintain desired levels of nutritional properties for the longest possible time span and to make value added products. Amongst these, spoilage is the foremost reason for employing food preservation techniques. Spoilage or deterioration of food occurs during handling or due to mechanical, physical, chemical or microbial damage. Out of these, chemical and microbial damages are most frequent causes. (Rahman, 1999; Mujumdar, 2004) Microbial growth depends on the storage conditions and the moisture level in the product. Different micro-organisms have different growth rates depending on the conditions. There can also be several chemical and enzymatic changes during processing and storage of foods, e.g. browning. Both of these phenomena result in loss of sensory properties and sometimes even nutritional qualities causing food products to become unacceptable for consumption. Commonly employed methods for food preservation are, freezing, vacuum packing, canning, preserving in syrup, food irradiation, adding preservatives and most popular dehydration or drying. Although it is said that drying will never replace canning and freezing because these methods do a better job of retaining the taste, appearance, and nutritive value of fresh food, but drying is an excellent way to preserve foods that can add variety to meals and provide delicious, nutritious snacks. One of the biggest advantages of dried foods is that they take much less storage space than canned or frozen foods.

Drying is one of the most cost-effective ways of preserving foods of all variety which involves removal of water by application of heat. A variety of food sub-types are preserved using drying, these include: marine products, meat products as well as all fruits and vegetables. Food products can have moisture content as high as 90% or more (e.g. water melon has moisture content as high as 93%) which needs to be reduced to an acceptable value so as to avoid microbial growth. These limits are reported for different micro-organism in terms of water activity and will be discussed in detail later in this chapter. In addition, each food product needs to be dried in a different way, using appropriate pre and post-processing step(s) and proper dryer type so as to add satisfactory value upon drying (Mujumdar 2004; Mujumdar 2008; Chen and Mujumdar, 2008). The pre and/or post processing steps are very important to reduce the drying load as well as to make better quality products. Various pre-processing steps such as osmotic dehydration, blanching, salting, soaking are used depending on the food variety to be dried. Whereas post-processing such as coating, packaging also have a great importance after drying of food products. Selection of dryers for particular food product is itself a complex step as there are hundreds of dryers available and more than one dryer can suit a particular application. Traditionally food products are dried by open sun drying. Although this method is still common at several places for non-commercial use, there have been numerous efforts to develop advanced drying methods for food products on commercial scale. It is necessary to improve the drying techniques to reduce the spoilage

and enhance the quality at minimal cost, e.g. new drying techniques such as heat pump dryer is better option for highly expensive freeze drying, certainly not for all products (Kudra and Mujumdar, 2009).

Drying is a complex operation involving transient transfer of heat and mass along with several rate processes, such as physical or chemical transformations, which, in turn, may cause changes in product quality as well as the mechanisms of heat and mass transfer (Mujumdar 2008). Physical changes that may occur include: shrinkage, puffing, crystallization, glass transitions. In some cases, desirable or undesirable chemical or biochemical reactions may occur leading to changes in color, texture, odor or other properties of the solid product. Drying is highly energy consuming unit operation and competes with distillation as the most energy-intensive unit operation due to the high latent heat of vaporization of water and the inherent inefficiency of using hot air as the (most common) drying medium. Various studies report national energy consumption for industrial drying operations ranging from 10-15% for USA, Canada, France, and UK to 20-25% for Denmark and Germany (Mujumdar, 2008). The latter figures have been obtained recently based on mandatory energy audit data supplied by industry and hence are more reliable. Hence, it is also necessity to develop energy efficient drying process as well. This can be accomplished by use of renewable source of energy for drying, by recovering exhaust heat, by developing new energy efficient systems such as heat pump drying or by improving the existing drying process itself. Food quality and safety are other issue which are very important and need to be discussed when drying of food is studied. All these aspects related to drying of food, vegetables and fruits will be covered as special topics in following chapters of this book.

It is very important to understand basic concepts of drying before heading to the detailed study of this complex phenomenon of heat, mass and momentum transfer. This chapter mainly discusses the basic terms used in the field of drying. It is useful to note the following unique features of drying which make it a fascinating and challenging area for R&D, not just for food sectors but also for other applications:

- Product size may range from microns to tens of centimeters (in thickness or depth)
- Product porosity may range from zero to 99.9 percent
- Drying times range from 0.25 sec (drying of tissue paper) to five months (for certain hardwood species)
- Production capacities may range from 0.10 kg/h to 100 t/h
- Drying temperatures range from below the triple point to above the critical point of the liquid
- Operating pressure may range from fraction of a millibar to 25 atmospheres
- Heat may be transferred continuously or intermittently by convection, conduction, radiation or electromagnetic fields

Clearly, no single design procedure that can apply to all or even several of the dryer variants is possible. It is therefore essential to revert to the fundamentals of heat, mass and momentum transfer coupled with knowledge of the material properties (quality) when attempting design of a dryer or analysis of an existing dryer. Mathematically speaking, all processes involved, even in the simplest dryer, are highly nonlinear and hence scale-up of dryers is generally very difficult. Experimentation at laboratory and

pilot scales coupled with field experience and know-how is essential to the development of a new dryer application. Dryer vendors are necessarily specialized and normally offer only a narrow range of drying equipment. The buyer must therefore be reasonably conversant with the basic knowledge of the wide assortment of dryers and be able to come up with an informal preliminary selection before going to the vendors with notable exceptions.

1.2. MICROBIAL DAMAGE

During harvesting and subsequent steps involved in processing, food products are prone to different kinds of damage involving mechanical, physical, chemical and microbial damage. Mechanical and physical damage can contribute to enhance the chemical and microbial damages (Rahman, 1999; Mujumdar 2004). Amongst these drying mainly concentrates on reducing or completely overcoming potential microbial damages. Microbial growth can occur during post harvest processing and storage and the main contaminant are soil, water, air and animals. The main microorganisms contributing to such damages are bacteria, fungi (molds and yeast), protozoa, however, insects can also contribute to the microbial damage (Mujumdar 2004). Each microorganism has an optimum temperature for its growth; however, increasing temperature above certain value suppresses the growth and microorganisms have absolute demand for water which enhances the growth of microorganism. Each microorganism needs minimum quantity of water to grow which will be discussed in the next section in terms of so called water activity. Microbial growth can result into loss of sensory characteristics of the food items (fruits and vegetables) and in many cases the damages food will be of unacceptable quality (various fish products, fruits). Several chemical reactions occur during storage of food products such as enzymatic browning, lipid oxidation. For example, fruits when cut become brown, such as, apple. However, reduction in moisture content below certain level can reduce the microbial damage of food materials and drying accompanied by proper pre treatment can help reduce the chemical damages. The rate of deterioration by different reactions will be discussed later in this chapter based on the water activity values.

1.3. BASIC TERMINOLOGIES IN DRYING

Drying occurs by effecting vaporization of the liquid by supplying heat to the wet feedstock. As noted earlier, heat may be supplied by convection (direct dryers), by conduction (contact or indirect dryers), radiation or volumetrically by placing the wet material in a microwave or radio frequency electromagnetic field. Over 85 percent of industrial dryers are of the convective type with hot air or direct combustion gases as the drying medium. Over 99 percent of the applications in food drying involve removal of water. All modes except the dielectric (microwave and radio frequency) supply heat at the boundaries of the drying object so that the heat must diffuse into the solid primarily by conduction. The liquid must travel to the boundary of the material before it is transported away by the carrier gas (or by application of vacuum for non-convective dryers). Transport of moisture within the solid may occur by any one or more of the following mechanisms of mass transfer:

- Liquid diffusion, if the wet solid is at a temperature below the boiling point of the liquid
- Vapor diffusion, if the liquid vaporizes within material
- Knudsen diffusion, if drying takes place at very low temperatures and pressures, e.g., in freeze drying
- Surface diffusion (possible although not proven)
- Hydrostatic pressure differences, when internal vaporization rates exceed the rate of vapor transport through the solid to the surroundings
- Combinations of the above mechanisms

Note that since the physical structure of the drying solid is subject to change during drying the mechanisms of moisture transfer may also change with elapsed time of drying.

1.3.1. Thermodynamic Properties of Air-water mixture and moist solids

1.3.1.1. Psychrometry

As noted earlier, a majority of dryers are of direct (or convective) type. In other words, hot air is used both to supply the heat for evaporation and to carry away the evaporated moisture from the product. Notable exceptions are freeze and vacuum dryers, which are used almost exclusively for drying heat-sensitive products because they tend to be significantly more expensive than dryers operate near to atmospheric pressure. Another exception is the emerging technology of superheated steam drying (Mujumdar, 1995). In certain cases, such as the drum drying of pasty foods, some or all of the heat is supplied indirectly by conduction.

Drying with heated air implies humidification and cooling of the air in a well-insulated (adiabatic) dryer. Thus, hygrothermal properties of humid air are required for the design calculations of such dryers. **Table 1.1** summarizes the essential thermodynamic and transport properties of the air-water system. In **Table 1.2**, a listing of brief definitions of various terms encountered in drying and psychrometry is given. It also includes several terms not explicitly discussed in the text.

Table 1.1. Thermodynamic and transport properties of air-water system

(Mujumdar, 1995; Pakowski et al., 1991)

Property	Expression
P_v	$P_v = 100\exp[27.0214 - (6887 / T_{abs}) - 5.32\ln(T_{abs} / 273.16)]$
Y	$Y = 0.622 RH\, P_v / (P - RH\, P_v)$
c_{pg}	$c_{pg} = 1.00926\times10^{3} - 4.0403\times10^{-2}T + 6.1759\times10^{-4}T^{2} - 4.097\times10^{-7}T^{3}$
k_g	$k_g = 2.425\times10^{-2} - 7.889\times10^{-5}T - 1.790\times10^{-8}T^{2} - 8.570\times10^{-12}T^{3}$
ρ_g	$\rho_g = PM_g / (RT_{abs})$
μ_g	$\mu_g = 1.691\times10^{-5} + 4.984\times10^{-8}T - 3.187\times10^{-11}T^{2} + 1.319\times10^{-14}T^{3}$
c_{pv}	$c_{pv} = 1.883 - 1.6737\times10^{-4}T + 8.4386\times10^{-7}T^{2} - 2.6966\times10^{-10}T^{3}$
c_{pw}	$c_{pw} = 2.8223 + 1.1828\times10^{-2}T - 3.5043\times10^{-5}T^{2} + 3.601\times10^{-8}T^{3}$

Figure 1.1 is a psychrometric chart for the air-water system. It shows the relationship between the temperature (abscissa) and absolute humidity (ordinate, in kg water per kg dry air) of humid air at one atmosphere absolute pressure over 0 to 130°C. Line

representing percent humidity and adiabatic saturation are drawn according to the thermodynamic definitions of these terms. Equations for the adiabatic saturation and wet-bulb temperature lines on the chart are as follows (Geankoplis, 1993)

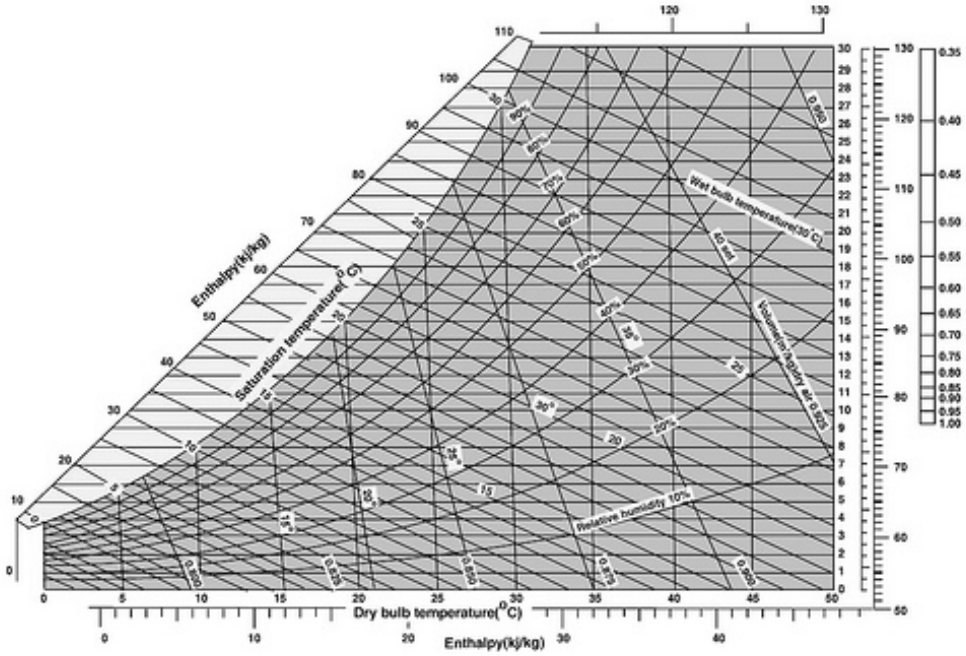

Figure 1.1. Psychrometric chart for Air-water system

Most handbooks of engineering provide more detailed psychrometric charts including additional information and extended temperature ranges. Mujumdar (1995) includes numerous psychrometric charts for several gas-organic vapor systems as well.

$$\frac{Y-Y_{as}}{T-T_{as}}=-\frac{c_s}{\lambda_{as}}=-\frac{1.005+1.88Y}{\lambda_{as}} \tag{1.1}$$

and

$$\frac{Y-Y_{wb}}{T-T_{wb}}=-\frac{h/M_{air}k_y}{\lambda_{wb}} \tag{1.2}$$

The ratio ($h/M_{air}k_y$), the psychrometric ratio, lies between 0.96 - 1.005 for air-water vapor mixtures; thus it is nearly equal to the value of humid heat c_s. If the effect of humidity is neglected, the adiabatic saturation and wet-bulb temperatures (T_{as} and T_{wb}, respectively) are almost equal for the air-water system. Note, however, that T_{as} and T_w are conceptually quite different. The adiabatic saturation temperature is a gas temperature and a thermodynamic entity while the wet-bulb temperature is a heat and mass transfer rate-based entity and refers to the temperature of the liquid phase. Under constant drying conditions, the surface of the drying material attains the wet-bulb temperature if heat transfer is by pure convection. The wet-bulb temperature is independent of surface geometry as a result of the analogy between heat and mass transfer

Table 1.2. Basic terminologies in drying

Terms/Symbol	Meaning
Adiabatic saturation temperature, T_{ad}	Equilibrium gas temperature reached by unsaturated gas and vaporizing liquid under adiabatic conditions. Only for air/water system, it is equal to the wet bulb temperature
Bound moisture	Liquid physically and/or chemically bound to solid matrix so as to exert a vapor pressure lower than that of pure liquid at the same temperature
Constant rate drying period, N_C	Under constant drying conditions, drying period when evaporation rate per unit drying area is constant (when surface moisture is removed
Dew point, T_d	Temperature at which a given unsaturated air-vapor mixture becomes saturated
Dry bulb temperature, T_{db}	Temperature measured by a (dry) thermometer immersed in vapor-gas mixture.
Equilibrium moisture content, X_e	At a given temperature and pressure, the moisture content of moist solid in equilibrium with the gas-vapor mixture (zero for non-hygroscopic materials)
Critical moisture content, X_c	Moisture content at which the drying rate first begins to drop (under constant drying conditions)
Falling rate period N_F	Drying period under constant drying conditions during which the rate false continuously with time
Free moisture,	Moisture content in excess of the equilibrium moisture content (hence free to be removed) at given air humidity and temperature.
Humid heat	Heat required to raise the temperature of unit mass of dry air and its associated vapor through one degree (J kg^{-1} K^{-1})
Humidity, absolute, Y	Mass of water vapor per unit mass of dry air (kg kg^{-1})
Humidity, relative	Ratio of partial pressure of water vapor in gas-vapor mixture to equilibrium vapor pressure at the same temperature.
Unbound moisture	Moisture in solid which exerts vapor pressure equal to that of pure liquid at the same temperature.
Water activity, a_w	Ratio of vapor pressure exerted by water in solid to that of pure water at the same temperature
Wet bulb temperature, T_{wb}	Liquid temperature attained when large amount of air-vapor mixture is contacted with the surface. In purely convective drying, drying surface reaches T_{wb} during constant rate period
Wet bulb temperature, T_{wb}	Liquid temperature attained when large amount of air-vapor mixture is contacted with the surface. In purely convective drying, drying surface reaches T_{wb} during constant rate period

1.3.1.2. Water Activity

In drying of some materials, which require careful hygienic attention, e.g., food, the availability of water for growth of microorganisms, germination of spores, and participation in several types of chemical reaction becomes an important issue. This availability, which depends on relative pressure, or water activity, aw, is defined as the ratio of the partial pressure, *P*, of water over the wet solid system to the equilibrium vapor pressure, pw, of water at the same temperature. Thus, a_w, which is also equal to the equilibrium relative humidity of the surrounding humid air, is defined as:

$$a_w = \frac{p}{p_w} = \frac{RH_{eq}}{100} \tag{1.3}$$

Different shapes of the *X* versus a_w curves are observed, depending on the type of material (e.g., high, medium or low hygroscopicity solids) and which will be discussed in the next section on sorption isotherms.

Water activity (a_w) is one of the most critical factors in determining quality and safety of the goods which are consumed every day. Water activity affects the shelf life, safety, texture, flavor, and smell of foods. It is also important to the stability of pharmaceuticals and cosmetics. While temperature, pH and several other factors can influence if and how fast organisms will grow in a product, water activity may be the most important factor in controlling spoilage. It predicts stability with respect to physical properties, rates of deteriorative reactions, and microbial growth. Foods containing proteins and carbohydrates, for example, are prone to non-enzymatic browning reactions, called Maillard reactions. The likelihood of Maillard reactions browning a product increases as the water activity increases, reaching a maximum at water activities in the range of 0.6 to 0.7 (Okos et al., 1992). In some cases, though, further increases in water activity will hinder Maillard reactions. So, for some samples, measuring and controlling water activity is a good way to control Maillard browning problems.

Table 1.3 lists the measured minimum a_w values for microbial growth or spore germination. If a_w is reduced below these values by dehydration or by adding water-binding agents like sugars, glycerol, or salt, microbial growth is inhibited. Such additives should not affect the flavor, taste, or other quality criteria, however. Since the amounts of soluble additives needed to depress a_w even by 0.1 is quite large, dehydration becomes particularly attractive for high moisture foods as a way to reduce aw. **Figure 1.2** shows schematically the water activity versus moisture content curve for different types of food. Rockland and Beuchat (1987) provide an extensive compilation of results on water activity and its applications.

Figure 1.3 shows the general nature of the deterioration reaction rates as a function of aw for food systems. Aside from microbial damage, which typically occurs for a_w > 0.70, oxidation, non-enzymatic browning (Maillard reactions) and enzymatic reactions can occur even at very low aw levels during drying. Laboratory or pilot testing is essential to ascertain that no damage occurs in the selected drying process since this cannot, in general, be predicted.

Table 1.3. Minimum water activity, aw, for microbial growth and spore germination (adapted from Brockmann, 1973)

Micro-organism	Water activity
Organisms producing slime on meat	0.98
Pseudomonas, Bacillus cereus spores	0.97
B. subtilis, C. botulinum spores	0.95
C. botulinum, Salmonella	0.93
Most bacteria	0.91
Most yeast	0.88
Aspergillus niger	0.85
Most molds	0.80
Halophilic bacteria	0.75
Xerophilic fungi	0.65
Osmophilic yeast	0.62

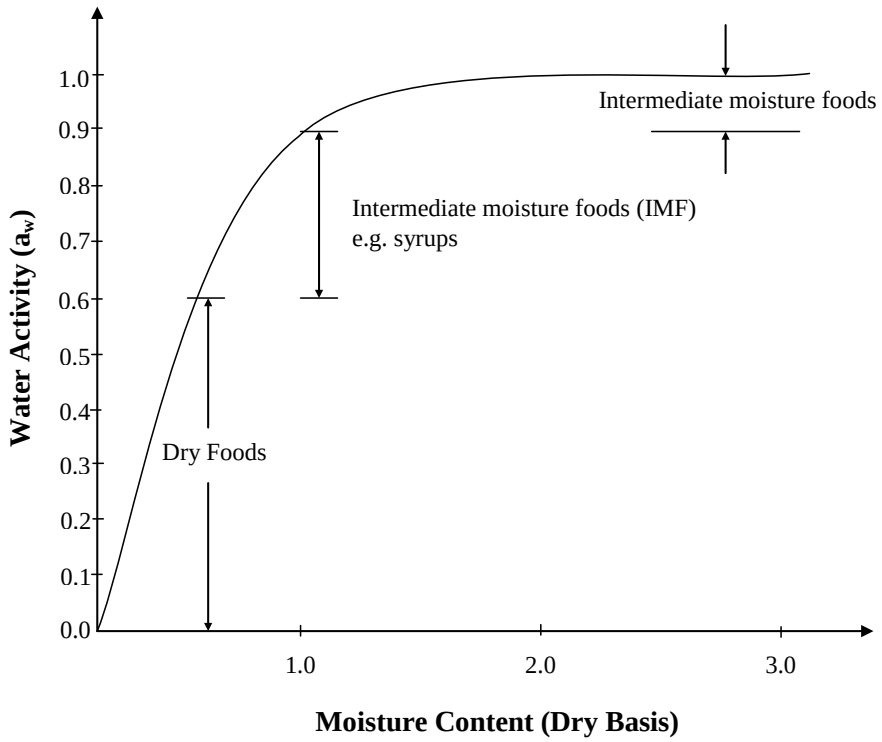

Figure 1.2. Water activity versus moisture content plot for different types of food

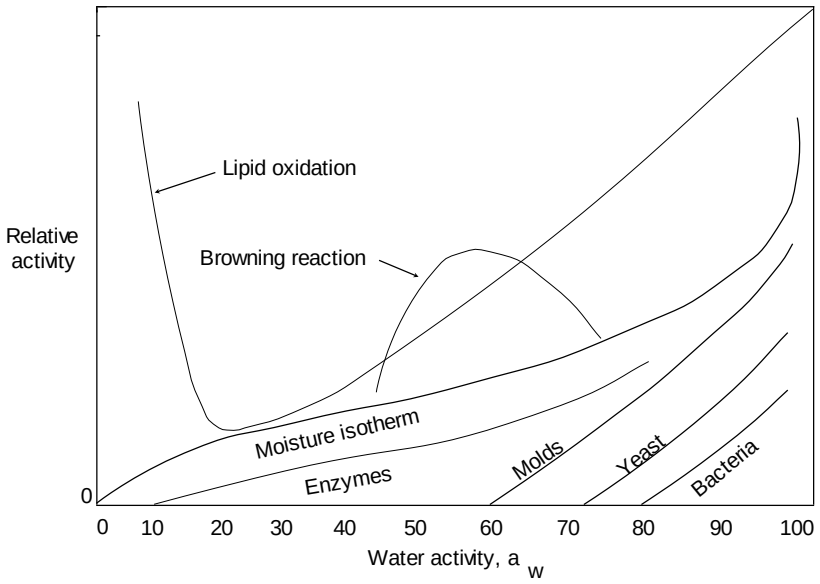

Figure 1.3. Deterioration rates as a function of water activity for food systems

Water activity is temperature dependent. Temperature changes water activity due to changes in water binding, dissociation of water, solubility of solutes in water, or the state of the matrix. Although solubility of solutes can be a controlling factor, control is usually from the state of the matrix. Since, the state of the matrix (glassy vs. rubbery state) is dependent on temperature, one should not be surprised that temperature affects the water activity of the food. The effect of temperature on the water activity of a food is product specific. Some products shows an increase in water activity with increasing temperature, others decrease a_w with increasing temperature, while most high moisture foods have negligible change with temperature. One can therefore not predict even the direction of the change of water activity with temperature, since it depends on how temperature affects the factors that control water activity in the food.

1.3.1.3. Equilibrium Moisture Content and Sorption Isotherms

The moisture content of a wet solid in equilibrium with air of given humidity and temperature is termed the equilibrium moisture content (EMC). A plot of EMC at a given temperature versus the relative humidity is termed sorption isotherm. An isotherm obtained by exposing the solid to air of increasing humidity gives the adsorption isotherm. That obtained by exposing the solid to air of decreasing humidity is known as the desorption isotherm. Clearly, the latter is of interest in drying as the moisture content of the solids progressively decreases. Most drying materials display “hysteresis” in that the two isotherms are not identical.

Figure 1.4 shows the general shape of the typical sorption isotherms. They are characterized by three distinct zones, A, B and C, which are indicative of different water binding mechanisms at individual sites on the solid matrix. In region A, water is tightly bound to the sites and is unavailable for reaction. In this region, there is essentially monolayer adsorption of water vapor and no distinction exists between the adsorption and desorption isotherms. In region B, the water is more loosely bound. The vapor pressure

depression below the equilibrium vapor pressure of water at the same temperature is due to its confinement in smaller capillaries. Water in region C is even more loosely held in larger capillaries. It is available for reactions and as a solvent.

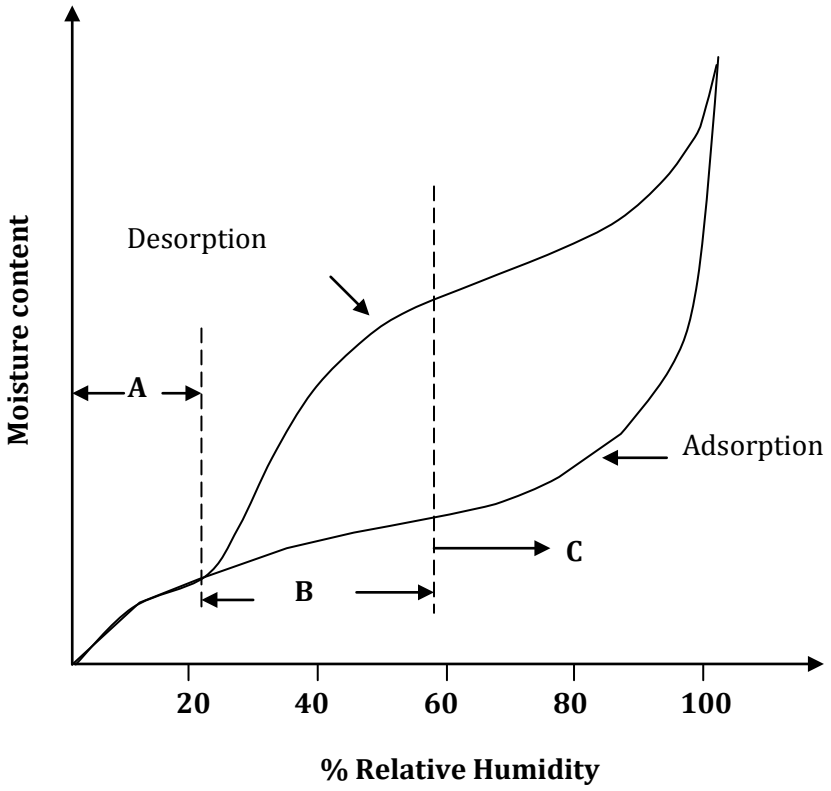

Figure 1.4. Typical sorption isotherm

Figure 1. 5 shows the various types of moisture defined in **Error! Reference source not found.**. Desorption isotherms are also dependent on external pressure. However, in all practical cases of interest, this effect may be neglected.

According to Keey (1978), the temperature dependence of the equilibrium moisture content can be correlated by:

$$\left[\frac{\Delta X^*}{\Delta T}\right]_{\Psi=cons\,tan\,t} = -\alpha X^* \tag{1.4}$$

where X^* is the dry-basis equilibrium moisture content, T is the temperature and Ψ is the relative humidity of air. The parameter ranges from 0.005 to 0.01 K^{-1}. This correlation may be used to estimate the temperature dependence of X^* if no data are available.

For hygroscopic solids, the enthalpy of the attached moisture is less than that of pure liquid by an amount equal to the binding energy, which is also termed the enthalpy of wetting, H_w (Keey, 1978). It includes the heat of sorption, hydration and solution and may be estimated from the following equation:

$$\left.\frac{d(ln\,\Psi)}{d(1/T)}\right|_{X=constant} = -\frac{\Delta H_w}{R_g T} \tag{1.5}$$

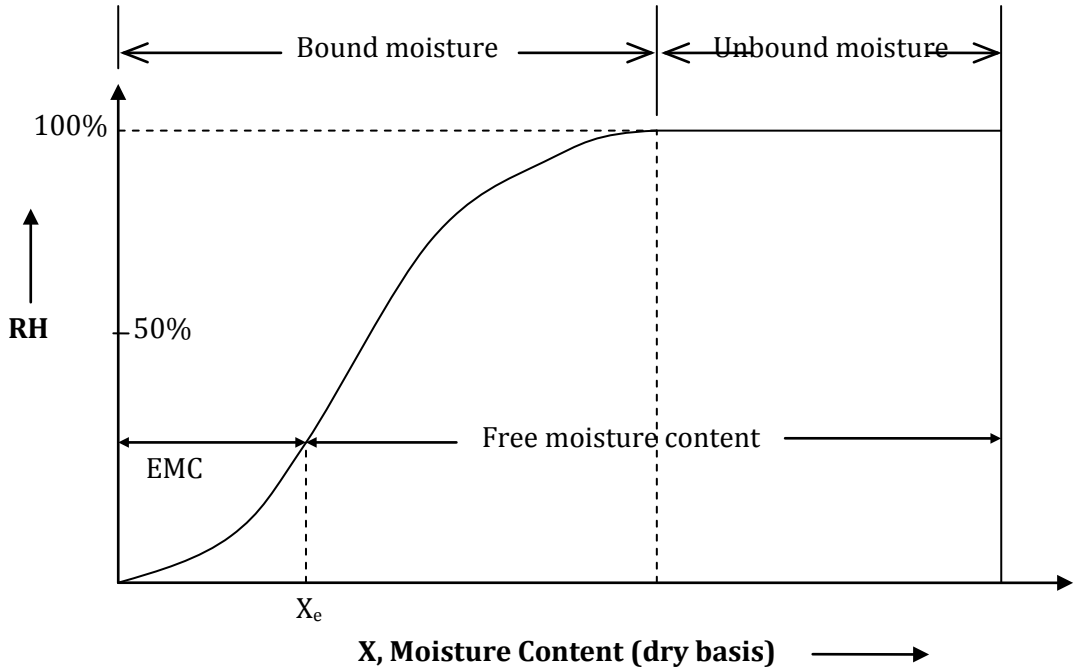

Figure 1. 5. Various types of moisture content

A plot of $\ln(\Psi)$ against $1/T$ is linear with a slope of H_w/R_g where R_g is the universal gas constant ($R_g = 8.314 \times 10^3$ kg kgmol^{-1} K^{-1}). Note that the total heat required to evaporate bound water is the sum of the latent heat of vaporization and the heat of wetting; the latter is a function of the moisture content X. The heat of wetting is zero for unbound water and increases with decreasing X. Since H_w is responsible for lowering the vapor pressure of bound water, at the same relative humidity, H_w is almost the same for all materials (Keey, 1978).

For most materials, the moisture binding energy is positive; generally it is a monotonically decreasing function of the moisture content, with a value of zero for unbound moisture. For hydrophobic food materials (e.g., peanut oil, starches at lower temperatures) the binding energy can, however, be negative.

Figure 1.6 shows schematically possible shapes of different sorption isotherms. Type 1 is the well known Langmuir isotherm obtained by assuming monomolecular adsorption of gas by the porous solids in a finite volume of voids. Type 2 is sigmoid isotherm generally found for soluble products. Type 3 is known as Flory-Higgins isotherm, accounts for a solvent or plasticizer such as glycerol above the glass transition temperature. The type 4 represents adsorption for swellable solids until maximum of hydration site are reached. Type 5 is the BET multilayer adsorption isotherm observed for adsorption of water on charcoal. Two isotherms commonly found in food products are types 2 and 4 (Basu et al., 2006).

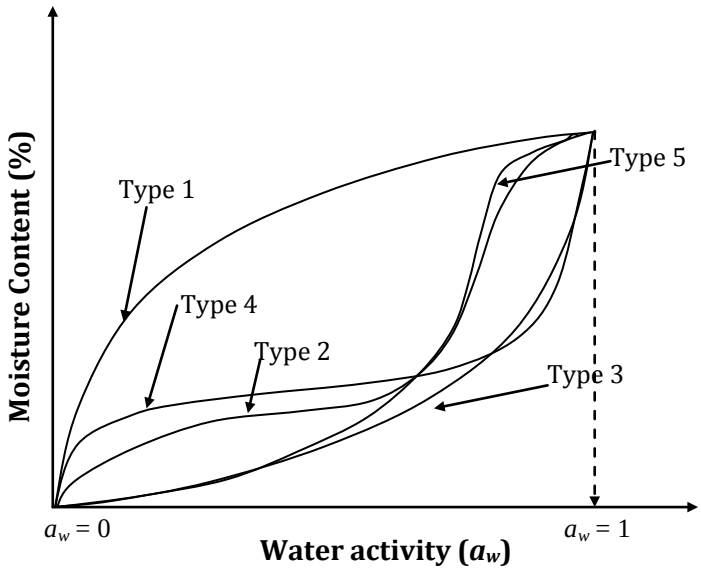

Figure 1.6. Different types of sorption isotherms

Measurement of sorption isotherm

The sorption isotherms are determined using diverse methods which can be classified as, gravimetric, manometric and hygrometric methods. The gravimetric method is the most common and involves measurement of mass changes which is done continuous or periodic manner. The manometric methods involve use of highly sensitive manometers to measure the vapor pressure of water in equilibrium with the food product under study at particular moisture content. However, the hygrometric method measures the relative humidity of the air surrounding the food material of given moisture content (Basu et al., 2006). There have been numerous efforts to develop more accurate methods for measurement of sorption isotherms. The most commonly method uses small containers with salt solutions at the bottom to maintain certain relative humidity in the container where the food material is placed. The main drawback of this process is long equilibration time and inability to maintain high relative humidity values. Mujumdar (2000) has reported the most important features of the method to be used, which should involve maintaining the constant temperature, accurate measurement of the initial moisture content, maintaining desired relative humidity around the sample, faster equilibration and repeatability. See Mujumdar (2006), Handbook of Industrial Drying for discussion of various experimental methods for measurement of equilibrium moisture content

Modeling of sorption isotherm

Various researchers have discussed modeling of sorption isotherms and numerous models have been proposed based on different theories. Some 80 correlations, ranging from those based on theory to those that are purely empirical, have appeared in the literature. Two of the most extensive compilations are due to Wolf et al. (1985) and Iglesias and Chirife (1982). Aside from temperature, the physical structure as well as composition of the material also affects water sorption. The pore structure and size as well as physical and/or chemical transformations during drying can cause significant variations

in the moisture binding ability of the solid. **Table 1.4** summarizes some of the commonly used models for sorption isotherms.

Table 1.4. Various sorption models

Type of Model	Equation	Details
Langmuir equation	$a_w\left(\frac{1}{X}-\frac{1}{X_m}\right)=\frac{1}{CX_m}$	
Brunauer-Emmett-Teller (BET) equation	$\frac{X}{X_m}=\frac{Ca_w}{(1-a_w)[1+(C-1)a_w]}$	C is a dimensionless parameter depending on heat of sorption for monolayer region
Oswin equation	$X=K\left(\frac{a_w}{1-a_w}\right)^N$	K is temperature dependent
Halsey equation	$a_w=\exp\left(-\frac{AX^{-C}}{RT}\right)$	A is temperature dependent
Chung-Pfost equation	$a_w=\exp\left(\frac{-A}{T+C}\exp(-BM)\right)$	
Modified Henderson equation	$a_w=1-\exp(-A(T+B)\,X^C)$	A, B and C are constants
Chung-Pfost equation	$a_w=\exp\left[\frac{-A}{T+C}\exp(-BM)\right]$	
Guggenheim-Anderson-Boer (GAB) equation; modification of BET equation	$\frac{X}{X_m}=\frac{CKa_w}{(1-Ka_w)(1-Ka_w+KCa_w)}$	C and K are dimensionless parameters depending on heat of sorption for mono and multilayer region
Lewicki model	$X=A\left(\frac{1}{a_w}-1\right)^{b-1}$	A and b are constants
Peleg model	$X=X_i\left(\frac{t}{k_1+k_2\,t}\right)$	

1.3.2. Drying Kinetics

Consider the drying of a wet solid under fixed drying conditions. In the most general cases, after an initial period of adjustment, the dry-basis moisture content, X, decreases linearly with time, t, following the start of the evaporation. This is followed by a nonlinear decrease in X with t until, after a very long time, the solid reaches its equilibrium moisture content, X^* and drying stops. In terms of free moisture content, defined as:

$$X_f = (X - X^*) \tag{1.6}$$

the drying rate drop to zero at $X_f = 0$.

By convention, the drying rate, N, is defined as:

$$N = -\frac{M_s}{A}\frac{dX}{dt} or -\frac{M_s}{A}\frac{dX_f}{dt} \tag{1.7}$$

under constant drying conditions. Here, N (kg m^{-2} h^{-1}) is the rate of water evaporation, A is the evaporation area (may be different from heat transfer area) and M_s is the mass of bone dry solid. If A is not known, then the drying rate may be expressed in kg water evaporated per hour.

A plot of N versus X (or X_f) is the so-called drying rate curve. This curve must always be obtained under constant drying conditions. Note that, in actual dryers, the drying material is generally exposed to varying drying conditions (e.g., different relative gas-solid velocities, different gas temperatures and humidities, different flow orientations). Thus, it is necessary to develop a methodology in order to interpolate or extrapolate limited drying rate data over a range of operating conditions.

Figure 1.7 shows a typical "textbook" drying rate curve displaying an initial constant rate period where $N = N_c$ = constant. The constant rate period is governed fully by the rates of external heat and mass transfer since a film of free water is always available at the evaporating surface. This drying period is nearly independent of the material being dried. Many foods and agricultural products, however, do not display the constant rate period at all since internal heat and mass transfer rates determine the rate at which water becomes available at the exposed evaporating surface.

At the so-called critical moisture content, X_c, N begins to fall with further decrease in X since water cannot migrate at the rate N_c to the surface due to internal transport limitations. The mechanism underlying this phenomenon depends on both the material and drying conditions. The drying surface becomes first partially unsaturated and then fully unsaturated until it reaches the equilibrium moisture content X^*.

Note that a material may display more than one critical moisture contents at which the drying rate curve shows a sharp change of shape. This is generally associated with changes in the underlying mechanisms of drying due to structural or chemical changes. It is also important to note that X_c is not solely a material property. It depends on the drying rate under otherwise similar conditions. It must be determined experimentally. It is easy to see that N_c can be calculated using empirical or analytical techniques to estimate the external heat/mass transfer rates (Keey, 1978; Geankoplis, 1993). Thus,

$$N_c = \frac{\sum q}{\lambda_s} \tag{1.8}$$

where $\sum q$ represents the sum of heat fluxes due to convection, conduction and/or radiation and λ_s is the latent heat of vaporization at the solid temperature. In the case of purely convective drying, the drying surface is always saturated with water in the constant rate period and thus the liquid film attains the wet-bulb temperature. The wet-

bulb temperature is independent of the geometry of the drying object due to the analogy between heat and mass transfer.

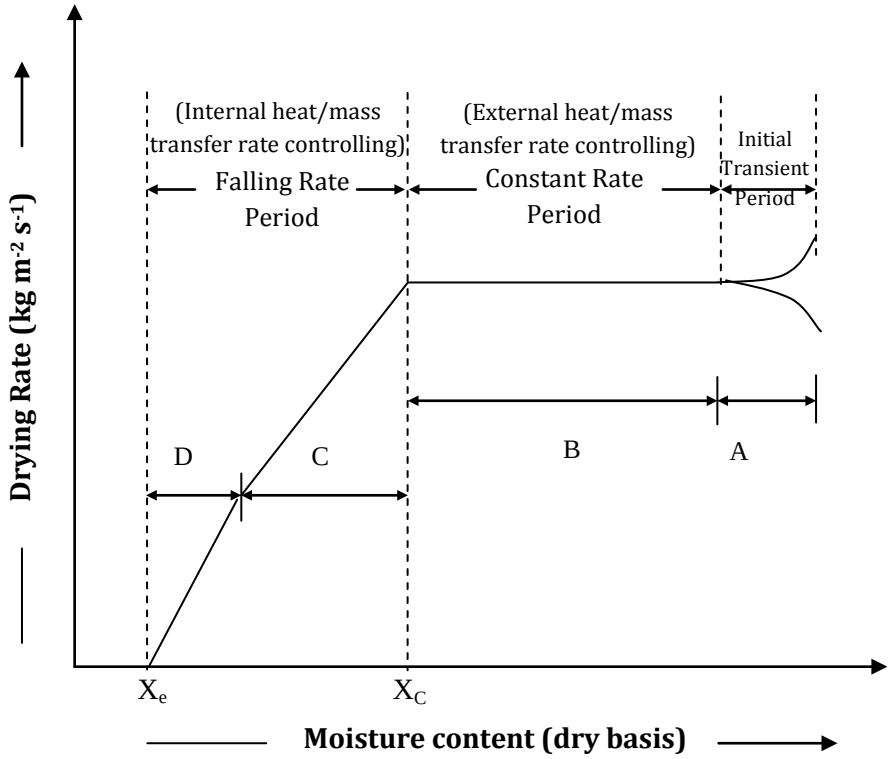

Figure 1.7. Typical textbook batch drying rate curve under constant drying conditions

The drying rate in the falling rate period(s) is a function of X (or X_f) and must be determined experimentally for a given material being dried in a given type of dryer. If the drying rate curve (N versus X) is known, the total drying time required to reduce the solid moisture content from X_1 to X_2 can be simply calculated by:

$$t_d = -\int_{X_1}^{X_2} \frac{M_s}{A}\frac{dX}{N} \tag{1.9}$$

Table 1.5 lists expressions for the drying time for constant rate, linear falling rates and a falling rate controlled by liquid diffusion of water in a thin slab. The subscripts c and f refer to the constant and falling rate periods, respectively. The total drying time is, of course, a sum of drying times in two succeeding periods. Different analytical expressions are obtained for the drying times t_f depending on the functional form of N or the model used to describe the falling rate, e.g., liquid diffusion, capillarity, evaporation-condensation. For some solids, a receding front model (wherein the evaporating surface recedes into the drying solid) yields a good agreement with experimental observations. The principal goal of all falling rate drying models is to allow reliable extrapolation of drying kinetic data over various operating conditions and product geometries.

The expression for t_f in **Table 1.5** using the liquid diffusion model (Fick's second law of diffusion form applied to diffusion in solids with no real fundamental basis) is obtained by solving analytically the following partial differential equation:

$$\frac{\partial X_f}{\partial t} = D_L \frac{\partial^2 X_f}{\partial x^2} \tag{1.10}$$

subject to the following initial and boundary conditions:

$$\left.\begin{aligned} &X_f = X_i, \text{ everywhere in the slab at } t = 0 \\ &X_f = 0, \text{ at } x = a \text{ (top, evaporating surface), and} \\ &\frac{\partial X_f}{\partial x} = 0, \text{ at } x=0 \text{ (bottom, non-evaporating surface)} \end{aligned}\right\} \tag{1.11}$$

The model assumes one-dimensional liquid diffusion with constant effective diffusivity, D_L, and no heat (Soret) effects. X_2 is the average free moisture content at $t = t_f$ obtained by integrating the analytical solution $X_f(x,t_f)$ over the thickness of the slab, a. The expression in **Table 1.5** is applicable only for long drying times since it is obtained by retaining only the first term in the infinite series solution of the partial differential equation.

Table 1.5. Drying times for various drying rate models (Mujumdar, 1997)

Model	Drying time
Kinetic model, $N = -\frac{M_s}{A}\frac{dX}{dt}$	t_d = Drying time to reach final moisture content X_2 from initial moisture content X_1
$N = N(X)$ (General)	$t_d = \frac{M_s}{A}\int_{X_2}^{X_1}\frac{dX}{N}$
$N = N_c$ (Constant rate period)	$t_c = -\frac{M_s}{A}\frac{(X_2 - X_1)}{N_c}$
$N = aX + b$ (Falling rate period)	$t_f = \frac{M_s}{A}\frac{(X_1 - X_2)}{(N_1 - N_2)}ln\frac{N_1}{N_2}$
$N = Ax$ $X^* \le X_2 \le X_c$	$t_f = \frac{M_s X_c}{AN_c}ln\frac{X_c}{X_2}$
Liquid diffusion model D_L = constant, $X_2 = X_c$ Slab; one-dimensional diffusion, evaporating surface at X^*	$t_f = \frac{4a^2}{\pi D_L}ln\frac{8X_1}{\pi^2 X_2}$ X = average free moisture content a = half-thickness of slab

The moisture diffusivity in solids is a function of both temperature and moisture content. For strongly shrinking materials the mathematical model used to define DL must account for the changes in diffusion path as well. The temperature dependence of diffusivity is adequately described by the Arrhenius equation as follows:

$$D_L = D_{L0}\, exp[-E_a / R_g T_{abs}] \tag{1.12}$$

where D_L is the diffusivity, E_a is the activation energy and T_{abs} is the absolute temperature. Okos et al. (1992) have given an extensive compilation of D_L and E_a values for various food materials. Zogzas et al. (1996) provide methods of moisture diffusivity measurement and an extensive bibliography on the topic. Approximate ranges of effective moisture diffusivity for some selected materials are given in **Table 1.6**. It should be noted that D_L is not a true material property and care should be taken in applying effec-

tive diffusivity correlations obtained with simple geometric shapes (e.g., slab, cylinder or sphere) to the more complex shapes actually encountered in practice as this may lead to incorrect calculated results (Gong et al., 1997).

Table 1.6. Approximate ranges of effective moisture diffusivity in some food materials (Zogzas et al. (1996), Marinos-Kouris and Marouris (1995) and other sources)

Material	Moisture content (kg/kg, d.b.)	Temperature (°C)	Diffusivity (m^2/s)
Alfalfa stems	3.70	26	2.6×10^{-10} - 2.6×10^{-9}
Animal feed	0.01 - 0.15	25	1.8×10^{-11} - 2.8×10^{-9}
Apple	0.10 - 1.50	30 - 70	1.0×10^{-11} - 3.3×10^{-9}
Avocado	-	30-58	3.3×10^{-10} - 1.2×10^{-9}
Banana	0.01 - 3.50	20 - 40	3.0×10^{-13} - 2.1×10^{-10}
Beef raw (freeze dried)	0.127	25	3.07×10^{-11}
Beet	-	65	1.5×10^{-9}
Biscuit	0.10 - 0.60	20 -100	8.6×10^{-10} - 9.4×10^{-8}
Bread	0.1-0.75	20-100	2.8×10^{-9} - 9.6×10^{-7}
Carrot	0.01 - 5.00	30 - 70	1.2×10^{-9} - 5.9×10^{-9}
Cauliflower	11.5 - 0.05	60-90	2.54×10^{-12} - 3.8×10^{-12}
Coconut (albumen)	0.2-0.6	45-110	4.6×10^{-11} - 6.6×10^{-10}
Coffee extra	0.08-1.5	30-70	1.0×10^{-11} - 3.3×10^{-10}
Corn	0.04-0.4	10-90	1.0×10^{-12} -1.0×10^{-10}
Egg liquid	-	85 -105	1.0×10^{-11} - 1.5×10^{-11}
Fish muscles	0.05 - 0.30	30	8.1×10^{-11} - 3.4×10^{-10}
Garlic	0.2-1.6	22-58	1.1×10^{-11} - 2.0×10^{-10}
Garlic	0.06-1.89	40-70	1.3×10^{-10} – 3.2×10^{-9}
Grain (sorghum)	0.021	55	2.8×10^{-11}
Glucose	0.08 - 1.50	30 - 70	4.5×10^{-12} - 6.5×10^{-10}
Lentil	0.1-0.2	30-50	2.8×10^{-11} - 2.8×10^{-9}
Milk (dry)	0.13	25	2.1×10^{-11}
Muffin	0.10 - 0.95	20 -100	8.5×10^{-10} - 1.6×10^{-7}
Onion	0.05-18.7	60-80	2.3×10^{-10} - 6.6×10^{-9}
Peanut (roasted)	0.01-0.02	25	3.8×10^{-12}
Pepper (Green)	0.04-16.2	60-80	3.8×10^{-10} - 1.2×10^{-8}
Pineapple	0.2-2.0	20-60	1.62×10^{-10} - 1.2×10^{-9}
Potato	0.03-5.0	60-100	2.8×10^{-10} - 5.3×10^{-9}
Potato (sweet)	0.1-3.5	32	3.7×10^{-10} - 4.35×10^{-10}
Raisins	0.15 - 2.40	60	5.0×10^{-11} - 2.5×10^{-10}
Rice	0.10 - 0.25	30 - 50	3.8×10^{-8} - 2.5×10^{-7}
Soybeans	0.07	30	7.5×10^{-13} - 5.4×10^{-12}
Starch gel	0.20 - 3.00	30 - 50	1.0×10^{-10} - 1.2×10^{-9}
Tobacco leaf	-	30 - 50	3.2×10^{-11} - 8.1×10^{-11}
Tomato (concentrate)	5.7	60-100	1.7×10^{-10} - 6.5×10^{-9}
Wheat	0.12 - 0.30	21 - 80	6.9×10^{-12} - 2.8×10^{-10}

In addition to being dependent on geometric shapes, diffusivity depends as well on the drying conditions. At very high activity levels, no differences might be observed but at lower activity levels, the diffusivities may differ by an order-of-magnitude due to the inherently different physical structure of the dried product. Thus, the effective diffusivi-

ty is regarded as a lumped property that does not really distinguish between the transport of water by liquid or vapor diffusion, capillary or hydrodynamic flow due to pressure gradients set up in the material during drying. Further, the diffusivity values will show marked variations if the material undergoes glass transition during the drying process. Keey (1978) has provided analytical expressions for liquid diffusion and capillarity models of falling rate drying. **Table 1.7** gives solution of the one-dimensional transient partial differential equations for cartesian, cylindrical and spherical coordinate systems. These results can be utilized to estimate the diffusivity from the falling rate drying data or to estimate the drying rate and drying time if the diffusivity value is known.

It is noteworthy that the diffusivity, D_L, is a strong function of X_f as well as temperature and must be determined experimentally. Thus, the liquid diffusion model should be regarded purely as an empirical representation drying in the falling rate period. More advanced models are, of course, available but their widespread use in the design of dryers is hampered by the need for extensive empirical information required to solve the governing equations. Turner and Mujumdar (1997) provide a wide assortment of mathematical models of drying and dryers, and also discuss the application of various techniques for the numerical solution of the complex governing equations.

One simple approach for interpolating a given falling rate curve over a relatively narrow range of operating conditions is that first proposed by van Meel (1958). It is found that the plot of normalized drying rate ν = N/Nc versus normalized free moisture content $\eta = (X - X^*)/(X_c - X^*)$ was nearly independent of the drying conditions. This plot, called the characteristic drying rate curve, is illustrated in **Figure 1.8**. Thus, if the constant rate-drying rate, N_c, can be estimated and the equilibrium moisture content data are available, then the falling rate curve can be estimated using this highly simplified approach. Extrapolation over wide ranges is not recommended, however.

Table 1.7. Solution to Fick's second law for some simple geometries (Pakowski and Mujumdar, 1995)

Geometry	Boundary conditions	Dimensionless average free M.C.
Flat plate of thickness $2b$	$t = 0; -b < z < b; X = X_0$ $t > 0; z = \pm b; X = X^*$	$X = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{(2n-1)} \exp\left[-(2n-1)^2 \frac{\pi^2}{4b}\left(\frac{D_L t}{b}\right)\right.$
Infinitely long cylinder of radius R	$t = 0; 0 < r < R; X = X_0$ $t > 0; r = R; X = X^*$	$X = 4\sum_{n=1}^{\infty} \frac{1}{R^2 \alpha_n^2} \exp(-D_L \alpha_n^2 t)$ where α_n are positive roots of the equation $J_0(R\alpha_n) = 0$
Sphere of radius R	$t = 0; 0 < r < R; X = X_0$ $t > 0; r = R; X = X^*$	$X = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left[\frac{-n^2\pi^2}{R}\left(\frac{D_L t}{R}\right)\right]$

Waananen et al. (1993) have provided an extensive bibliography of over 200 references dealing with models for drying of porous solids. Such models are useful to de-

scribe drying processes for the purposes of engineering design, analysis and optimization. A mathematical description of the process is based on the physical mechanisms of internal heat and mass transfer that control the process resistances, as well as the structural and thermodynamic assumptions made to formulate the model. In the constant rate period, the overall drying rate is determined solely by the heat and mass transfer conditions external to the material being dried, such as the temperature, gas velocity, total pressure and partial pressure of the vapor. In the falling rate period, the rates of internal heat and mass transfer determine the drying rate. Modeling of drying becomes complicated by the fact that more than one mechanism may contribute to the total mass transfer rate and the contributions from different mechanisms may even change during the drying process.

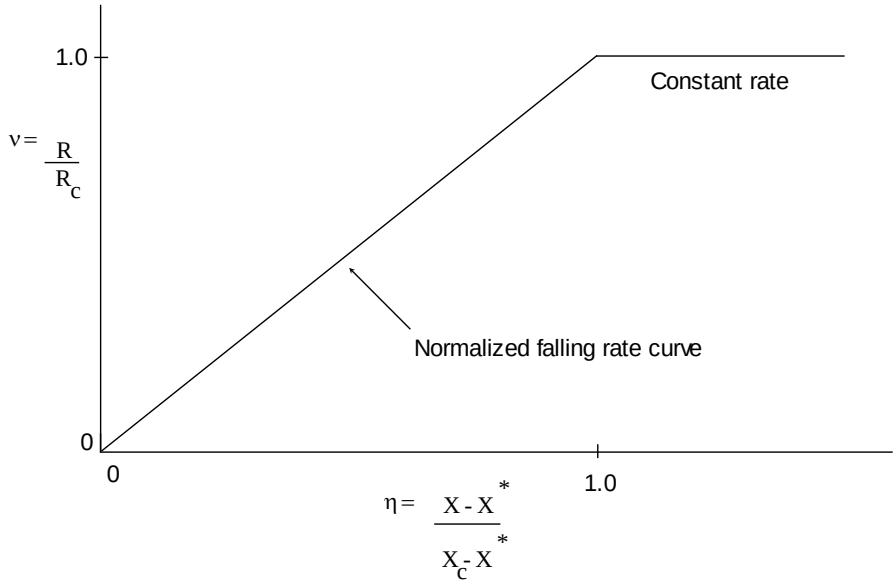

Figure 1.8. Characteristic drying rate curve

Diffusional mass transfer of the liquid phase, as discussed earlier, is the most commonly assumed mechanism of moisture transfer used in modeling drying that takes place at temperatures below the boiling point of the liquid under locally applied pressure. At higher temperatures, the pore pressure may rise substantially and cause a hydrodynamically driven flow of vapor, which, in turn, may cause a pressure driven flow of liquid in the porous material.

For solids with continuous pores, a surface tension driven flow (capillary flow) may occur as a result of capillary forces caused by the interfacial tension between the water and the solid. In the simplest model, a modified form of the Poiseuille flow can be used in conjunction with the capillary force equation to estimate the rate of drying. Geankoplis (1993) has shown that such a model predicts the drying rate in the falling rate period to be proportional to the free moisture content in the solid. At low solid moisture contents, however, the diffusion model may be more appropriate.

The moisture flux due to capillarity can be expressed in terms of the product of a liquid conductivity parameter and moisture gradient. In this case, the governing equation has, in fact, the same form as the diffusion equation.

For certain materials and under conditions such as those encountered in freeze drying, a "receding-front" model involving a moving boundary between "dry" and "wet" zones often describes the mechanism of drying much more realistically than does the simple liquid diffusion or capillarity model. Examination of the freeze drying of a thin slab indicates that the rate of drying is dependent on the rate of heat transfer to the "dry-wet" interface and the mass transfer resistance offered by the porous dry layer to permeation of the vapor which sublimes from the interface. Because of the low pressures encountered in freeze drying, Knudsen diffusion may be significant. Liapis and Marchello (1984) have discussed models of freeze drying involving both unbound and bound moisture.

When drying materials under intense drying conditions, diffusion or capillarity models generally do not apply. If evaporation can occur within the material there is a danger of the so-called "vapor-lock" that occurring within the capillary structure causing breaks in liquid-filled capillaries. This phenomenon can cause departure from the classical drying curve, e.g., no constant rate drying may appear under intense drying conditions but may do so under milder drying conditions (Zaharchuk, 1993).

1.4. ADVANCES IN FOOD DRYING

1.4.1. Use of advanced computational tools

Drying is a highly energy intensive unit operation. In food sectors, it is necessary to maintain the product quality during drying in addition to the reduced drying cost. Some products can be very high valued such as mango, strawberry, some marine products; even highly expensive freeze drying can also be used for these products with enough profit margins. However, products such as banana, sapota, green peas, corn, roots, vegetables cannot be dried using such expensive drying route. Hence it is very necessary to develop cost-effective and innovative drying methods in food sectors. It is accepted fact that mathematical modeling can be very helpful to achieve these expectations. Further, when a drying method is to be developed for certain product, it is difficult to test all the methods experimentally which is time consuming in addition to cost involvement. However, recently developed advanced computational tools can help compare different drying methods numerically.

Computational fluid dynamics is one of the well known tools used in various industrial sectors. It has been used in chemical industries to study numerous unit operations and can also be easily applied in drying. Jamaleddine and Ray (2010) have carried out a comprehensive review of the CFD techniques applied to diverse problems in industrial drying. They have reported that CFD solutions have been used in drying to optimize, to retrofit, to develop equipment and processing strategies and replacing expensive and time consuming experimentation. Mujumdar and Wu (2008) have highlighted the need for cost-effective solution that can push innovation and creativity in drying. This can be easily possible using highly efficient tools such as CFD. Some of the key advantages of CFD in the drying sector are its ability to give information on comparison of different geometries, its use as a powerful tool for troubleshooting purposes including the evaluation of the effect of various parameters even in complex geometries (Mujumdar and Wu,

2008). Mathematical modeling allows one to test innovative designs that may be too risky and too expensive as well as time-consuming to test experimentally.

Statistical tools have been used for years in almost all research sectors. Response Surface Methodology (RSM) is a statistical tool which is commonly used in drying of foods in recent years. RSM is mainly used for design of experiments and optimization of process parameters. This tool is used to relate several input parameters with the output parameters (also known as responses) using regression analysis. The significant parameters are then identified based on the relation between input and output parameters. Recently this technique has been used to optimize various operating parameters involved in drying process. Spray drying, micro-encapsulation, microwave drying are few examples where this technique is applied. In this e-book, a whole chapter is dedicated to this very important topic.

1.4.2. Reaction Engineering Approach in Drying

There are different ways to model drying processes, which is a necessary part for the development of innovative and energy efficient drying techniques. There are three different common approaches used for modeling the drying process. The concept of characteristic drying rate curve, use of empirical models: which are system specific and cannot be generalized as these does not involve any physical basis, the most famous model under this category is the Page model. The third approach is mechanistic models: which are based on the drying phenomenon as well as the physics involved and can be generalized, mainly involves coupled heat and mass diffusion equations. However, under mechanistic models, there are different mechanisms proposed and generally these models involve high mathematical complexity and determination of too many parameters. It is necessary to have simple, accurate and robust mathematical model with minimum mathematical complexity to reduce the computational time. Chen, 1998 has proposed Reaction Engineering Approach to model the drying processes.

Some of the constraints with characteristic drying rate curve approach are: one has to determine critical moisture content of the material which is a function of drying conditions, the experimental drying data is relatively scattered and the flux which is calculated using following equation is based on the wet bulb temperature (T_{WB}) for gas phase and not based on the actual surface temperature (T_S).

$$N = k_m \left(\rho_{v,sat}(T_S) - \rho_{v,\infty}\right) \approx k_m \left(\rho_{v,sat}(T_{wb}) - \rho_{v,\infty}\right) \tag{1.13}$$

Where, k_m is the mass transfer coefficient

However, according to REA model, which was intended particularly for small case of *Biot* number (< 0.1), the temperature of the sample air interface T_S is considered equal to the product temperature T_P.

Where *biot* number is defined as $Bi = \frac{h\,L_C}{k_s}$ (1.14)

According to REA the drying rate can be written as

$$m_S \frac{d\bar{X}}{dt} = k_m\, A \left(\rho_{v,s}(T_S) - \rho_{v,\infty}\right) \tag{1.15}$$

m_s is the dry mass of the solids and $\rho_{v,s}$ is the vapor concentration at the solid-gas interface. This is a unknown parameter and changes as the drying proceeds, but which is al-

ways less than $\rho_{v,\infty}$. The surface area for mass transfer can also change as the drying proceeds.

Chen 1998 has suggested that the surface vapor concentration can be written as

$$\rho_{v,s} = RH_S \cdot \rho_{v,sat}(T_S) \tag{1.16}$$

where, RH_S is the relative humidity at the interface, and it becomes 1 if the surface is covered by a liquid. Hence the equation becomes

$$m_S \frac{d\bar{X}}{dt} = k_m A \left(RH_S \cdot \rho_{v,sat}(T_S) - \rho_{v,\infty}\right) \tag{1.17}$$

RH_S and $\rho_{v,sat}$ can be approximated as follows

$$RH_S = \exp\left[-\frac{\Delta E_v}{RT_S}\right] \tag{1.18}$$

$$\rho_{v,sat} = K_v \exp\left[-\frac{E_v}{RT_S}\right] \tag{1.19}$$

where, ΔE_v is correction factor in apparent activation energy for drying due to the increasing difficulty of removing water, E_v is termed as activation energy for pure water evaporation (similar value of latent heat) and K_v is the apparent reaction frequency (for moist air at 1 atm, $K_v \approx 2.262236 \times 10^5$ kg.m^{-3} and $E_v \approx 40.207 \times 10^3$ J.mol^{-1}. After modifications the equation becomes

$$\begin{aligned} m_S \frac{d\bar{X}}{dt} &= -k_m A \left(K_v \exp\left[-\frac{E_v + \Delta E_v}{RT_S}\right] - \rho_{v,\infty}\right) \\ &= -k_m A K_v \exp\left[-\frac{E_v + \Delta E_v}{RT_S}\right] + k_m A \rho_{v,\infty} \end{aligned} \tag{1.20}$$

The first term on the right hand side is a zero order drying reaction while the second term is the first order wetting process. Chen, 2008 elaborates that if there is no hysteresis observed then the equation describes both the drying and wetting process. However, if there is a hysteresis, then different values of ΔE_v and thus K_v may corresponds to adsorption and desorption processes. There are various suggestions to modify these basic equations of the reaction engineering approach and can be found elsewhere. The REA has been successfully used to model drying of various products.

1.4.3. Advanced Drying Techniques for Foods

Although the conventional techniques used for food drying are well established, there is still need to develop new and innovative drying techniques (Kudra and Mujumdar, 2009; Mujumdar and Wu, 2008). Major reasons to trigger attempts for development of advanced drying techniques are: making the process cost effective, reducing the energy consumption, intensifying the drying rates (in turn reducing the size of the dryer required), improving the quality of dried food products, reducing the carbon foot print, increasing safety in operation and making the drying process easy to control. There are few facts that need to be highlighted with respect to food products. The drying of fruits mainly falls in the falling rate period hence it becomes a diffusion control process. However, higher temperatures cannot be implemented to enhance diffusion which may lead to thermal deterioration of the product. Higher temperature can also lead to unacceptable quality changes such as case hardening, flavor loss, nutritional loss and color degradation. Presence of microorganisms in drying medium can also lead to unfavorable quality of dried product; hence it needs to be filtered before using for drying. Freeze drying

is the best way to dehydrate most of the food products; however, it is associated with tremendous cost and cannot be applied for low value fruits and vegetables. Loss of volatiles is another important issue in drying of high valued fruits, spices, etc and needs to be handled properly but in a cost effective manner.

There have been numerous efforts from all around the world to come up with new ideas to achieve aforementioned goals in an innovative way. **Table 1.8** summarizes some of the advanced drying techniques developed for food products with their advantages and limitations. Some of these techniques will be discussed in detail in the chapters to follow. However, all the advanced techniques will not be covered as the main aim of the book is to provide knowledge about food drying to the readers from developing and underdeveloped countries where applying some of these techniques may not be feasible. Kudra and Mujumdar (2009) have discussed most of the new and advanced drying concepts, many of which are still at the laboratory and pilot scale.

Table 1.8. Advanced drying techniques

Dryer Type	Advantages	Limitations
Superheated steam drying	Higher drying rates (both in constant and falling rate period; recovery of volatiles; sterilization, deodorization and pasteurization of food products; no oxidative reactions; safe operation	More complex process; entail condensation of steam; some energy related issues; this technique cannot be applied to the food products undergoing melting and glass transition; high capital cost
Heat Pump Drying	Improved product quality; possibility of variable temperatures and humidity for drying; energy recovery (improved efficiency); excellent control of drying conditions; recovery of volatiles possible.	Use of CFCs in refrigeration cycle; high initial cost; initialization time needed for stabilization; regular maintenance required
Multi-stage drying	Reduce dryer size; better control of product physical properties; energy savings feasible	More equipment to be handled
Spray freeze drying	Better product quality; highly porous product; used for very selected applications of high value product	High energy consumption; long drying times compared to spray drying; low yield; expensive.
Inert atmosphere drying	Avoids oxidation reactions; better product quality	Costs are high; not easy to control
Microwave assisted drying	Volumetric heating; useful in final stages of drying; good product quality	Expensive operation; high initial cost; cost of electricity is important to consider

Contact sorption drying	Faster drying rates; lowers the material temperature during drying; stabilizes moisture evaporation	More complex; Little large scale experience
Impinging stream drying	High heat and mass transfer rates feasible	Not many commercial operations reported

1.5. CLOSING REMARKS

An attempt is made here to provide general information on the basic needs for food preservation and how drying is helpful. A concise overview of the fundamental principles and terminology used in the drying literature is given. Advanced models and calculation procedures for drying and dryers of various types can be found in the literature cited. It must be noted that the models and estimation methods given here are necessarily simplistic and caution must be exercised in applying them in practice. Almost without exception design and scale-up of most dryers must be preceded with appropriate laboratory and/or pilot scale experimentation. Drying affects product quality in a decisive manner and hence must be an essential part of any dryer calculation and specification, especially for food products.

NOMENCLATURE

A	evaporation area, m^2
a_w	water activity, -
c_p	specific heat, J kg^{-1} K^{-1}
c_s	humid heat, J kg^{-1} K^{-1}
D_L	effective diffusivity, m^2 s^{-1}
D_{L0}	effective diffusivity at reference temperature, m^2 s^{-1}
E_a	activation energy, J
H_w	enthalpy of wetting, J kg^{-1}
h	convective heat transfer coefficient, W m^{-2} K^{-1}
k_g	thermal conductivity, W m^{-1} K^{-1}
k_y	convective mass transfer coefficient, kg mol s^{-1} m^{-2} mol $frac^{-1}$
M_{air}	molar mass of air, kg mol^{-1}
M_s	mass of bone dry solid, kg
N	drying rate, kg m^{-2} h^{-1}
P_v	vapor pressure of pure water, Pa
p	partial pressure, Pa
p_w	equilibrium vapor pressure of water, Pa
RH	relative humidity, decimal fraction, -
R_g	universal gas constant, 8.314 J mol^{-1} K^{-1}
T	temperature, ^oC
T_{abs}	absolute temperature, K
T_{wb}	wet-bulb temperature, ^oC
t	time, s (or h)
X	total moisture content, kg water/kg dry solid, -
X_c	critical moisture content, kg water/kg dry solid, -
X_f	free moisture content, kg water/kg dry solid, -

X^*	equilibrium moisture content, kg water/kg dry solid, -
Y	absolute air humidity, kg water vapor/kg dry air

Greek letters

η	normalized drying rate, -
λ_s	latent heat of vaporization, J kg^{-1}
μ_g	dynamic viscosity, kg m^{-1} s^{-1}
ν	normalized drying rate, -
ρ_g	density, kg m^{-3}

Subscripts

c	constant rate period
f	falling rate period
g	gas
s	solid
v	vapor
w	water
wb	wet-bulb

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Chapter 2

Hygrothermal Properties of Various Foods, Vegetables and Fruits

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Contents

2.1. INTRODUCTION

Hygrothermal changes of material properties occur due to moisture absorption and temperature variation; they are very important in thermal processing of foods. As drying is a process involving simultaneous moisture and heat transport phenomena, application of the term hygrothermal in the context of food drying can be referred as changes in the drying medium and food material properties induced by moisture and temperature. At present, thermodynamic properties of drying air are very well documented. Reliable data for hygrothermal properties of the drying medium can be found in many engineering handbooks. Hence, no attempt is made to include this information in this chapter. On the other hand, hygrothermal data for diverse food materials is necessarily massive due to the vast variety of food products and the assorted parameters that are used to assess the product quality. Compilation of those data is very challenging. Therefore, for convenient and quick reference, only the fundamental knowledge on the effects of hygrothermal behavior to quality of food materials is reviewed and discussed here.

Selected literature is cited to illustrate the effects of moisture content and temperature changes in dehydrated product to the alteration of physical, chemistry and biochemistry properties of the food material. Appropriate mathematical descriptions applied in estimation of the hygrothermal properties are provided while details of measurement and experimental methodology can be found elsewhere. Overview of some major deteriorative reactions in foods is presented and the discussion includes both the physical properties (effective moisture diffusivity, thermal properties, shrinkage and volume change) and chemistry and biochemistry properties (non-enzymatic browning, vitamin degradation, protein denaturation and enzymatic reaction).

2.2. HYGROTHERMAL EFFECTS ON CHEMICAL AND BIOCHEMICAL PROPERTIES

2.2.1. Food Chemistry

Temperature, moisture content and water activity are important physical factors in influencing the chemistry and biochemistry properties of food product during drying and storage. Water is not only an important medium for heat transfer and heat storage but also takes part in various biochemical reactions in food. A water molecule provides protons (H+), hydroxide ions (OH-), hydrogen atoms (H), oxygen atoms (O) and radicals (H•, •OH). Hence, water may act as a solvent, reactant or dispersing agent in the food matrix (Chieh, 2006). As such, condition of the water presents in dehydrated foods is very important as it affects several deterioration reactions in food such as non-enzymatic browning, lipid oxidation, vitamin degradation, enzyme activity, microbial activity and pigment stability (Osuna-Garcia and Wall, 1998). Moreover, dissolved species in food matrix are concentrated as water is removed during drying. As a general rule of thumb, reaction rate increases with temperature and reactant concentration. Therefore, with the simultaneous concentration of dissolved solutes and elevated temperature during drying, reaction between species can be accelerated and thus increases the destruction rate of nutritional value (Labuza and Tannenbaum, 1972).

Reaction rate as a function of temperature and moisture content can be used to predict the extent of the deterioration of important nutritive factors during processing. Generally, first order reaction is assumed for most food deteriorations (Equation 2.1) unless the rate is too slow and zero order reaction has to be used (Labuza and Tannenbaum, 1972).

$$\frac{d[A]}{dt} = k[A] \tag{2.1}$$

where [A] (mol dm^{-3}) is the concentration of the interested quality parameter and k (s^{-1}) is the temperature dependant rate constant which can be described by Arrhenius equation (Equation 2.2). Details of quality parameters and quality attributes can be referred to Chapter 6.

$$k = k_0 e^{-E_a / RT} \tag{2.2}$$

where k_0 (s^{-1}) is the absolute rate constant, E_a (J mol^{-1}) is the activation energy, R (8.314 J mol^{-1} K^{-1}) is the gas constant and T(K) is the absolute temperature. Table 2.1**Table 2.1** shows the typical activation energies for some deteriorative reactions occur in food materials compiled by Labuza and Tannenbaum (1972). Integrated first order reaction rate in Equation 2.1 yields,

$$\ln[A] = -kt + \ln[A]_0 \tag{2.3}$$

A plot of ln[A] versus t gives a straight line with a slope of –k. Useful information can be extracted from Equation 2.3, for instance, half life of the nutrient at a particular temperature which is given by,

$$t_{1/2} = \frac{\ln(2)}{k} \tag{2.4}$$

Table 2.1. Typical activation energies for some deteriorative reactions in food

Reaction	E_a (kJ mol^{-1})
Diffusion controlled	**0-34**
Enzyme reactions	**42-63**
Hydrolysis	**63**
Lipid oxidation	**42-105**
Non-enzymatic browning	**105-209**
Spore destruction	**251-335**
Vegetative cell destruction	**209-628**
Protein denaturation	**335-502**
Ascorbic acid	**42-126**

2.2.2. Browning Reactions

Colour is one of the important quality attributes for dried food product. Although the optical property is often an assessment of the physical appearance of the product, the colour development is in fact the results of various chemical and biochemical reactions. Browning reaction, in either positive or negative way, is an important phenomena occurring in food during processing and storage. In brief, the major reactions leading to browning can be grouped into enzymatic phenol oxidation and non-enzymatic browning. Enzymatic browning is often catalyzed by the enzymes polyphenol oxidase (PPO), where the phenolics constituents are oxidized to quinones in the enzymatic reaction and then further polymerized to melanoidins (brown pigment) that has high molecular weight. On the other hand, non-enzymatic reactions are referring to Maillard reaction (reaction between carbonyl and amino compounds), caramelization, ascorbic acid browning, lipid browning and pigment destruction (Perera, 2005; Prachayawarakorn et al., 2004; Villamiel et al., 2006). The deterioration rates of the non-enzymatic browning are closely related to temperature and water activity. In most cases, the discolouration rates increase with water activity and processing temperature (Goula et al., 2006; Labuza and Tannenbaum, 1972; Maskan et al., 2002; McMinn and Magee, 1997; Rapusas and Driscoll, 1995; Topuz, 2008).

Generally the rates of degradation follow the zero or first order kinetics while the dependence of degradation rate constant on temperature can be described by Arrhenius-type equation. However, the browning rate decelerates at high water activity values because of dilution effect on reactants concentration. The same phenomenon occurs at low water activity because solute mobility is limited below the monolayer. Browning reaction is at maximum when water activity value is in the range of 0.5 to 0.8 in dried and partial dried foods (Leung, 1987; Villamiel et al., 2006). In addition, it has been reported that activation energy of the browning deterioration can be a function of moisture or water activity (Labuza and Tannenbaum, 1972). Followings are some examples from literature to show the different order of browning kinetics (**Error! Reference source not found. (a)** and **Error! Reference source not found. (a)**), the Arrhenius model for the browning rate constant (**Figure 2.1. (b)** and **Figure 2.2. (b)**) and the effects of water activity on the browning kinetics and activation energy (**Figure 2.3**).

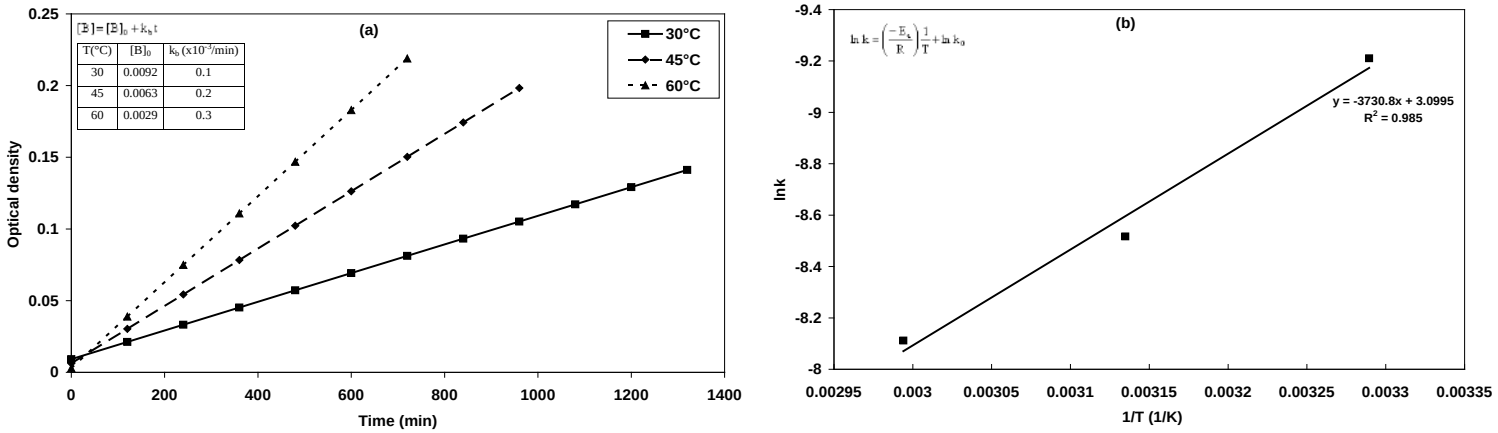


Figure 2.1. Colour changes of potato during drying at various temperatures (a) zero order kinetic model of optical density and (b) Arrhenius model of kinetic rate constant (McMinn and Magee, 1997)

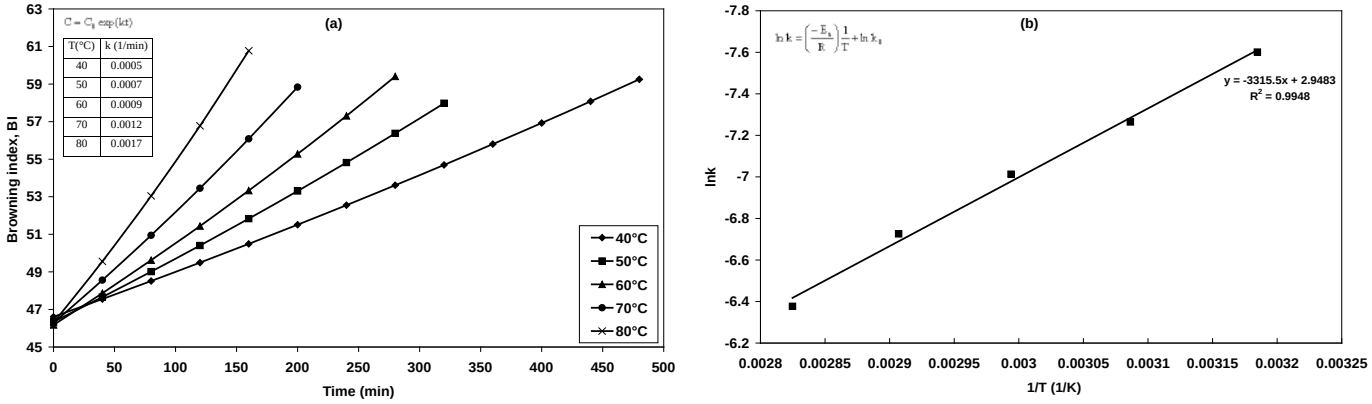


Figure 2.2. Colour changes of kiwifruit slices during drying at various temperatures (a) first order kinetic model of browning index and (b) Arrhenius model of kinetic rate constant (Mohammadi et al., 2008)

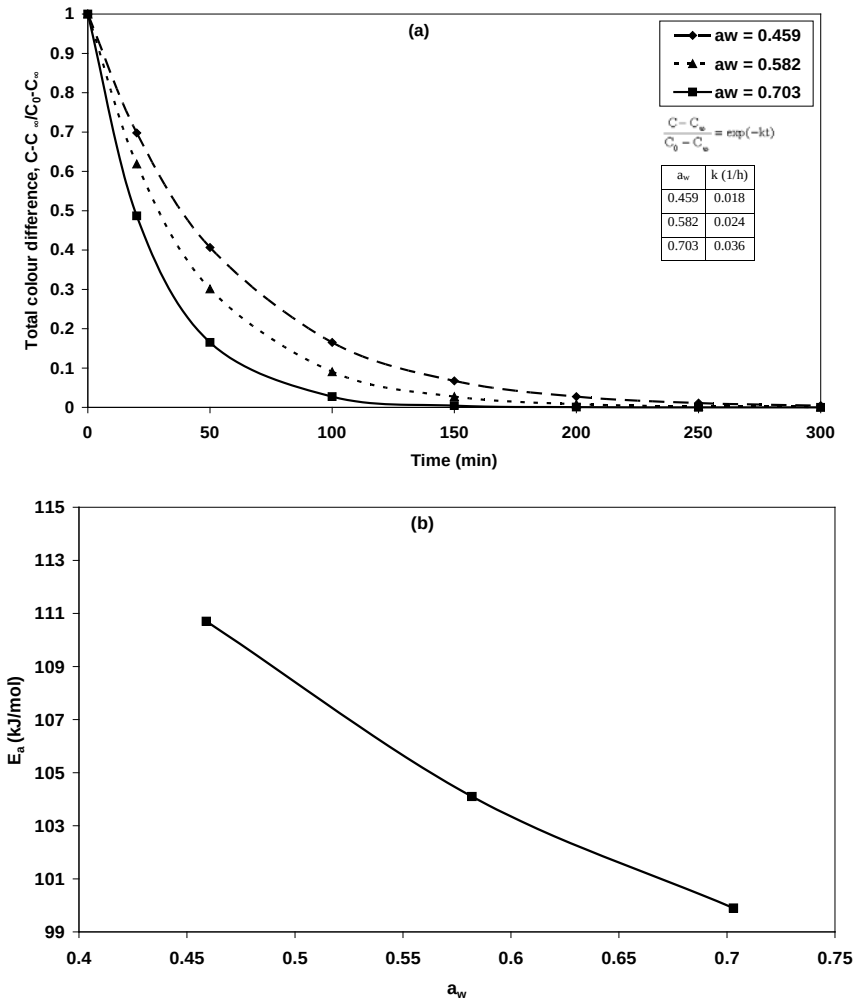


Figure 2.3. Colour degradation of paprika during thermal treatment (a) kinetics of degradation at various a_w and (b) activation energy as a function of a_w (Topuz, 2008)

2.2.3. Proteins

Proteins (also known as polypeptides) are basically polymers of amino acids. Examples of some important amino acids that are essential for humans are phenylalanine, valine, threonine, tryptophan, isoleucine, methionine, leucine, lysine, cysteine, tyrosine, histidine and arginine (Reeds, 2000; Young, 1994). Heating protein foods can cause loss of nutritive value due to several deteriorative reactions that occur with the presence of heat and water, for instances, amino acids destruction, protein denaturation and Maillard reaction. Desrosiers et al. (1987a) reported that heat treatment do not significantly affect amino acid profile of protein (except some reactive amino acids such as tyrosine, histidine, lysine and proline) but could change protein digestibility through conformational changes in the protein structure. The digestibility of individual amino acid in protein could be affected in different way during heating. For example, digestibility of most amino acids in diafiltered whey protein may increase when heated at 75°C or 100°C whilst the digestibility of cysteine, valine, methionine and phenylalanine remain the same (Desrosiers et al., 1987a). The increment of the digestibility of the amino acids may due to an unfolding of protein under the mild heating (60°C to 100°C), which favours the formation of an enzyme-substrate complex and allowed a more rapid cleavage of peptide linkages. Furthermore, the physical state of water in foods also affects the

susceptibility of protein to heat denaturation (Desrosiers et al., 1987b). As the amount of water absorbed by protein is reduced (a_w < 0.5), the protein becomes more resistant to denaturation because of electrostatic interactions that stabilize the protein. In contrary, severe and irreversible denaturation occurs when protein is heated in between a_w 0.5 to 0.97 due to the cross-linking between functional groups of amino acids side chains with the presence of water as a solvent. Similar phenomenon occurs in proteins of fava bean where denaturation temperatures of legumin and vicilin is in a function of water content (**Figure 2.4**) and the denaturation temperature is higher at lower water content (< 0.9 g^{-1} water g^{-1} protein). This could be due to insufficient water in the vicinity of protein to bring about the thermal transition at the low water activity (Leung, 1987).

On the other hand, some studies on soybean meal show that high loss of lysine is possible even for short drying if reducing sugar levels are high in the matrix (Labuza and Tannenbaum, 1972). The loss of lysine is maximum when a_w = 0.68 and negligible at a_w = 0.4. Hence, it can be associated to non-enzymatic browning which is also optimum at the medium a_w range. Sun et al. (2002) reported that the protein solubility of freeze-dried ground beef patties was the lowest at medium a_w (0.33-0.66) at 49°C and it could be related to Maillard-type browning reactions. In both cases, protein amino groups react with reducing sugars, leading to cross-linking and polymerization of proteins. Thus result in low protein extractability which in turn affects the availability of these amino acids biologically.

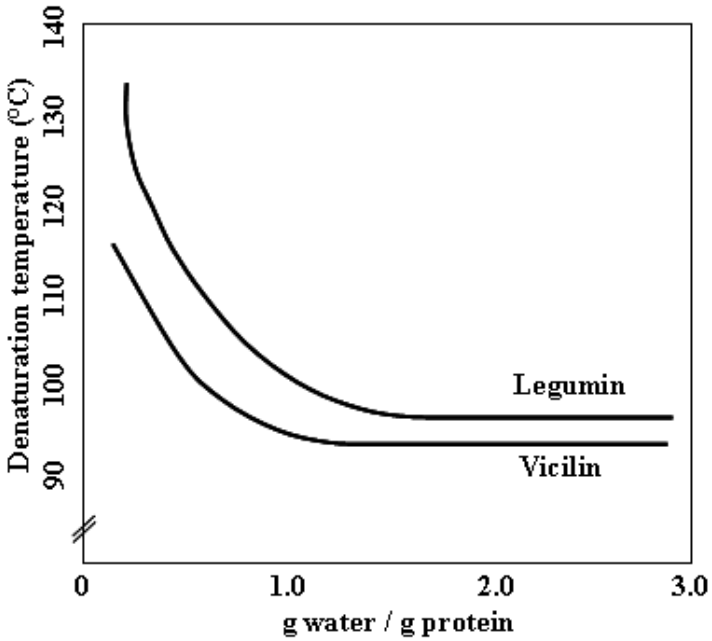


Figure 2.4. Effect of water content on denaturation temperature of legumin and vicilin (Arntfield et al., 1985)

2.2.4. Vitamins

Drying which involves simultaneous heat and moisture transfers can be a destruction process for both water soluble and fat soluble vitamins. Water soluble vitamin C (ascorbic acid) is the most labile component among all the vitamins contained in foods. Since ascorbic acid is soluble in water, it is readily lost via leaching from cut or bruised surfaces of food and also takes part in chemical degradation such as non-enzymatic browning

(Tannenbaum et al., 1985). It is rapidly destroyed by heat when in certain pH range and by oxidation. Compilation of ascorbic acid decay rate as a function of a_w for various food systems done by Labuza and Tannenbaum (1972) shows that ascorbic acid destruction rate increases with water activity and temperature. The loss of ascorbic acid significantly increases at higher water content in general but the destruction rates of the organic acid, somehow, do not fall at the same values for different foods at similar water activity value. The authors suggested that it could be due to various interactions with other components or diffusion limitation in each unique food system. Leung (1987) pointed out that reaction rates of vitamin A, B1 and B2 increase with increasing a_w (0.24-0.65) as well, however, the B vitamins are more stable than vitamins A and C at various a_w values. Fat soluble vitamin such as β-carotene (pro-vitamin A) exhibits the highest stability at intermediate water activity (Haralampu and Karel, 1983). Notable loss of fat soluble vitamins in drying is probably due to interaction of peroxides of free radicals with the vitamins where the peroxides and radicals are produced in the oxidation of lipids (Labuza and Tannenbaum, 1972). Hence, retention of vitamin A and tocopherol can be increased through minimizing lipid oxidation. The milder the heating process, the greater the retention of the fat soluble vitamins. Furthermore, destruction rate of carotenoids can be reduced when increasing the moisture content, similar trend occurs to lipid oxidation (Chou and Breene, 1972; Labuza and Tannenbaum, 1972). However, increasing the moisture level increases the destruction rate for other vitamins. The followings are some examples adopted from selected literature to depict the phenomena abovementioned. It can be seen from **Figure 2.5** that the degradation rate constants of ascorbic acid and carotene in dehydrated sweet potato depend very much on the water activity of the sample. While the degradation rate of ascorbic acid is decreasing with water activity, the degradation rate of carotene increases at low water activity. On the other hand, **Figure 2.6** and **Figure 2.7** show the typical temperature dependence degradation kinetics of ascorbic acid and β-carotene, respectively, where both vitamins degrade faster at increased temperature. Nevertheless,

Figure 2.8 illustrates that the moisture content may influence the degradation kinetics of the ascorbic acid and lycopene as well other the temperature factor and the degradation trends are dissimilar between two different phytochemicals. Therefore, it is important to know the destruction rates of interested vitamins in sample as a function of temperature, a_w and the food composition, in order to predict the losses more accurately during drying.

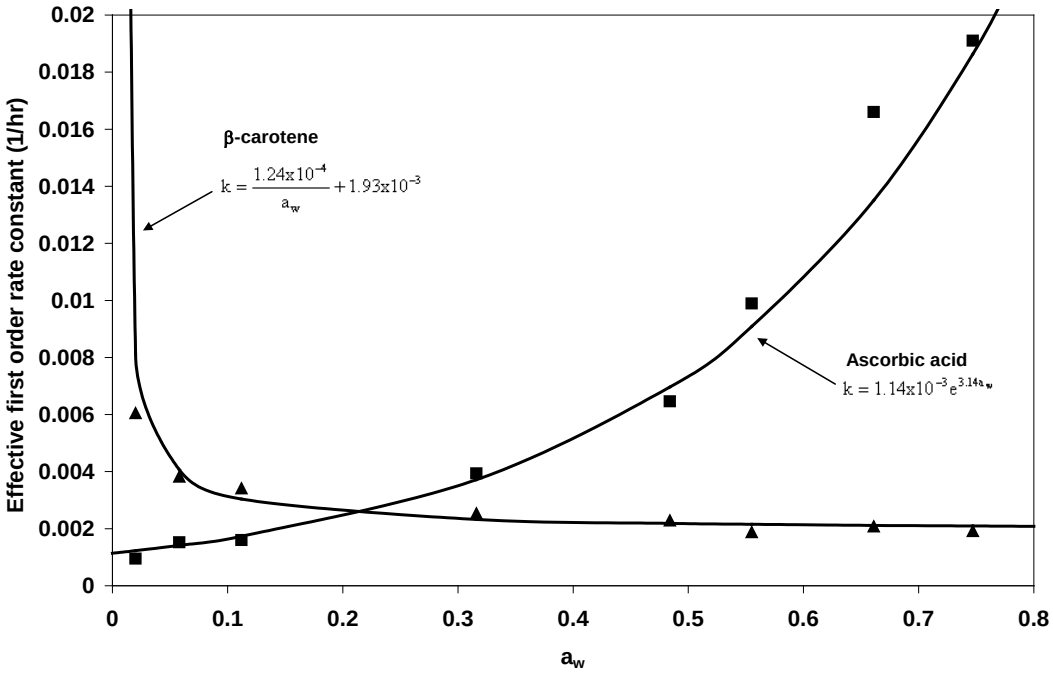


Figure 2.5. Moisture dependence degradation rate constants of ascorbic acid and -carotene in dehydrated sweet potato (Haralampu and Karel, 1983)

2.2.5. Microbial Growth and Enzymes Activity

Enzymatic reactions can occur in low moisture foods if the enzymes are not inactivated by heating. Hence, reduction of water activity in final product is a very important mean to ensure the stability of the dried foods. Final product with sufficient low water activity is safe from enzymatic spoilage in general because active water is not available for microbial growth (Chieh, 2006). **Error! Reference source not found.** shows the water activity limits for the growth of some microorganisms and food examples within the range. It can be seen that the growth of most harmful microorganisms is inhibited at water activity below 0.60 or moisture content less than 10% in general. On the other hand, the amount of water content and value of water activity have direct influence on the activity of enzymes that is naturally present in the food system as well. **Table 2.3**shows the minimum water activity for enzymatic reaction in selected foods and substrates compiled by Drapron (1985). Generally, enzyme activity increases with increasing water activity which also postulate increased subtract mobility. Water activity threshold for enzyme activity may vary with food composition and substrates structure. Leung (1987) pointed out that substrates of high molecular weight, such as starch and protein, are less mobile than low molecular weight substrates, such as glucose, and thus generally have a higher water activity threshold. In addition, enzyme activity still can be traced even at very low water activity for non-aqueous substrates, such as the lipases in olive oil, trilaurin and triolein, because water is not needed to provide mobility of these oil liquid substrates.

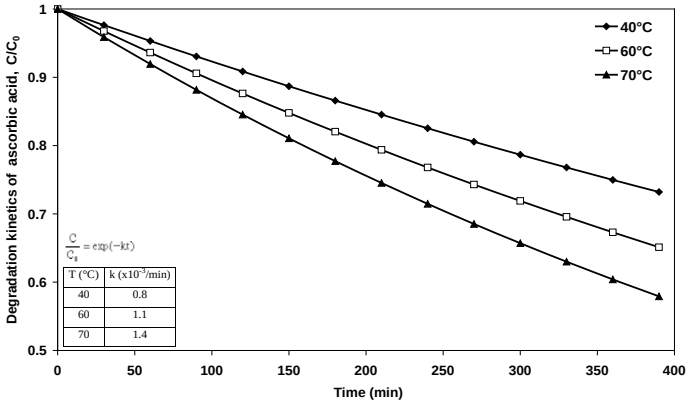


Figure 2.6. First order ascorbic acid degradation kinetics of apple at different drying temperatures (Timoumi et al., 2007)

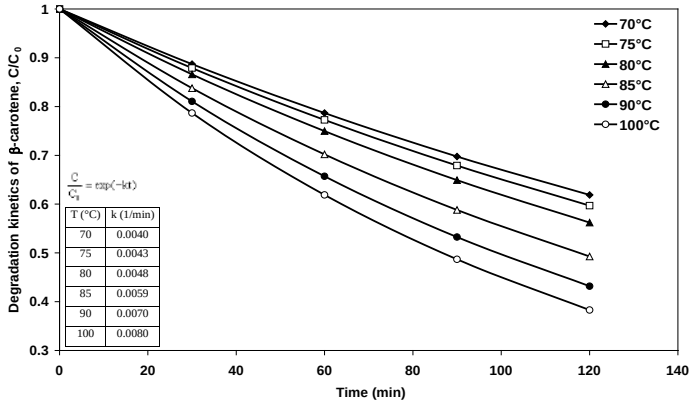
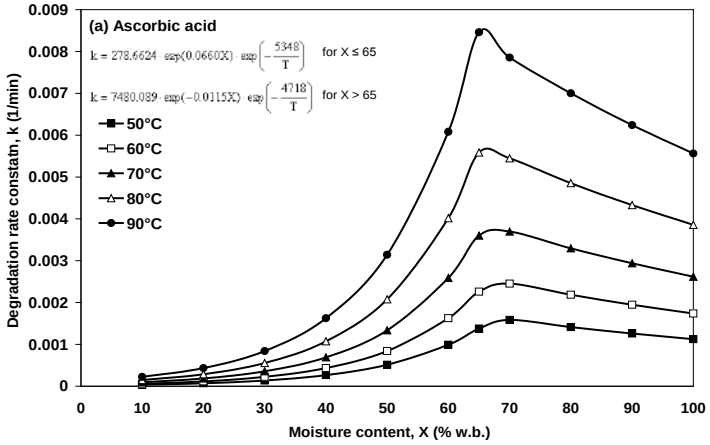


Figure 2.7. First order-carotene degradation kinetics of pumpkin at different drying temperatures (Dutta et al., 2006)



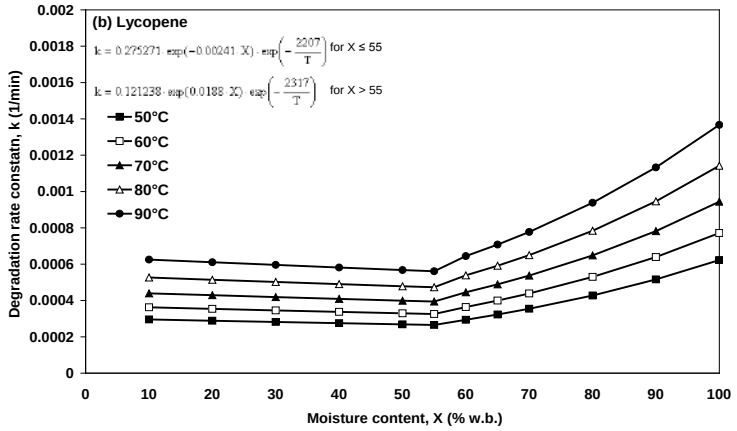


Figure 2.8. Degradation rate constant of (a) ascorbic acid and (b) lycopene in tomato pulp as a function of moisture content and drying temperature (Goula and Adamopoulos, 2006; Goula et al., 2006)

Table 2.2. Water activity (aw) and the microorganisms in foods (Beauchat, 1981)

a_w	Microorganisms	Product examples
0.95	*Pseudomonas, Escherichia, Proteus, Shigells, Klebsiella, Bacillus, Clostridium perfringens*	Fresh fruit, vegetable, meat and fish
0.91	*Salmonella, Vibrio parahaemolyticus, C. botulinum, Serratia, Lactobacillus, Pediococcus*	Cheese, ham, fruit juice concentrates
0.87	Most yeasts	Fermented sausage, sponge cakes, dry cheese, margarine
0.80	Most molds	Fruit juice concentrates, condensed milk, syrup, flour, rice
0.75	Halophilic bacteria	Jam, marmalade, glace fruits, marzipan, marshmallows
0.65	Xerophilic molds	Rolled oats with 10% moisture, jelly, molasses, nuts, dried fruits
0.60	Osmophilic yeasts	Dried fruits with 15-20% moisture, toffees, caramels, honey
0.50	No microbial proliferation	Pasta with 12% moisture, spices with 10% moisture
0.40	No microbial proliferation	Whole egg powder with 5% moisture
0.30	No microbial proliferation	Cookies, crackers and bread crusts with 3-5% moisture
0.20	No microbial proliferation	Whole milk powder with 2-3% moisture, dried vegetables with 5% moisture, corn flakes with 5% moisture

Table 2.3. Water activity threshold for enzymatic reaction in selected foods and substrates (Drapron, 1985)

Food /substrate	Enzyme	Temperature (°C)	Water activity threshold
Grain	Phytases	23	**0.90**
Wheat germ	Glycoside-hydrolases	20	**0.20**
Rye flour	Amylases	30	**0.75**
Macaroni	Phospholipases	25-30	**0.45**
Wheat flour	Proteases	35	**0.96**

dough			
Bread	Amylases	30	**0.36**
Casein	Trypsin	30	**0.50**
Starch	Amylases	37	**0.40/0.75**
Galactose	Galactosidase	30	**0.40-0.60**
Olive oil	Lipase	5-40	**0.025**
Triolein, trilaurin	Phospholipases	30	**0.45**
Glucose	Glucose oxidase	30	**0.40**
Linoleic acid	**Lipoxygenase**	**25**	**0.50/0.70**

2.3. HYGROTHERMAL EFFECTS ON PHYSICAL PROPERTIES

2.3.1. Effective Moisture Diffusivity

The moisture migration process during drying is complex and often involves one or more transport mechanisms such as liquid diffusion, vapour diffusion, Knudsen diffusion, surface diffusion and hydrostatic pressure differences (Mujumdar and Devahastin, 2008). The term effective diffusivity (D_{eff}) is defined to describe the rate of moisture movement, no matter which mechanism is involved. From Fick's second law of diffusion (Equation 2.5),

$$\frac{\partial X}{\partial t} = \nabla.(D_{eff} \nabla X) \tag{2.5}$$

X is the moisture content (kg^{-1} water kg^{-1} dry matter), t is the drying time and D_{eff} is the effective diffusivity ($m^2\ s^{-1}$).

The general solution of Equation 2.5 can be derived for various standard geometries (slab, cylinder and sphere) using appropriate boundary conditions (Crank, 1975). In many cases the effective diffusivity is estimated by using only the first term of the general solution (Zogzas et al., 1996b). However, this method only assumes a constant diffusion coefficient throughout the whole drying process and it can be related to product temperature via the Arrhenius equation. In reality, the diffusion coefficient is rarely constant but varies with moisture content, temperature and spatial coordinate (Puyate and Lawrence, 2006). Karathanos et al. (1990) provided detail step in determining the effective diffusivity of the material. In most cases, the total diffusivity is the sum of the vapour phase and liquid phase diffusivities as shown in **Figure 2.9**. At high moisture content liquid diffusion is the dominant means of transport mechanism and vice versa at lower moisture content (De Vries, 1958).

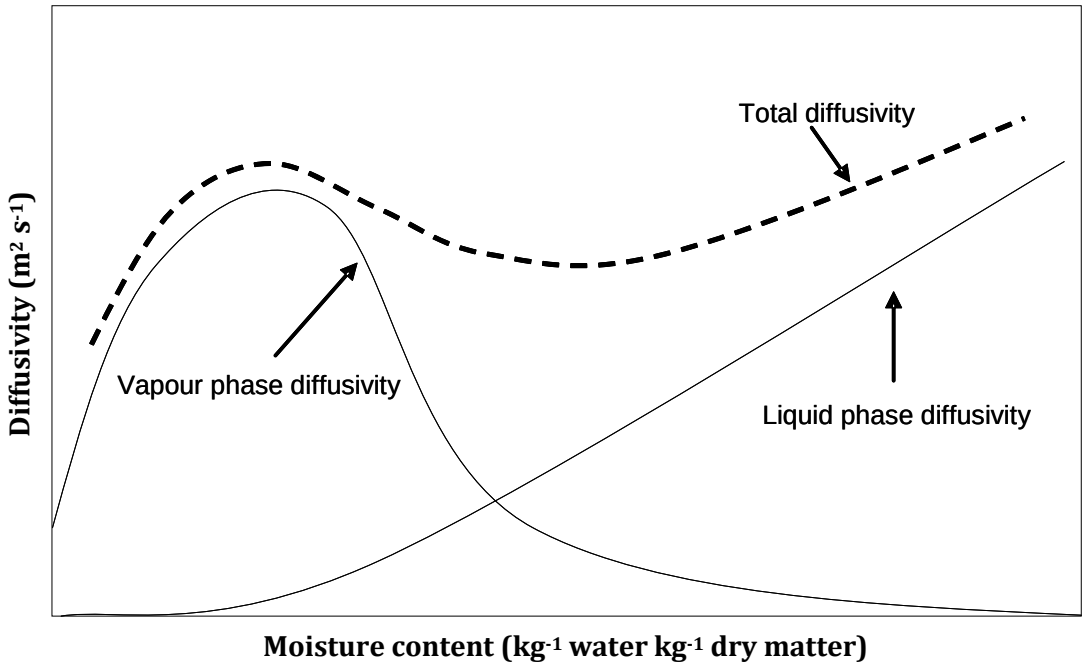


Figure 2.9. Variation of moisture diffusivity with moisture content during drying

Extensive reviews with regard to the methods of experimental determination and compilation of moisture diffusivity data for various foodstuffs have been published elsewhere (Zogas et al., 1994; Zogas et al., 1996a). Generally, the diffusivity values fall between 10^{-13} and 10^{-6} $m^2 s^{-1}$ while majority (about 92%) falls within 10^{-12} and 10^{-8} $m^2 s^{-1}$ (Zogzas et al., 1996b). Various empirical models relating effective diffusivity as a function of temperature and moisture content have been compiled and reported by the authors. The followings are some selected examples of effective diffusivity model reported from recent published literatures (**Figure 2.10.** and **Figure 2.11**). Overall, it can be seen from the figures that effective diffusivity increases with temperature but varying trends are observed with respect to moisture content. At high temperature the water molecules are loosely bound to the food matrix, thus requiring less energy to remove than at lower temperature (Xiong et al., 1992). In contrast, the dependency of moisture content depends greatly on the structure of the food product and void fraction has been known to affect diffusivity significantly. It has been reported that for low porosity materials the value of D_{eff} is very close to liquid diffusivity while for granular and porous materials moisture is transported mainly by vapour diffusion through the void space (Karathanos et al., 1990).

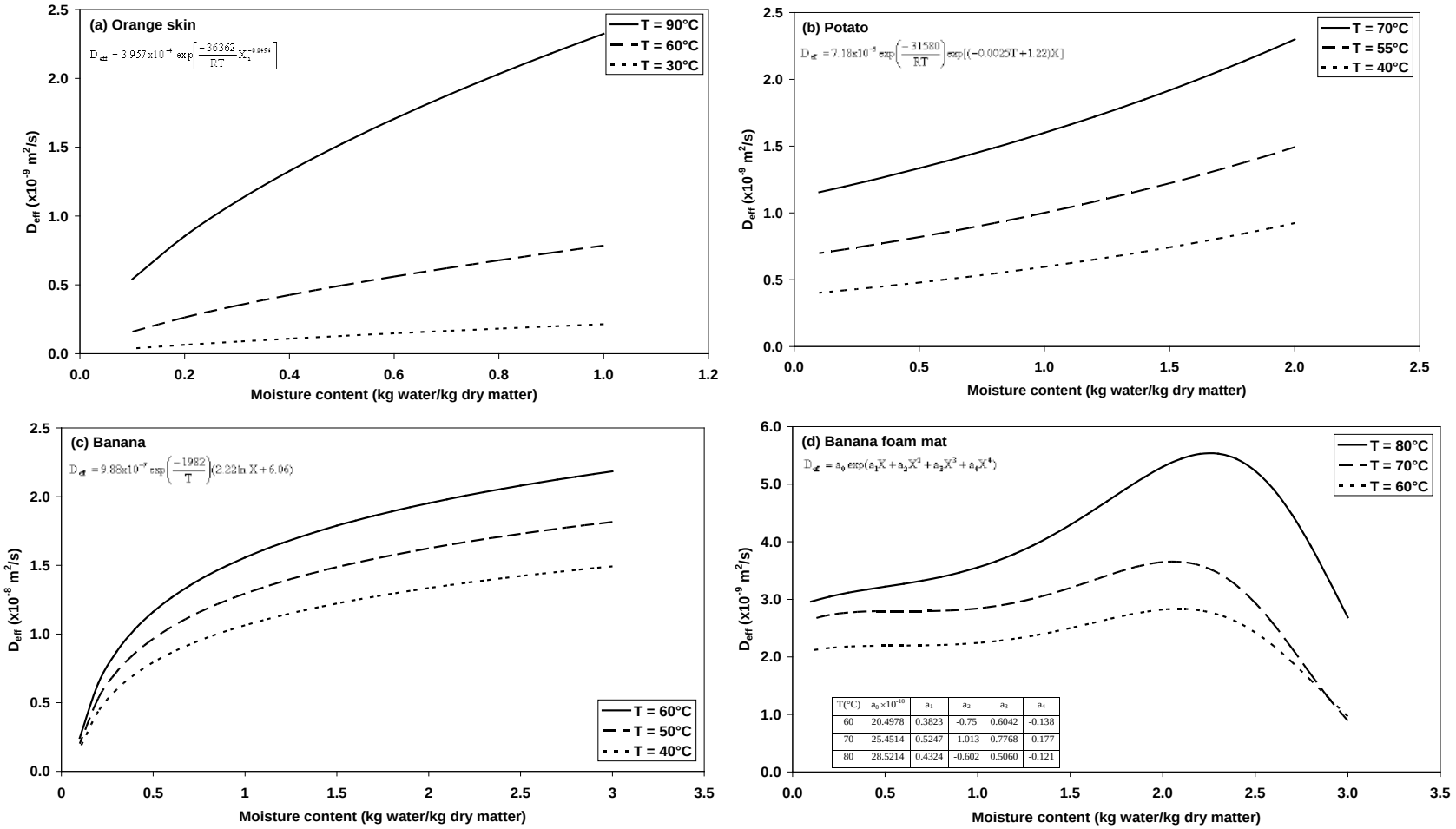
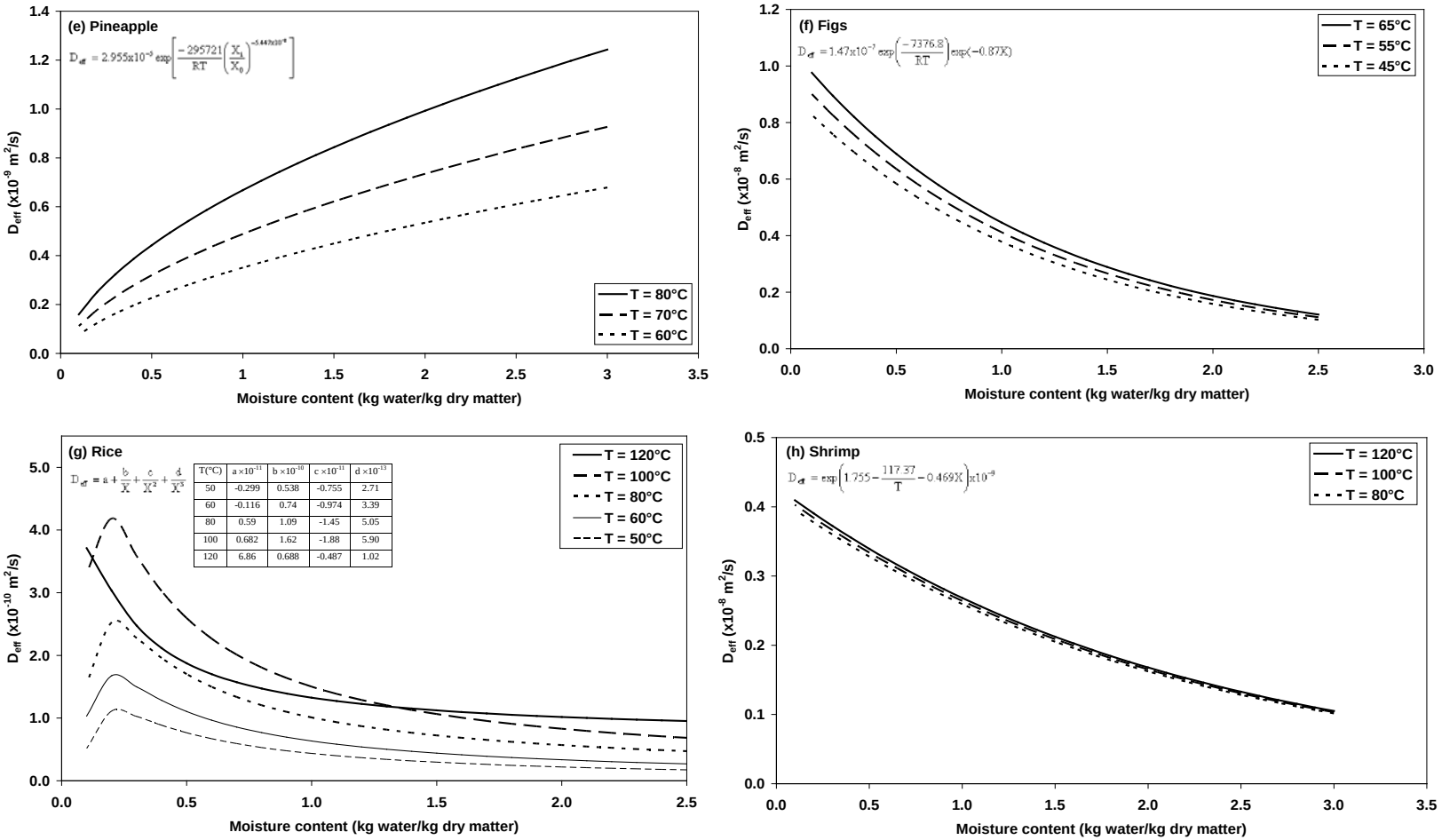


Figure 2.10. Variation of effective diffusivity (D_{eff}) with moisture content and temperature in (a) orange skin (Garau et al., 2006), (b) potato(Hassini et al., 2007), (c) banana (Baini and Langrish, 2008) and (d) banana foam mat (Thuwapanichayanan et al., 2008)



T(°C)	a ×10⁻¹¹	b ×10⁻¹⁰	c ×10⁻¹¹	d ×10⁻¹³
50	-0.299	0.538	-0.755	2.71
60	-0.116	0.74	-0.974	3.39
80	0.59	1.09	-1.45	5.05
100	0.682	1.62	-1.88	5.90
120	6.86	0.688	-0.487	1.02

Figure 2.11. Variation of effective diffusivity (D_{eff}) with moisture content and temperature in (e) pineapple (Simal et al., 2006), (f) figs (Xanthopoulos et al., 2006), (g) carrot (Suvarnakuta et al., 2007) and (h) shrimp (Niamnuy et al., 2008a)

2.3.2. Thermal Properties

The thermal properties of food product, include the specific heat capacity and thermal conductivity, are intrinsic properties of the materials and represent the ability of the materials to accumulate and to transport heat (Lewicki and Jakubczyk, 2004). These properties are important parameters in the modelling and evaluation of food processing operations that involve heat transfer, energy utilization and food product quality. Generally, the heat transfer characteristics within a food product during drying can be described using the Fourier's heat conduction model (Equation 2.6).

$$\frac{\partial T}{\partial t} = \nabla.\left(\frac{\mathrm{k}}{\rho \mathrm{c_p}} \nabla T\right) \tag{2.6}$$

where k is the thermal conductivity (W m^{-1} K^{-1}), ρ is the density (kg m^{-3}) and c_p is the specific heat capacity (kJ kg^{-1} K^{-1}), T is the temperature (K) and t is the time (s).

The term thermal diffusivity (Equation 2.7) is usually defined for the above equation. It has the similar unit as that of moisture diffusivity (m^2 s^{-1}).

$$\alpha = \frac{\mathrm{k}}{\rho \mathrm{c_p}} \tag{2.7}$$

The thermal properties of food materials depend on the temperature and composition of the individual constituent. The constituents that commonly present are such as water, protein, fat, carbohydrate and ash. By knowing the composition of these constituents the thermal properties of the food material can be determined empirically. Various equations are available in literatures that relate the thermal properties of these constituents with temperature. The individual values are then added up by the additive principle to obtain an overall value. However, by using such equations, the values obtained should serve as a preliminary estimation only because thermal resistance of each food material is somehow depends on the structural arrangement of the constituents in food. Experimental verification is recommended for better estimation. For porous food materials, the porosity or volume fraction of the air is included into the estimation. Air has a low value of thermal conductivity and thus porous foods are poor heat conductors in general. The various methods of estimation have been extensively reviewed and readers are advised to refer to literatures published elsewhere (Chen, 2008; Geankoplis, 2003; Marinos-Kouris and Maroulis, 2006).

Some selected examples of the variation of thermal properties with moisture content and temperature from recent published literatures are illustrated in **Figure 2.12** to **Error! Reference source not found.**. In most cases, the thermal conductivity and heat capacity of food material increase with increasing moisture content above freezing temperature. This is because water has a much higher specific heat and thermal conductivity than the other major food constituents such as the protein, fat, and carbohydrates (Nesvadba, 2005). Thus moisture content can greatly influence the thermal properties of foods. In some instances, temperature may cause changes in the physical properties and composition of the food material hence affects the thermal properties as well (Kouchakzadeh and Tavakoli, 2009; Rahman et al., 1997; Sweat, 1995).

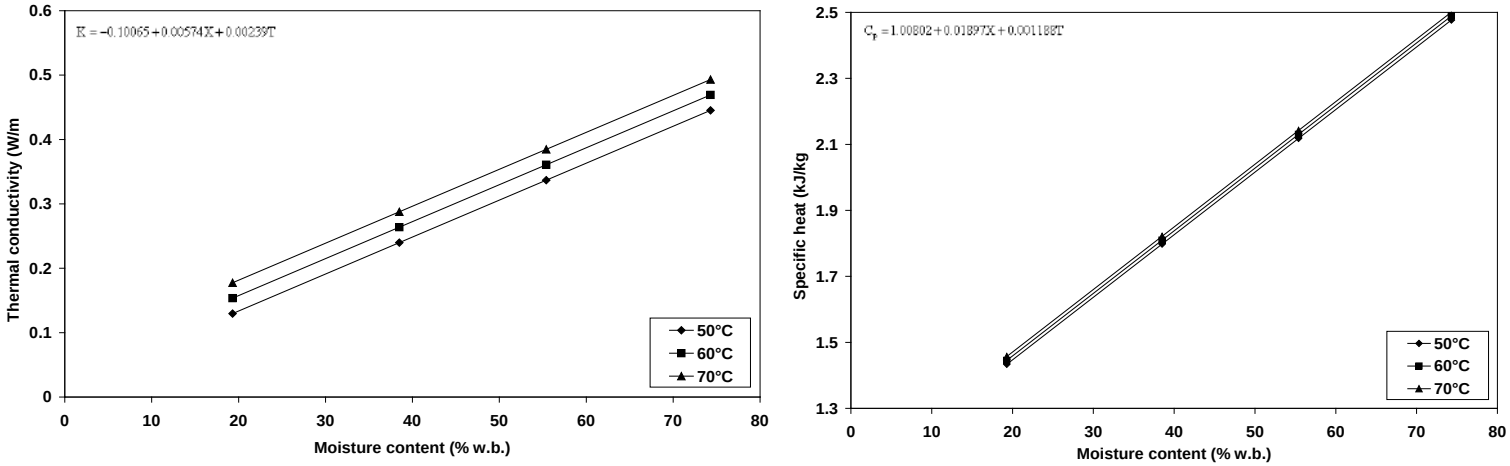


Figure 2.12. Thermal properties of Berberis fruits (Aghbashlo et al., 2008)

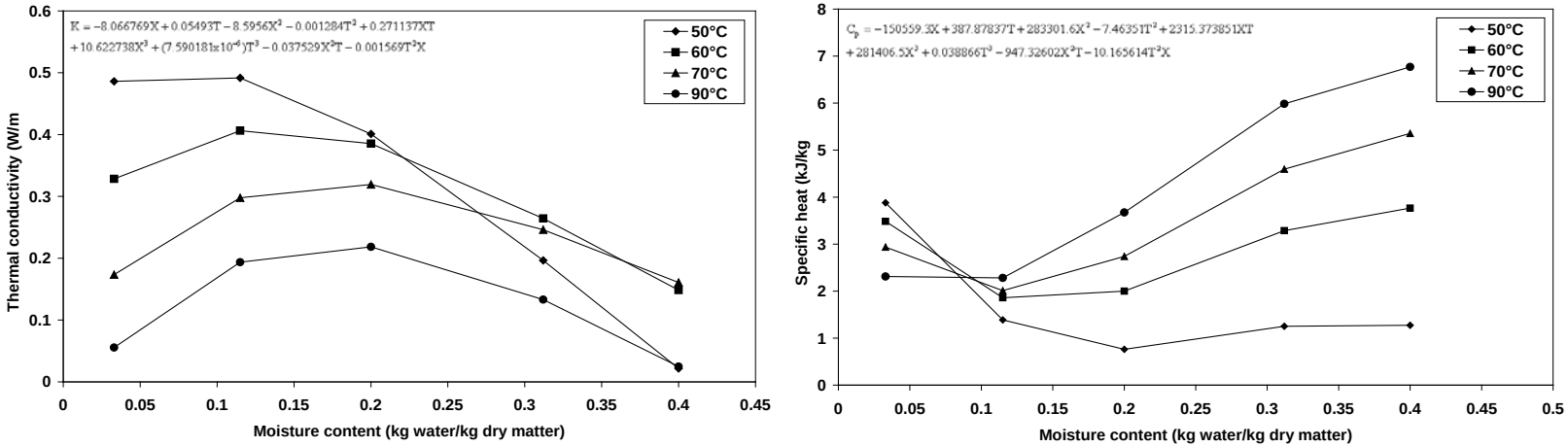


Figure 2.13. Thermal properties of pistachio (Kouchakzadeh and Tavakoli, 2009)

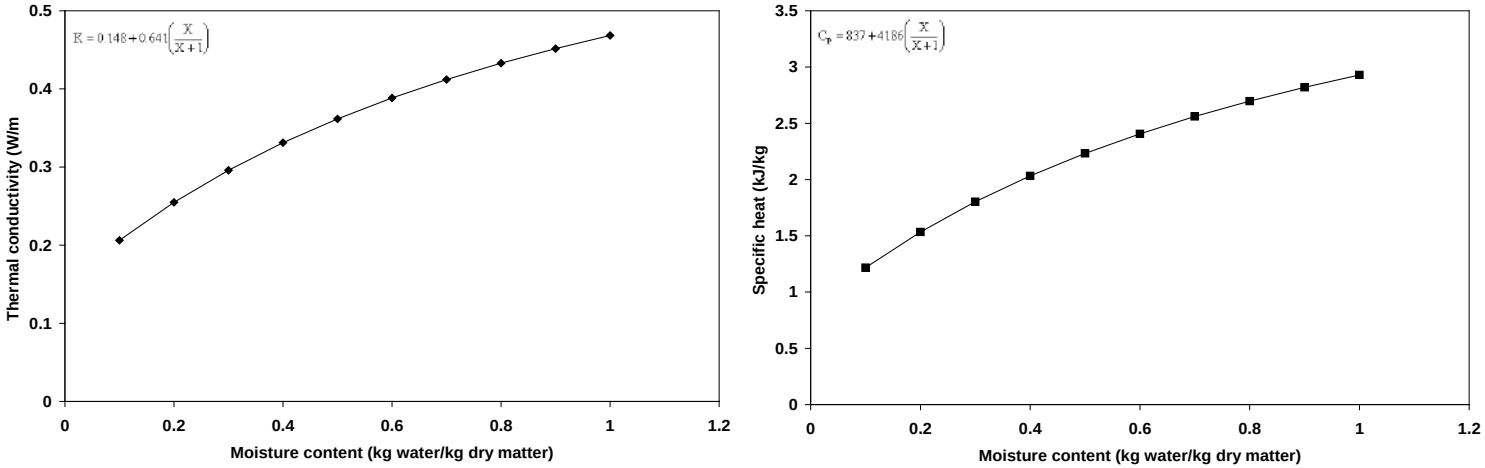


Figure 2.14. Thermal properties of carrot (Suvarnakuta et al., 2007)

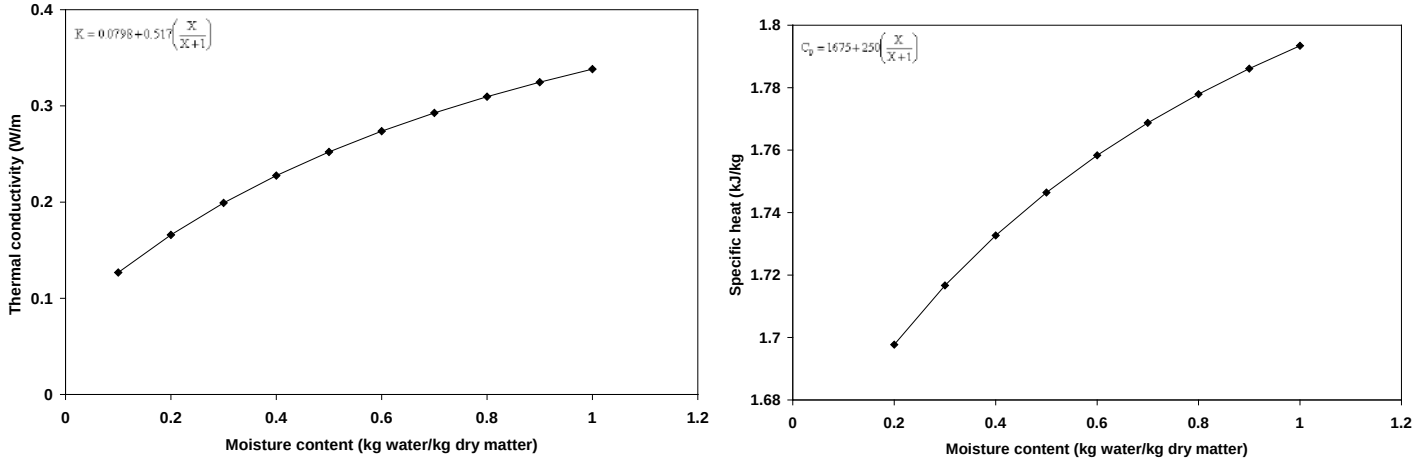


Figure 2.15. Thermal properties of Shrimp (Niamnuy et al., 2008a)

2.3.3. Shrinkage and Volume Change

Shrinkage of foodstuff during drying is unavoidable because heating and removal of water from the food matrix may cause stresses in the cellular structure, hence leading to structural collapse, changes in volume, shape deformation and capillaries contraction (Mayor and Sereno, 2004). Ideally, it can be considered that the shrinkage of the material is equal to the volume of the removed water. Therefore, a parametric relationship can be obtained that relates the volume shrinkage to the moisture content of the material.

Drying temperature alone is not a significant variable that influences shrinkage especially when the material is in rubbery state at high moisture content level. The influence of temperature can be neglected i.e. experimental results from banana drying has reported percentage error of less than 4% by not taking into account drying temperature (Talla et al., 2004). However, at low moisture content the glass transition temperature increases and this causes phase transition from rubbery to glassy state. As a result, the rate of shrinkage reduces significantly due to the rigidity of the material. In addition, temperature affects the rate of moisture removal and hence influences the rate of shrinkage during drying. The effective diffusivity of the material is affected due to the shorter distance that moisture needs to travel before evaporates to the surrounding. Published results have indicated better estimation in the diffusivity values by taking into account the shrinkage effect during drying (Katekawa and Silva, 2006). Some articles have been published on the effect of drying on product shrinkage (Katekawa and Silva, 2006; Koç et al., 2008; Mayor and Sereno, 2004; Talla et al., 2004; Yan et al., 2008). Readers may refer to these papers for additional information.

Principally, shrinkage of food material increases with the amount of water being removed since the more the water is removed, the more contraction stresses are exerted on the material. **Error! Reference source not found.(a-d)** shows some selected examples of shrinkage characteristics of food materials during drying. It can be seen that shrinkage increases (reduction in volume ratio) with decreasing moisture content in general, but shrinkage characteristics vary among drying products and drying methods. This is probably due to the unique biopolymer structure of individual agricultural product and the combined effect of process conditions that determines the type and extent of shrinkage.

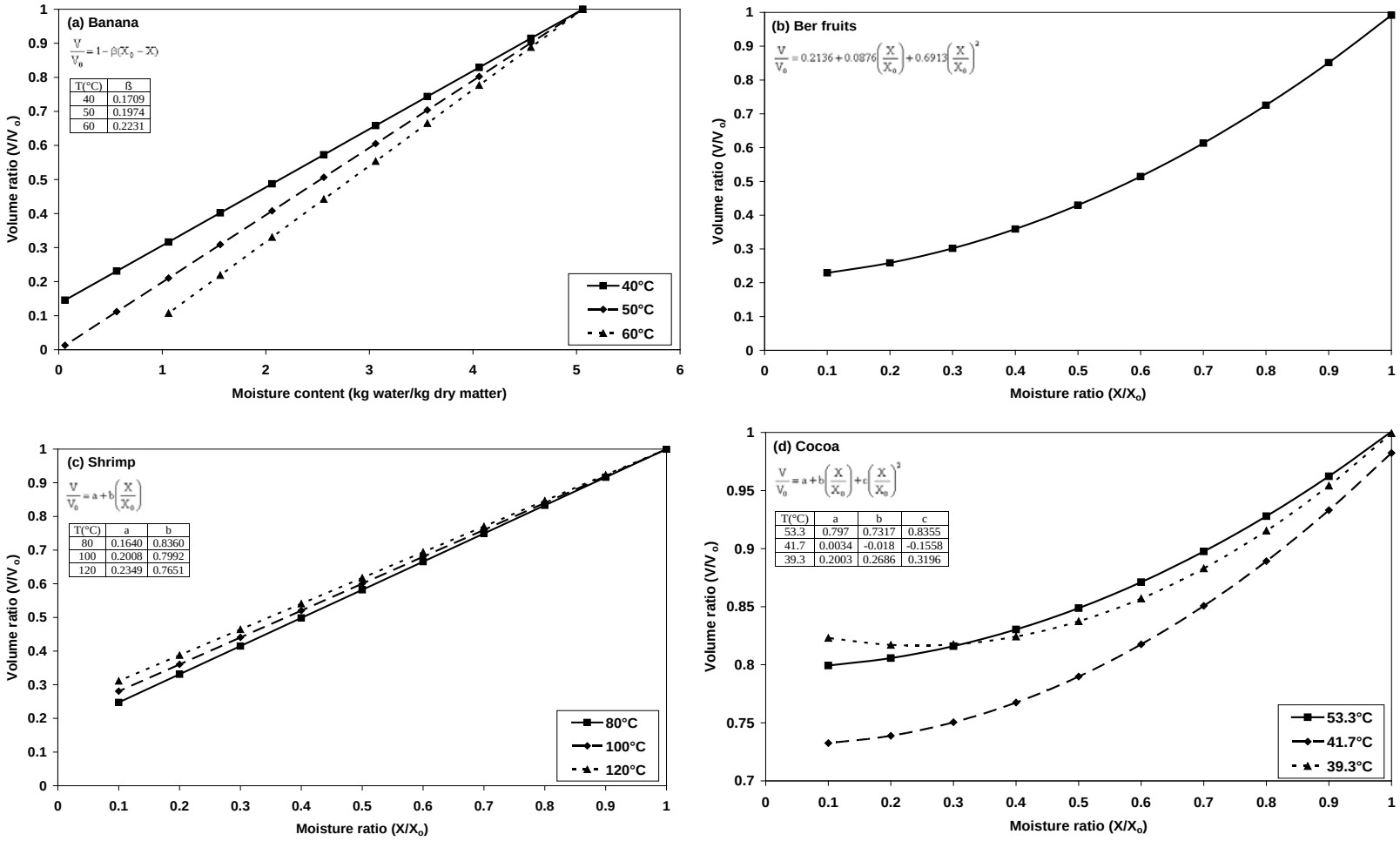


Figure 2.16. Volume shrinkage of (a) banana (Talla et al., 2004), (b) ber fruits during sun drying (Kingsly et al., 2007), (c) shrimp (Niamnuy et al., 2008b) and (d) cocoa (Hii et al., 2009)

2.4. CLOSING REMARKS

Heat and moisture are two important elements in food drying. Simultaneous heating and moisture removal during drying affect both the physical and biochemical properties of food materials. Overview on the hygrothermal data of various foods, vegetable and fruits indicates that the effects of temperature, moisture content and water activity to hygrothermal behavior of foodstuffs vary from product to product. Vast hygrothermal data for various quality properties is available in literature. Nonetheless, basic knowledge on the measurement and interpretation of the hygrothermal properties is of fundamental importance for the design, control and optimization of the drying process.

NOMENCLATURE

[A]	concentration, mol dm^{-3}
a_w	water activity
c_p	specific heat capacity, kJ kg^{-1} K^{-1}
D_{eff}	effective moisture diffusivity, m^2 s^{-1}
E_a	activation energy, J mol^{-1}
k	thermal conductivity, W m^{-1} K^{-1} or temperature dependent rate constant, s^{-1} or min^{-1}
k_0	constant or absolute rate constant, s^{-1} or min^{-1}
R	universal gas constant, 8.314 J mol^{-1} K^{-1}
T	absolute temperature, K
t	time, min or s
X	moisture content, kg kg^{-1} dry solid
X_0	monolayer moisture content, kg kg^{-1} dry solid

Greek letters

α	thermal diffusivity, m^2 s^{-1}
ρ	density, kg m^{-3}

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Chapter 3
Classification and Selection of Dryers for Foods

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Contents

3.1. INTRODUCTION

Dryer selection has long been practiced as an art rather than science depending more on prior experience and vendors' recommendations. As drying technologies have evolved and become more diverse and complex, this has become an increasingly difficult and demanding task for the non-expert not conversant with the numerous types of equipment, their pros and cons, etc. Further, the task is exasperated by the need to meet stricter quality specifications, higher production rates, higher energy costs and stringent environmental regulations. In the absence of in-house experts in drying, there have been some attempts, albeit not fully successful, to develop expert systems for a non-expert to use. It is therefore necessary for an engineer responsible for selection of a dryer or, more appropriately, a drying system to be aware of what is available in the market, what the key criteria are in the selection process and thus arrive at alternative possibilities before going to vendors of such equipment for comparative quotes. It is time and effort well spent since the cost of incorrect selection can be very high.

The selection of dryers for foods is more critical as the selected dryer should be good in both ways; the quality as well as the cost involved. Many of the food products are low valued products and use of expensive techniques such as freeze drying is not recommended although the product quality can be superior. Hence it is necessary to critically evaluate the steps involved in classification and selection of dryers for food products. There have been tremendous efforts in the development of novel drying techniques which are compared with conventional drying techniques in this chapter. It should be noted that over 80 percent of major chemical companies in Europe – each using over 1000 dryers in their production facilities – made errors in selecting dryers in the past year alone (Mujumdar 2008). What is optimal choice in one location at one point in time may be a wrong choice for another geographic location some years later. Prior use is a definite help but not the only criterion to be used in selecting drying systems.

As an example, coffee beans are dried in different parts of the world using flash dryers, vibrated fluid bed dryers and so on. It is thus not a simple task to select a dryer for such applications based on what is done elsewhere.

Over 400 dryer types have been cited in the technical literature although only about 50 types are commonly found in practice. In this chapter, we will examine the key classification criteria for industrial dryers and then proceed to selection criteria with the explicit understanding that the latter is a complex process, which is not entirely scientific but also involves subjective judgment as well as considerable empiricism. It should also be noted that the pre-drying as well as post-drying stages have important bearing on the selection of appropriate dryer types for a given application; this is very important in case of food products as it decides the quality as well as the drying time. Indeed, for an optimal selection of process, one must examine the overall flowsheet as well as the "drying system." This chapter will be confined, however, only to the classification and selection of dryers. In addition, few case studies will be discussed such as milk powder and some fruits and the detailed stepwise procedure will be given for selection of dryer for the these products.

Another important point to note is that several dryer types (or drying systems) may be equally suited (technically and economically) for a given food product. A careful evaluation of as many of the possible factors affecting the selection will help reduce the

number of options. For a new application (new product or new process), it is important to follow a careful procedure leading to the choice of the dryers. Characteristics of different dryer types should be recognized when selecting dryers. Changes in operating conditions of the same dryer can affect the quality of the product. So, aside from the dryer type, it is also important to choose the right operating conditions for optimal quality and cost of thermal dehydration.

According to a very recent survey conducted by SPIN (Solids Processing Industrial Network, UK, founded by 14 large chemical companies based in Europe) selection of dryers is a key problem faced by all companies (Slangen, 2000). Over ninety percent of the companies had made errors in selection of their new dryers. Sometimes the selection is easy but when a new product is involved or the production capacity required for exceeds current practice, it is not always an easy task. New requirements on safety and environmental aspects can also make the selection more difficult. The SPIN report recommends development of user-friendly expert systems and better standardization to assist with this complex selection process. It should be noted that the selection process is further complicated by the fact that each category of dryers (e.g., fluid bed, flash, spray, rotary) has a wide assortment of sub-classes and, furthermore, each must be operated at optimal conditions to benefit from appropriate selection.

Baker (1997) has presented a "structural approach" for dryer selection, which is iterative. It includes the following steps:

- List all key process specifications
- Carry out preliminary selection
- Carry out bench scale tests including quality tests
- Make economic evaluation of alternatives
- Conduct pilot-scale trials
- Select most appropriate dryer types

Often, for same materials, a specific dryer type is indicated from the outset. If selection is based exclusively on past experience, it has some limitations:

- If the original selection is not optimal (although it works satisfactorily), the new choice will be less-than-optimal
- No new drying technologies are considered by default
- It is implicitly assumed the "old" choice was arrived at logically, which is often not the case

3.2. CLASSIFICATION OF DRYERS

There are numerous schemes used to classify dryers (Mujumdar, 1995; van't Land, 1991; Mujumdar, 2008). **Table 3.1** lists the criteria and typical dryer types. Types marked with an asterisk (*) are among the most common in practice.

Table 3.1. Classification of dryers

Criterion	Types
Mode of operation	• Batch • Continuous*
Heat input-type	• Convection*, conduction, radiation, electromagnetic fields, combination of heat transfer modes • Intermittent or continuous* • Adiabatic or non-adiabatic
State of material in dryer	• Stationary • Moving, agitated, dispersed
Operating pressure	• Vacuum* • Atmospheric
Drying medium (convection)	• Air* • Superheated steam • Flue gases
Drying temperature	• Below boiling temperature* • Above boiling temperature • Below freezing point
Relative motion between drying medium and drying solids	• Co-current • Counter-current • Mixed flow
Number of stages	• Single* • Multi-stage
Residence time	• Short (< 1 minute) • Medium (1 – 60 minutes) • Long (> 60 minutes)

* Most common in practice

The above classification is rather coarse. Just the fluidized bed dryer can be subclassified into over thirty types depending on additional criteria and will be discussed in more detail later in this chapter.

Each type of dryer has specific characteristics, which make it suited or unsuitable for specific applications. Details can be found in Mujumdar (1995). Certain types are inherently expensive (e.g., freeze dryers) while others are inherently more efficient (e.g., indirect or conductive dryers). Thus, it is necessary to be aware of the wide variety of dryers available in the market as well as their special advantages and limitations. It should be noted that the aforementioned classification does not include most of the novel drying technologies, which are applicable for very specific applications. The reader is referred to Kudra and Mujumdar (2009) for details on novel drying technologies. However some of the techniques will be discussed. **Figure 3.1** is a general scheme proposed by Baker (1997) for classification of batch and continuous dryers. Note that there is a more limited choice of batch dryers – only a few types can be operated in both batch and continuous modes.

Classification of dryers on the basis of the mode of thermal energy input is perhaps the most useful since it allows one to identify some key features of each class of dryers.

3.2.1. Direct dryers

These are also known as convective dryers–are by far the most common. About 85 percent of industrial dryers are estimated to be of this type despite their relatively low thermal efficiency caused by the difficulty in recovering the latent heat of vaporization contained in the dryer exhaust in a cost-effective manner. Hot air produced by indirect heating or direct firing is the most common drying medium although for some special applications superheated steam has recently been shown to yield higher efficiency and often higher product quality. In direct dryers, the drying medium contacts the material to be dried directly and supplies the heat required for drying by convection; the evaporated moisture is carried away by the same drying medium.

Drying gas temperatures may range from 50ºC to 400ºC depending on the material (of course this is general information and the temperature does not go so high for food products). Dehumidified air may be needed when drying highly heat-sensitive materials. An inert gas such as Nitrogen may be needed when drying explosive or flammable solids or when an organic solvent is to be removed. Solvents must be recovered from the exhaust by condensation so that the inert (with some solvent vapor) can be reheated and returned to the dryer.

Because of the need to handle large volumes of gas, gas cleaning and product recovery (for particulate solids) becomes a major part of the drying plant. Higher gas temperatures yield better thermal efficiencies subject to product quality constraints.

3.2.2. Indirect dryers

These type of dryers involve supplying of heat to the drying material without direct contact with the heat transfer medium, i.e., heat is transferred from the heat transfer medium (steam, hot gas, thermal fluids, etc.) to the wet solid by conduction. Since no gas flow is presented on the wet solid side it is necessary to either apply vacuum or use gentle gas flow to remove the evaporated moisture so that the dryer chamber is not saturated with vapor. Heat transfer surfaces may range in temperature from -40º C (as in freeze drying) to about 300ºC (of course not for food products). In vacuum operation, there is no danger of fire or explosion. Vacuum operation also eases recovery of solvents (in case to be removed) by direct condensation thus alleviating serious environmental problem. Dust recovery is obviously simpler so that such dryers are especially suited for drying of toxic, dusty products, which must not be entrained in gases. Furthermore, vacuum operation lowers the boiling point of the liquid being removed; this allows drying of heat-sensitive solids at relatively fast rates.

Heat may also be supplied by radiation (using electric or natural gas-fired radiators) or volumetrically by placing the wet solid in dielectric fields in the microwave or radio frequency range. Since radiant heat flux can be adjusted locally over a wide range it is possible to obtain high drying rates for surface-wet materials. Convection (gas flow) or vacuum operation is needed to remove the evaporated moisture. The most popular applications involve use of combined convection and radiation. It is often useful to boost the drying capacity of an existing convective dryer as well as to easily remove the final traces of moisture which otherwise are difficult to remove only by convection.

Microwave dryers are expensive both in terms of the capital and operating (energy) costs. Only about 50 percent of line power is converted into the electromagnet-

ic field and only a part of it is actually absorbed by the drying solid. They have found limited applications to date. However, they do seem to have special advantages in terms of product quality when handling heat-sensitive materials. They are worth considering as devices to speed up drying in the tail end of the falling rate period. Similarly, RF dryers have limited industrial applicability. Both microwave and RF dryers must be used in conjunction with convection or under vacuum to remove the evaporated moisture. Stand-alone dielectric dryers are unlikely to be cost-effective except for high value products in the next decade. See Schiffmann (1995) for detailed discussion of dielectric dryers.

It is possible, indeed desirable in some cases, to use combined heat transfer modes, e.g., convection and conduction, convection and radiation, convection and dielectric fields, to reduce the need for increased gas flow which results in lower thermal efficiencies. Use of such combinations increases the capital costs but these may be offset by reduced energy costs and enhanced product quality. No generalization can be made a priori without careful tests and economic evaluation. Finally, the heat input may be steady (continuous) or time varying. Also, different heat transfer modes may be deployed simultaneously or consecutively depending on individual application. In view of the significant increase in the number of design and operational parameters it is desirable to select the optimal operating conditions via a mathematical model. In batch drying intermittent energy input has great potential for reducing energy consumption and for improving quality of heat-sensitive products.

3.3. SELECTION OF DRYERS

In view of the enormous choices of dryer types one could possibly deploy for most products, selection of the best type is a challenging task that should not be taken lightly nor should it be left entirely to dryer vendors who typically specialize in only a few types of dryers. The user must take a proactive role and employ vendors' experience and bench-scale or pilot-scale facilities to obtain data, which can be assessed for a comparative evaluation of several options. A wrong dryer for a given application is still a poor dryer, regardless of how well it is designed. Note that minor changes in composition or physical properties of a given product can influence its drying characteristics, handling properties, etc., leading to a different product and in some cases severe blockages in the dryer itself. Tests should be carried out with the “real” feed material and not a “simulated” one where feasible.

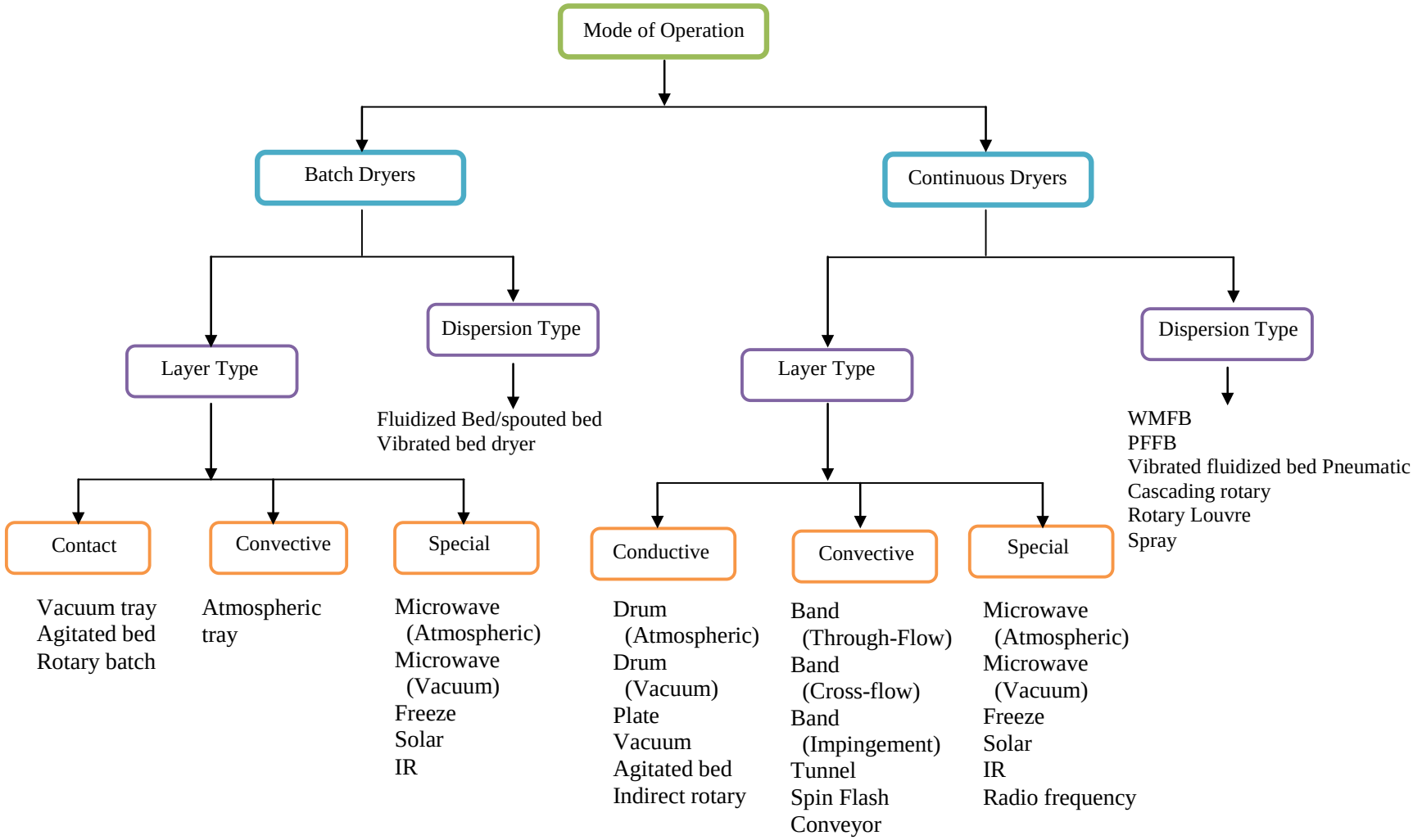


Figure 3.1. Classification of dryers

Although here we will focus only on the selection of the dryer, it is very important to note that in practice one must select and specify a drying system which includes pre-drying stages (e.g., mechanical dewatering, evaporation, pre-conditioning of feed by solids backmixing, dilution or pelletization and feeding) as well as the post-drying stages of exhaust gas cleaning, product collection, partial recirculation of exhausts, cooling of product, coating of product, agglomeration, etc. The optimal cost-effective choice of dryer will depend, in some cases significantly, on these stages. For example, a hard pasty feedstock can be diluted to pumpable slurry, atomized and dried in a spray dryer to produce a powder, or it may be pelletized and dried in a fluid bed or in a through circulation dryer, or dried as is in a rotary or fluid bed unit. Also, in some cases, it may be necessary to examine the entire flowsheet to see if the drying problem can be simplified or even eliminated. Typically, non-thermal dewatering is an order-of-magnitude less expensive than evaporation which, in turn, is many-fold energy efficient than thermal drying. Demands on product quality may not always permit one to select the least expensive option based solely on heat and mass transfer considerations, however. Often, product quality requirements have over-riding influence on the selection process (see Section 4).

As a minimum, the following quantitative information is necessary to arrive at a suitable dryer:

- Dryer throughput; mode of feedstock production (batch/continuous)
- Physical, chemical and biochemical properties of the wet feed as well as desired product specifications; expected variability in feed characteristics
- Upstream and downstream processing operations
- Moisture content of the feed and product
- Drying kinetics; moist solid sorption isotherms
- Quality parameters (physical, chemical, biochemical)
- Safety aspects, e.g., fire hazard and explosion hazards, toxicity
- Value of the product
- Need for automatic control
- Toxicological properties of the product
- Turndown ratio, flexibility in capacity requirements
- Type and cost of fuel, cost of electricity
- Environmental regulations
- Space in plant

For certain high value foods quality considerations override other considerations since the cost of drying is unimportant. Throughputs of such products are also relatively low, in general. In some cases, the feed may be conditioned (e.g., size reduction, flaking, pelletizing, extrusion, back-mixing with dry product) prior to drying which affects the choice of dryers. As a rule, in the interest of energy savings and reduction of dryer size, it

is desirable to reduce the feed liquid content by less expensive operations such as filtration, centrifugation and evaporation. It is also desirable to avoid over-drying, which increases the energy consumption as well as drying time.

Drying of food products require adherence to GMP (Good Manufacturing Practice) and hygienic equipment design and operation. Such materials are subject to thermal as well as microbiological degradation during drying as well as in storage. If the feed rate is low (< 100 kg/h), a batch-type dryer may be suited. Note that there is a limited choice of dryers that can operate in the batch mode.

In less than one percent of cases the liquid to be removed is a non-aqueous (organic) solvent or a mixture of water with a solvent (rare cases in food products). Special care is needed to recover the solvent and to avoid potential danger of fire and explosion. **Table 3.2** presents a typical checklist most dryer vendors use to select and quote an industrial dryer.

Table 3.2. Typical checklist for selection of industrial dryers

Physical form of feed	• Granular, particulate, sludge, crystalline, liquid, pasty, suspension, solution, continuous sheets, planks, odd-shapes (small/large) • Sticky, lumpy
Average throughput	• kg/h (dry/wet); continuous • kg per batch (dry/wet)
Expected variation in throughput (turndown ratio)	
Fuel choice	• Oil • Gas • Electricity
Pre- and post-drying operations (if any)	
For particulate feed products	• Mean particle size • Size distribution • Particle density • Bulk density • Rehydration properties
Inlet/outlet moisture content	• Dry basis • Wet basis
Chemical / biochemical / microbiological activity	
Heat sensitivity	• Melting point • Glass transition temperature
Sorption isotherms (equilibrium moisture content)	

Drying time	• Drying curves • Effect of process variables
Special requirements	• Material of construction • Corrosion • Toxicity • Non-aqueous solution • Flammability limits • Fire hazard • Color/texture/aroma requirements (if any)
Foot print of drying system	• Space availability for dryer and ancillaries

Drying kinetics play a significant role in the selection of dryers. Aside from simply deciding the residence time required, it limits the types of suitable dryers. Location of the moisture (whether near surface or distributed in the material), nature of moisture (free or strongly bound to solid), mechanisms of moisture transfer (rate limiting step), physical size of product, conditions of drying medium (e.g., temperature, humidity, flow rate of hot air for a convective dryer), pressure in dryer (low for heat-sensitive products), etc., have a bearing on the type of suitable dryer as well as the operating conditions. Most often, not more than one dryer type will likely meet the specified selection criteria. Finally we will discuss a bit on advanced drying techniques as well.

3.4. COMPARISON OF CONVENTIONAL DRYERS BASED ON FEED PROPERTIES

As discussed earlier there are various drying options available for food products. The first way to compare the dryer types for preliminary selection is based on the type of feedstock and residence time in a dryer to be handled. The type of feed material may be liquid (fruit juices, milk), slurry, cake (partially dried fruit pulp mixed with additives), free flowing solids (green peas, grains) or formed solids. Selection of a proper drying technique based on the physical form of the feed is very useful step. **Table 3.3** shows the variety of dryers available based on the type of feed.

3.5. SELECTION OF FLUIDIZED BED DRYERS

Fluidized bed dryers are one of the most common dryer types used for decades because of the high heat and mass transfer rates. Fluidized bed dryers have wide applications in food industry for drying of variety of products such as, green peas, sweet corn, coffee, tea, milk powder, grains, etc and more recently for drying of pastes and slurries. In recent years, there have been numerous improvements in the design of fluidized beds to enhance the efficiency. Particles/powders can be classified into four major groups according to their characteristics when exposed to fluidizing gas stream.

Table 3.3. Dryer selection versus feedstock form

Nature of Feed	Liquids			Cakes		Free-Flowing Solids					Formed
	Solution	Slurry	Paste	Centrifuge	Filter	Powder	Granule	Fragile crystals	Pellet	Fiber	Solids
Convective dryers											
Belt conveyor dryer							√	√	√	√	√
Flash dryer				√	√	√	√			√	
Fluid bed dryer	√	√		√	√	√	√		√		
Rotary dryer				√	√	√	√		√	√	
Spray dryer	√	√	√								
Tray dryer (batch)				√	√	√	√	√	√	√	√
Tray dryer (continuous)				√	√	√	√	√	√	√	
Conduction dryers											
Drum dryer	√	√	√								
Steam jacket rotary dryer				√	√	√	√		√	√	
Steam tube rotary dryer				√	√	√	√		√	√	
Tray dryer (batch)				√	√	√	√	√	√	√	√
Tray dryer (continuous)				√	√	√	√	√	√	√	√
Cone (batch)				√	√	√	√		√		
Thin-film contact		√	√	√	√	√	√		√	√	

Table 3.4 shows the properties of various groups of particles/powders. Again, these figures are applicable to dry powders and may need adjustments for wet particles and poly-disperse particles where additional surface forces come into play. There are various configurations of fluidized bed dryers and selecting proper fluidized bed dryer for certain application is a big task itself. **Figure 3.2** shows the classification of fluidized bed dryers based on various criteria such as the mode of operation, flow regime, temperature and pressure used, the drying media used, the way of fluidization and the type of heat transfer. There are different designs of fluidized bed dryers and the commonly used are the following; well mixed, plug flow, spouted bed, agitated, vibrated and pulsating fluid bed. Each of these types is suitable for product with specific properties. **Figure 3.3** shows various types of fluidized bed dryers available for feed particles of different characteristics. Note that different design strategies are needed for different dryer types. Also, often the same dryer type can behave differently when different materials are dried in it. Presence of sugar in fruits makes drying especially "tricky" due to unquantifiable effects of stickiness. Note that **Table 3.4** is located on very extensive experimental observations using "dry" particulates. Hence, the classification scheme may not in general work for surface-wet particles. Experimental testing is therefore required.

Table 3.4. Characteristics and properties of various types of dry powders and particulates

Group	Characteristics and Properties
A	• Good fluidization quality, aeratable, easily fluidized, smooth at low velocity and bubbling at higher velocity and slug at high velocity, bed expands, Good solids mixing. • Small mean particle size, low density, typically $30< d_p <100\mu m$ and $\rho<1400\ kgm^{-3}$.
B	• Good fluidization quality, sand-like particles, vigorous bubbling, slug at high velocity, small bed expansion, good solids mixing in bubbling. • Typically $40\mu m<d_p<500\mu m$, $1400kgm^{-3}<\rho<4000kgm^{-3}$.
C	• Bad fluidization quality, cohesive due to strong interparticle force, severe slugging and agglomeration, may generates electrostatic charges, poor solids mixing. • Fine and ultra-fine particles.
D	• Poor fluidization quality, spoutable, difficult to fluidize in deep bed depth, large bubbles, severe channeling, relatively poor solids mixing. • Large and/or dense particles, typically $d_p >500\mu m$, $\rho>1400kgm^{-3}$.

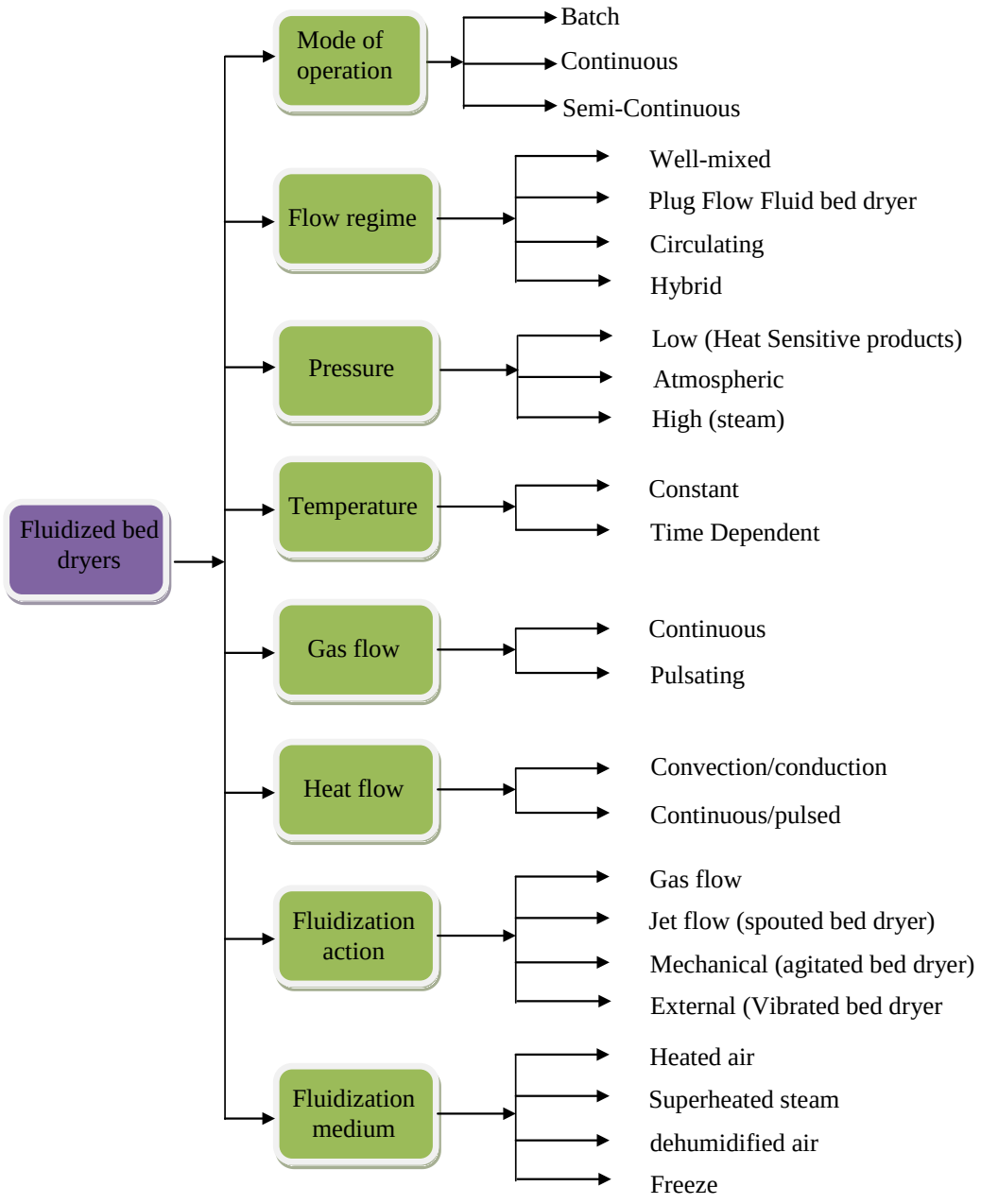
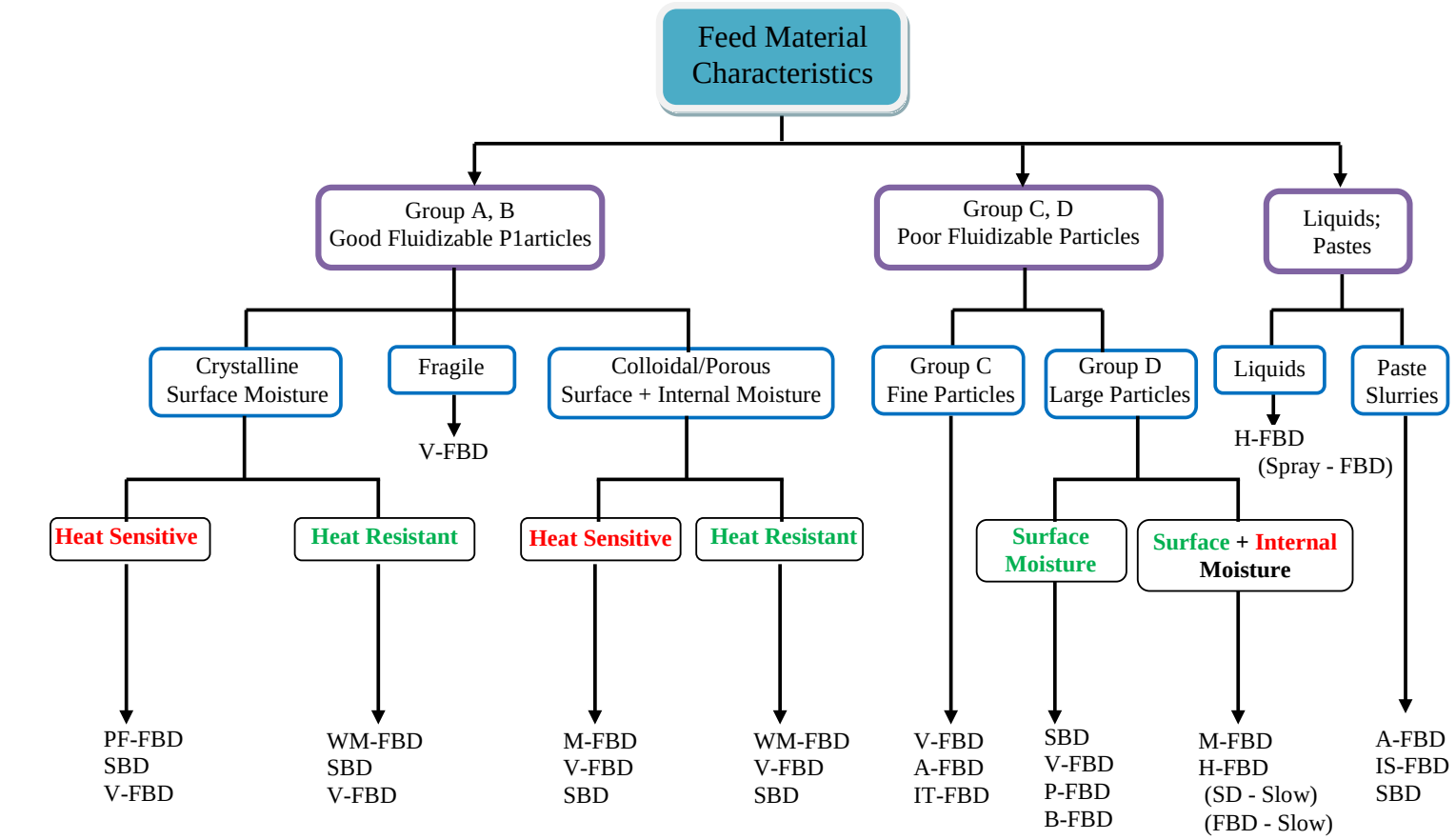


Figure 3.2. Classification of fluidized bed dryer based on different criteria



Abbreviations

WM-FBD	Well-mixed FBD	SBD	Spouted bed	P-FBD	Pulsating FBD	H-FBD	Hybrid FBD
PF-FBD	Plug flow FBD	M-FBD	Multi stage FBD	IT-FBD	Immersed tubes FBD	IS-FBD	Inert Solids FBD
V-FBD	Vibrated FBD	A-FBD	Agitated FBD	B-FBD	Baffled FBD	SD	Spray Drying

Figure 3.3. Selection of fluidized bed dryer

3.5. SELECTION OF SPRAY DRYERS

Spray dryer is the second most important dryer type used in the food processing sector. Some of the common applications are drying of fruit juices, herbal extracts, milk and many more. The detailed chapter on spray drying of food products is covered in this book. However, we have tried to give some information on selection criteria as the spray dryers are available in a wide range of designs. The selection choices can be limited to the following categories of dryers.

Co-current single-stage dryer with pneumatic powder conveying: This basic design is widely used to process relatively easy to dry, non- and low-fat formulation. Fairly high outlet temperatures are used to achieve the desired final outlet moisture content before the powder is discharged into the pneumatic conveying system.

Co-current, two-stage dryer with an external fluidized bed: This versatile layout can be used to produce standard, semi-agglomerated and fully agglomerated powders. The externally mounted vibrating fluidized bed acts as a post-dryer, a cooler or a combination of the two.

Co-current, two-stage dryer with integrated fluidized bed and pneumatic conveying system: In this variant, an annular fluidized bed is located in the base of the spray-drying chamber. This enables higher moisture contents to be handled in the drying chamber. Moreover, the drying process can be completed at relatively low product temperatures, which can be of advantage in some circumstances. It is, however, restricted to non- or low-fat formulations. The product is a standard or a semi-agglomerated powder.

Figure 3.4 elaborates the general classification of spray dryers based on their operating characteristics. Note that selection of the spray drying system also must consider product quality and pilot scale test results

Another important part in spray dryer selection is the choice of a suitable atomizer. A spray dryer is indicated when a pumpable slurry, solution or suspension is to be reduced to a free-flowing powder. With proper choice of atomizer, spray chamber design, gas temperature and flow rate it is possible to “engineer” powders of desired particle size and size distribution.

Table 5 shows how the choice of the atomizer affects chamber design, size, as well as energy consumption for atomization and particle size distribution. The newly developed two-fluid sonic nozzles appear to be especially attractive choices when nearly monodispersed powders need to be produced from relatively moderate viscosity feeds (e.g., under 250 cp) at capacities up to 80 t/h by using multiple nozzles. More examples may be found in Masters (1985) and Mujumdar (2006). **Table 3.5** is a case study not from the food industry but it is included here to demonstrate the effect of atomizer selection on overall performance of a spray dryer.

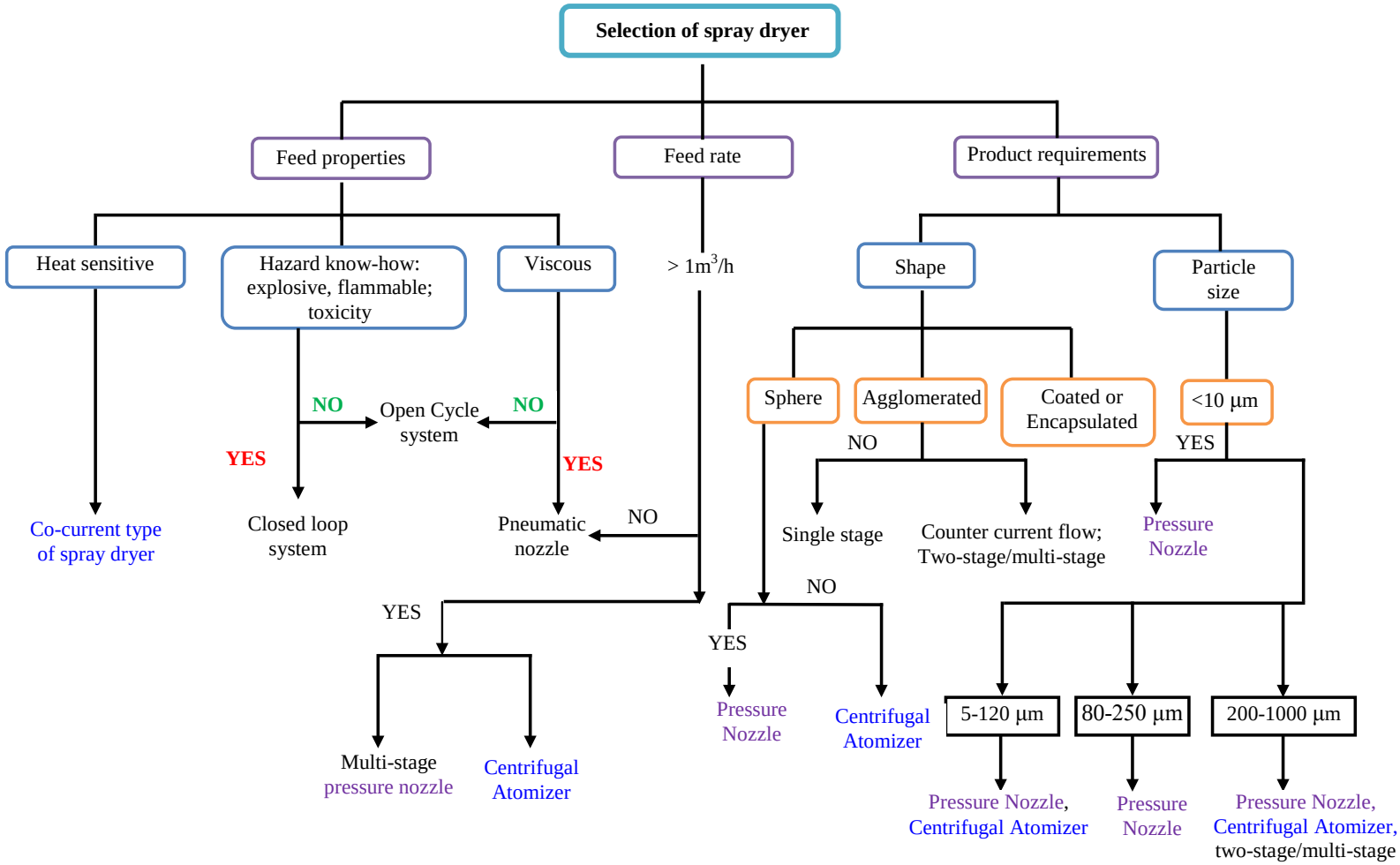


Figure 3.4. Selection tree for spray dryers/atomizers

Table 3.5. Spray drying of emulsion-PVC. Effect of selection of atomizer on spray dryer performance: A Comparison between different atomizers

Parameter	Rotary disk	Two-fluid (sonic)	Two-fluid (standard)
Dryer geometry	Conical/cylindrical $H/D \approx 1.2$-1.5	Tall-form Cylindrical $H/D \approx 4$	Tall-form Cylindrical $H/D \approx 5$
Evaporation capacity (water)	1600 kg/h	1600 kg/h	1600 kg/h
Chamber ($D \times H$)	6.5 m × 8 m	3.5 m × 15 m	3 m × 18 m
Number of nozzles	1, 175-mm disk 15,000 rpm	16 nozzles 4 bar pressure	18 nozzles 4 bar pressure
Power for atomizer	25 W/kg slurry	20 W/kg slurry	80 W/kg slurry
Capital cost	High	Medium	Medium
Operating cost	Medium	Low	High

3.6. COMPARISON OF CONVENTIONAL DRYERS WITH NEWER DRYERS

It is worth mentioning that many of the new techniques for food drying use superheated steam or inert gases (nitrogen) as the drying medium or are simply intelligent combinations of traditional drying techniques, e.g., combination of heat transfer modes, multi-staging of different dryer types. Superheated steam as the convective drying medium offers several advantages, e.g., higher drying rates under certain conditions, better quality for certain products, lower net energy consumption if the excess steam produced in the dryer is used elsewhere in the process, elimination of fire and explosion hazard. Use of nitrogen as a drying medium has added advantage of avoiding the oxidation reactions in food drying; however, this is expensive operation and needs closed loop system.

New dryers are being developed continuously as a result of industrial demands. Over 250 US patents are granted each year related to dryers (equipment) and drying (process); in the European Community about 80 patents are issued annually on dryers. Kudra and Mujumdar (2009) have discussed a wide assortment of novel drying technologies, which are beyond the scope of this chapter. Suffice it to note that many of the new technologies (e.g., superheated steam, pulse combustion – newer gas-particle contactors as dryers) will eventually replace conventional dryers in the next decade or two. New technologies are inherently more risky and more difficult-to-scale-up. Hence there is natural reluctance to their adoption. Readers are encouraged to review the new developments in order to be sure their selection is the most appropriate one for the application at hand. Some conventional and more recent drying techniques are listed in the **Table 3.6**.

Table 3.6. Conventional versus innovative drying techniques

Feed type	Dryer type	New techniques*
Liquid Suspension	• Drum • Spray	• Fluid/spouted beds of inert particles • Spray/fluid bed combination • Vacuum belt dryer • Pulse combustion dryers • Spray freeze drying
Paste/sludge	• Spray • Drum • Paddle	• Spouted bed of inert particles • Fluid bed (with solid backmixing) • Superheated steam dryers • Screw conveyor dryer
Particles	• Rotary • Flash • Fluidized bed (hot air or combustion gas)	• Superheated steam FBD • Vibrated bed • Ring dryer • Pulsated fluid bed • Jet-zone dryer • Yamato rotary dryer • Screw conveyor dryer • Immerse heat exchanged dryer
Continuous sheets	• Multi-cylinder contact dryers • Impingement (air)	• Combined impingement/radiation dryers • Combined impingement and through dryers (textiles, low basis weight paper) • Impingement and MW or RF

*New dryers do not necessarily offer better techno-economic performance for all products

3.6.1. Classification of superheated steam dryers

Superheated steam drying technology was first proposed over 120 years ago but the commercial applications started very recently. Superheated steam drying mainly involves use of superheated steam as a drying medium instead of heated air or flue gases to supply heat in a direct type of dryer. SSD is more complex and recovering heat from the exhaust steam is a difficult task. However the net energy consumption can be lowered if the exhaust steam is used elsewhere. Main advantages of superheated steam drying to be highlighted are absence of any oxidation reaction during drying of food products, improved drying rates (this has been proved for many food products), recovery of toxic/expensive organic solvent removed during drying and pasteurization/sterilization of food products. These types of dryers also have some limitations such as complexity, initial condensation of steam, problems with drying of materials which tend to melt or undergo glass transition. The superheated steam dryers can be classified based on the operating pressure as shown in **Figure 3.5**.

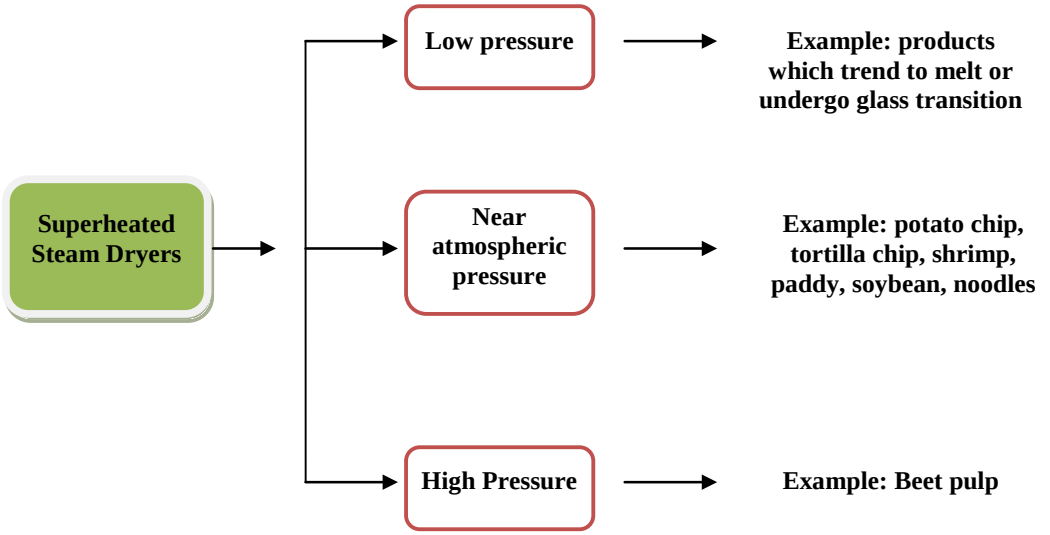


Figure 3.5. Classification of superheated steam drying

6.3.2. Developments in fluid bed drying

We already have summarized the large number of possible variants of FBDs that are now used to dry not only particulates (which was the original idea) but also slurries, pastes, continuous webs and sheet-form materials. Large pieces that cannot be fluidized by themselves can be immersed in a fluidized bed of smaller fluidizable inert particles and dried. Most of the variants shown are used in industrial drying applications to varying extent. Many users seem to be unaware of some of these innovative modifications of the FBDs.

Interestingly, by fluidizing only parts of the particulate bed at a time, it is possible to effect a major saving in energy costs, e.g., so-called pulsed fluid beds (Gawrzynski and Glaser, 1996). In batch fluidized bed drying, a control strategy that keeps the bed temperature constant by adjusting heat input saves energy (and time) while enhancing the quality of heat-sensitive products (Devahastin and Mujumdar, 1999). Such a dryer based on a fuzzy logic control is already on the market. **Table 3.7** compares the conventional and innovative fluidized beds based on different operational variants.

6.3.3. Hybrid drying technologies

The use of hybrid technologies is being employed recently mainly to hasten the drying rate. It was noted earlier that drying of most foods lies in falling rate period and that the drying rate is very sluggish in the final stages when the interstitial water is to be removed and the performance of convection dryers is very poor which results in to longer residence time. This can lead to higher energy consumption, loss of important nutritional as well sensory properties of food products making it unacceptable. Use of high temperature to remove this part of water at faster rate may lead to case hardening and similar problems. The best way to enhance the drying rate is to either to use multi-stage drying approach or using radiative heat source. Similar limitations are associated with spray dryer. In many cases it is difficult to reach the expected final moisture content hence multi-stage drying system is used. **Figure 3.6** shows different options available for hybrid drying system.

Table 3.7. Comparison of conventional and innovative fluid bed dryers

Variant	Conventional	Innovative
Mode of heat transfer	Only convection	Convection + conduction (immersed heaters in bed) + radiative heat transfer (MW assisted fluid beds)
Gas flow	Steady	Pulsating; on/off
Mode of fluidization	Pneumatic	Mechanically agitated / vibrations
Drying media	Air / flue gases	Superheated steam / heat pump assisted (even using inert media)
Type of material dried	Particulate material	Drying of pastes / slurries using bed of inert particles

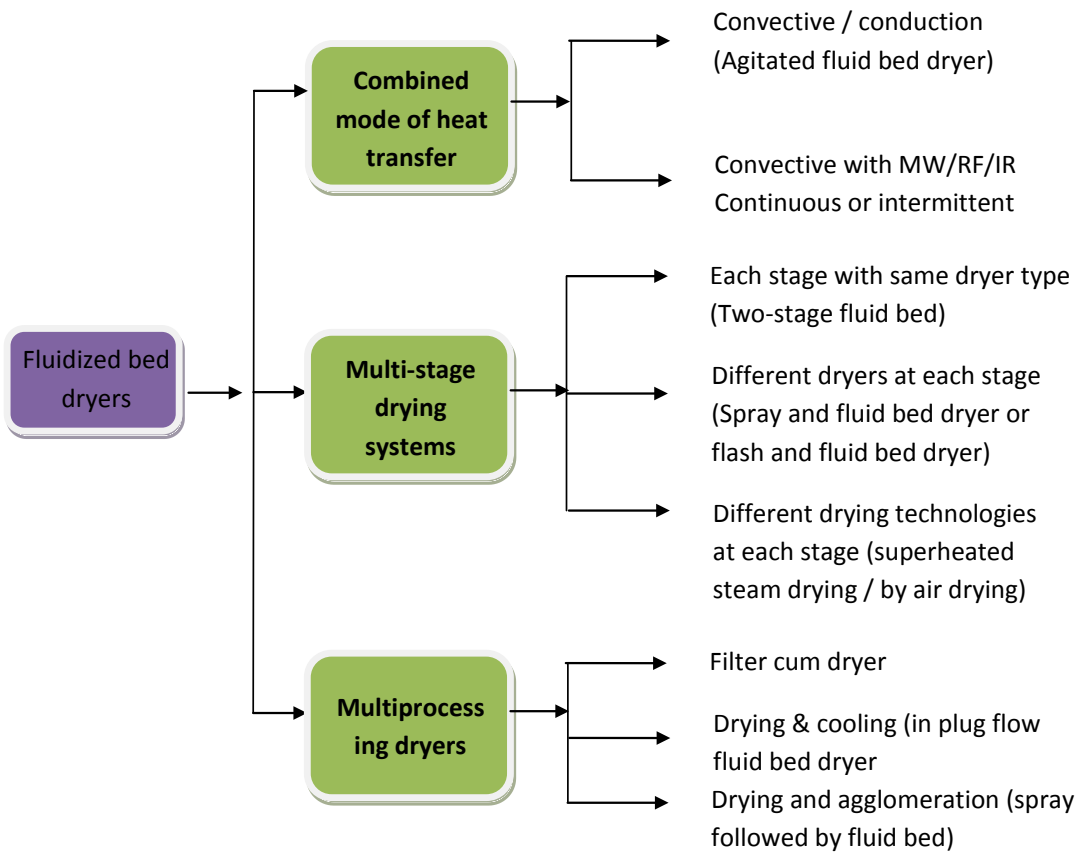


Figure 3.6. Hybrid drying technologies

3.7. CASE STUDIES

3.7.1. Production of milk powder

It should be noted that the selection of dryer or drying system not only depends on the physical properties of the feedstock but also on the mode of operation, capacity required, heat sensitivity. Apart from this, the initial and required final moisture content, drying kinetics also affects the dryer selection. In case of the production of milk powder, the feedstock is in a liquid form hence the basic choice of dryers is limited referring to the Table 3 (spray dryer, drum dryer and fluidized bed dryer with some improvements which is difficult to use for this application). However, if the final material is required to be in a sufficiently free flowing form, it is best choice to use spray dryer. Nevertheless, spray dryer alone does not serve the purpose as the required final moisture content cannot be reached. It is recommended to go for two-stage drying option with fluidized bed as a second dryer which takes care of final drying of relatively wet powder from spray dryer. The choice of fluidized bed depends on the physical properties of material to be dried. The milk powder from spray dryer is of Geldart type 'A/B' with porous structure and good fluidization characteristics. In addition milk powder is heat sensitive hence it can be seen from **Figure 3.3** that, one can have three options of fluidized bed (multi-stage fluidized bed, vibrated fluidized bed and spouted bed). However because of the colloidal nature of the milk powder it is recommended to use vibrated fluid bed dryer. Although these are just suggestions the detailed experimental validation should be done on pilot scale dryers.

3.7.2. Drying of grains

Most of the grains fall in the Geldart type 'D' of particles and have both surface as well as the internal moisture. For particulate materials fluidized beds are the best choice because of high heat and mass transfer. However, this class of particles have poor fluidization quality (because of the funny shapes of particles) hence the use of well mixed or plug flow fluidized bed dryer can be ruled out. Referring to **Figure 3.3** suggest that for class D of particles with surface and internal moisture, the best choice is to use multi-stage fluidized bed dryers or spouted bed dryer. In multi-stage drying of grains, the first stage can be flash dryer or cyclone dryer to remove the surface moisture and the second stage can be a plug flow fluid bed dryer or vibrated fluid bed dryer depending on the type of grain to be dried. If the spouted bed dryer is used alone, higher drying gas flow rates can be used in initial staged to remove surface moisture and low gas flow in later stage.

3.8. CLOSING REMARKS

It is difficult to generate definitive general rules for both classification and selection of dryers because exceptions occur rather frequently. Often, minor changes in feed or product characteristics result in different dryer types being the appropriate choices. It is not uncommon to find different dryer types being used to dry apparently the same material. The choice is dependent on production throughput, flexibility requirements, cost of fuel as well as on the subjective judgment of the individual who specified the equipment.

We have also discussed some novel dryers in this chapter. However, Kudra and Mujumdar (2000) have discussed in detail most of the non-conventional and novel drying technologies reported in the literature. Most of them have yet to mature; a few have been commercialized successfully for certain products. It is useful to be aware of such advances so that the user can make intelligent decisions about dryer selection. Since dryer life is typically 25-40 years that effect of a poor "prescription" can have a long-term impact on the economic health of the plant. It is typically not a desirable option to depend exclusively on prior experience, reports in the literature or vendors' recommendations. Each drying problem deserves its own independent evaluation and solution. Finally some ideas are presented for selection of dryer for drying of selected food products. However, these are just suggestions and this should be experimentally tested.

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Chapter 4
Osmotic Dehydration

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Contents

4.1. INTRODUCTION

Dehydration is a versatile, widespread technique in the food industry; it is the oldest and most frequently used method of food preservation. The main objective of drying is the removal of moisture so as to reduce the water activity and hence the associated microbial and enzymatic activity and product quality deterioration. Drying methods have been applied to extend the shelf life of the product; however, they often affect the quality of the final product. The most common quality defects associated dehydrated products are poor reconstitution, loss in texture, loss in the nutritive and sensory properties such as flavor and color. These are mainly due to the exposure of the product to high temperatures and long drying times mostly in the presence of air (Lenart, 1996; Lin et al., 1998). A new interest has recently arisen in finding new ways to improve the quality of dried food products. Many alternatives have been recognized such as the use of vacuum so that lower temperatures could be used, use of freeze drying which is done under conditions below the triple point of water facilitating sublimation thereby protecting the product texture and other quality factors, use of rapid drying techniques which would reduce the drying time, use of novel heating sources like microwave and radio frequency heating (significant reducing in drying time), use of various treatments which promote better mass transport phenomena etc. Osmotic dehydration has been lately recognized as a good pretreatment prior to regular drying to promote better quality and reduce energy needs (Torreggiani, 1993). Osmotic dehydration has the potential to remove water at low temperatures; in addition, it is an energy efficient method, as water does not go through a phase change (Bolin et al., 1983).

Osmotic dehydration is gaining popularity as a complementary processing step in the chain of integrated food processing in the food industry due to its quality and energy related advantages. It has been shown that osmotic pre-treatment improves the quality of dried products including: reduced discoloration of the fruit by enzymatic browning (Ponting et al., 1966; Contreras and Smyrl, 1981), reduced heat damage to texture, color (Torreggiani, 1993), increased retention of volatiles (Flink, 1975; Dixon and Jen, 1977), increased sugar to acid ratio which improves the textural quality (Raoult-Wack, 1994) and low operating costs (Bolin et al., 1983). Osmotic dehydration is acknowledged to be an excellent energy saving method as moisture is efficiently removed from a food product without a phase change (Bolin et al., 1983). In addition, the product is processed in a liquid phase, generally giving good heat- and mass-transfer coefficients (Raoult-Wack, 1994). The cost of shipping, packing and storing is also reduced due to the lower moisture content of the product (Rao, 1977; Biswal and Bozorgmehr, 1992). Since the water activity of the product is decreased, microbial growth is largely inhibited. However, the product is not shelf-stable since relatively large proportion of moisture still exists (up to 50%). Additionally, complementary treatments such as freezing (Tregunno and Goff, 1996), freeze drying (Donsì et al., 2001), vacuum drying (Rahman and Mujumdar, 2007), air drying, osmo-convective drying (Islam and Flink, 1982; Corzo et al., 2008) and microwave drying (Orsat et al., 2007) are necessary in order to provide shelf stability to the product. Osmotic dehydration is a time-consuming process; therefore, supplementary methods are needed to increase the mass transfer without affecting the product quality (Rastogi et al., 2002). One of the distinctive aspects of osmotic dehydration in compar-

ison with other dehydration methods is the incorporation of solute into the food system, to a certain extent, which can change the functional properties of the product; it is possible to achieve specific formulation properties without modifying its integrity (Torreggiani, 1993). Research on osmotic dehydration of foods was pioneered by Ponting et al. (1966), and since then a steady stream of publications have appeared. These in general have dealt with various parameters, such as the mechanism of osmotic dehydration, the effect of operating variables on osmotic dehydration, modeling of water loss and solid gain, and enhancement of mass transfer (Lenart and Lewicki, 1987; Torreggiani, 1993, Raoult-Wack, 1994; Raoult-Wack et al., 1994; Azuara et al, 1992; Lenart, 1996; LeMaguer, 1996; Rastogi et al., 1997; Lewiciki, 1998; Nsonzi and Ramaswamy, 1998a,b; Khin et al., 2005; Mastrocola et al., 2005; Falade and Igbeka, 2007; Vadivambal and Jayas, 2007; Li and Ramaswamy 2006a,b,c).

Despite its well-recognized advantages and the large amount of research work that has been published in this area, industrial application of osmotic dehydration is limited. This chapter details the basic concepts and recent developments in osmotic dehydration highlighting the effect of process variables, modeling of mass transfer, techniques developed to enhance mass transfer rates, factors affecting quality parameters as well as a brief overview of the different techniques employed for the finish drying.

4.2. BASIC PRINCIPLES OF OSMOTIC DEHYDRATION

Osmotic dehydration can be defined as a 'dewatering and impregnation soaking process' (DISP) (Torreggiani, 1993; Raoult-Wack, 1994), a combination of dehydration and impregnation processes which can modify the functional properties of food materials, thereby creating new products. Osmotic dehydration can be defined as a simultaneous counter-current mass transfer process in which biological materials (such as fruits and vegetables) are immersed in a hypertonic aqueous solution for a selected period. The driving force for the diffusion of water from the tissue into the solution is the higher osmotic pressure of osmotic solution and its lower water activity that results in the transfer of water from the product across the cell wall. The diffusion of water is associated with the simultaneous counter diffusion of solutes from the osmotic solution into the tissue. This contributes to a net opposite flux of water and solutes that allow the tissue to become concentrated with a determined ratio solute gain/water loss (SG/WL) depending on process conditions (Chiralt and Fito, 2003). Since the membrane responsible for osmotic transport is not perfectly selective, other solutes (sugar, organic acids, minerals, vitamins) present in the cells can also leach into the osmotic solution (Lenart and Flink, 1984a; Torreggiani, 1993) in amounts that are quantitatively negligible compared with the other transfer; however, they are important in terms of final product quality (Dixon and Jen, 1977). During osmotic dehydration, there are different variables that affect the rate of water diffusion from any materials; therefore, it is difficult to establish general rules about them. However, osmotic pressure, plant tissue structure and mass transport relationship, are the most important ones (Islam and Flink, 1982; Lerici et al., 1985).

4.2.1. Osmotic pressure

Water as the main constituent of most foods affects food stability. During osmotic dehydration, water in solution is in an interaction with solute. This interaction is characterized by the thermodynamic state of water. Energetic state of each substance can be defined as its internal energy which is called chemical potential. Chemical potential is a function of concentration, temperature, and pressure, however under isothermal conditions; it is just determined by concentration and pressure. The chemical potential can be defined according to the following relationship:

$$\mu_w = \mu_{0w} + \mathrm{RT} \ln a_w \tag{4.1}$$

μ_w – chemical potential of water

μ_{0w} – chemical potential in a sandard state

T – absolute temperature

R - gas constant

a_w – water activity coefficent

The energy is exchanged during the interaction of two systems with different energy state until reaching the equilibrium state. Under isothermal conditions, chemical potentials of two systems are the same, and can be achieved by the change of either concentration or pressure. Osmotic pressure is the excess pressure that pushes the system to reach the state of equilibrium between pure solvent and a solution and is expressed by the formula:

$$\Pi = -\frac{\mathrm{RT}}{\mathrm{V}} \ln a_w \tag{4.2}$$

Where $\prod$ is the osmotic pressure and V is molar volume of water.

Osmotic dewatering of fruits and vegetables utilized by the difference in osmotic pressure between two systems results in mass transfer (Lewicki and Lenart, 2007).

4.2.2.The plant tissue structure

Plant tissue as a living material plays an important role during osmotic dehydration (Marcotte and LeMaguer, 1991). Although different parts of a plant such as roots, stems, shoots, leaves, flowers, fruits and seeds can be used during osmotic dehydration, all of them consist of cells that are highly specialized and are called tissues. Tissues consist of epidermal tissue which forms the outermost layer of cells which are thick and covered with a waxy substance known as cutin. Parnchymatous tissue, the main parts of organ, which has the ability to produce and store nutritional substances; and the vascular tissue which can carry the solution of minerals and nutritional substances in a plant (Rahman and Perera, 1999).

A fresh plant tissue is composed of cells connected to each other by the middle lamella, and the protoplast. The cell wall consists of three independent materials; cellulose microfibrils, hemicelluloses and pectin substance (Carpita, 1996). Hemicelluloses with branched polymers (xyloglucans, glucomannans) link with cellulose and pectin by hydrogen bonds. Generally, the rigidity of a dried product comes from the cellulose whe-

reas plasticity comes from pectin and hemicelluloses (Lewicki and Pawlak, 2003). Middle lamella has two thin semi-permeable membranes: the tonoplast and the plasmalemma. Protoplast is separated by the plasmalemma from the cell wall, and cytosol solution. The osmotic phenomenon is largely controlled by the plasmalemma (Nobel, 1999). The cytosol is the major component of protoplast which contains different organelles such as the chloroplasts, mitochondria, peroxisomes, ribosomes, and proteins. These macromolecules and structures can affect the thermodynamic properties of water. The vacuole is a large central space inside the protoplast filled with water and surrounded by tonoplast. A vacuole has an osmotic pressure that pushes protoplasm and plasmalemma toward the cell wall. This osmotic pressure is called turgor pressure which is the difference between the osmotic pressure in the cell and its surroundings. When the cell and the surroundings have the same osmotic pressure, the turgor pressure is zero and the system is in equilibrium. If the osmotic pressure of the surroundings is higher than the cell, the water transfers into the cell and the cell swells. During osmotic dehydration, the plant cell is placed in a hypertonic solution with the osmotic pressure higher than that of the cell; as a result, the cell loses its water and decreases its volume. Consequently, plasmalemma is detached from the cell wall. This process is called plamolysis.

A mass transfer phenomenon is a complex mechanism occurring in plant tissue during osmotic dehydration. Water is transferred from the inner tissue to the outside, through the porous tissue structure, and then through the outside boundary layers. There are three important pathways during osmotic dehydration; symplastic (the transport within the intracellular volume), free-space transport (the transport within the extracellular volume) and apoplastic (water passing through plasma membranes) (Shi and LeMaguer, 2002). The transport of water between cells along the symplastic rout is mediated by plasmodesmata, whereas in the transcelluar path water has to cross plasma membranes. Furthermore, water moves across a tissue by crossing two membranes per cell layer and the apoplast (Steudle and Frensch, 1996). The removal of water during the osmotic process is mainly by diffusion and capillary flow, whereas solute uptake or leaching is only by diffusion.

4.2.3. Osmotic dehydration mass transport phenomena

In fruits or vegetables, the cell wall membranes are living biological units which can stretch and expand under the influence of growth and turgor pressure generated inside the cells. The Semi-permeable membranes present in biological materials are the dominant resistance to mass transfer during osmotic dehydration. The cell membrane can change from being partially to totally permeable, leading to significant changes in tissue architecture (Rastogi et al., 2002). When plant cells are placed in a hypertonic solution, water removal starts from the surface that is in contact with the osmotic solution, resulting in cell disintegration (Rastogi et al., 2000b). It is reported that sugars penetrate to a depth of 2-3 mm into the plant tissue while changes in water content are observed up to 5 mm (Bolin et al., 1983; Lenart and Flink, 1984b). Water leaves the cell surface by osmosis; therefore, the vacuole and the rest of the protoplasm will shrink, and plosmolysis occurs. However, the interior surface of the material can remain in full turgor pressure. A turgor pressure gradient results in detaching of plasma membrane and the middle lamella due to the degradation or denaturation of the components of the middle lamella.

Consequently, the mechanical properties of the product will change and the structure will deform. Lewicki and Porzecka-Pawlak (2005) reported cell debonding during osmotic dehydration of apple. Consequently, the cell is damaged and reduces in size by the loss of water and contact between the outer cell membrane and the cell wall (Rastogi et al., 2000b; Rastogi et al., 2002). Extensive uptake of osmoactive substance results in the development of a concentrated solids surface layer posing an additional resistance to mass transfer (Lenart and Lewicki, 1987; Lenart, 1994).

Consequently, porosity of the product will increase, and the tissue shrinks because the amount of water flowing out is generally greater than the solutes diffusing in. The diffusing substances are assumed to consist of water and sucrose only (Marcotte et al., 1991). Therefore, the weight of the foods will decrease, as will the water activity. It is reported that up to a 50% reduction in the fresh weight of fruits or vegetables may be brought about by osmosis (Rastogi et al., 1997; Kar and Gupta, 2001). All these mass exchanges may have an effect on the organoleptic and/or nutritional quality of the dehydrated product (Sablani et al., 2002). As a consequence of this exchange, the product loses weight and shrinks. Cellular shrinkage during dehydration has been observed during osmotic dehydration of apple (Lewicki and Porzecka-Pawlak, 2005).

4.3. FACTORS AFFECTING OSMOTIC DEHYDRATION

The rate of diffusion of water from any material during osmotic dehydration is dependent upon factors such as type of osmotic agent, concentration of the osmotic solution, temperature, the size and geometry of the material, the solution-to-material mass ratio and the level of agitation of the solution. There are several publications which describe the influence of these variables on mass transfer rate (Lerici et al., 1985; Raoult-Wack, 1989; Raoult-Wack, 1994; Rastogi et al., 1997; Rastogi and Niranjan, 1998; Rastogi et al., 1999; Corzo and Gomez, 2004). However, the variables mentioned above can be manipulated over a limited range; outside of these ranges, the quality was adversely affected even though mass transfer rates may be enhanced (Rastogi et al., 2002). There are also some techniques which can combine with osmotic dehydration, and have the ability to alter membranes in order to enhance mass transfer rate. They include: ultrasound (Rodrigues and Fernandes, 2007) high-intensity electric field (Rastogi et al., 1999), or high hydrostatic pressure (Akyol et al., 2006) and microwave (Li and Ramaswamy, 2006c; Azarpazhooh and Ramaswamy, 2010a,b). The choice of process conditions depends on the expected water loss, soluble solids gain, and the sensory properties of the food products.

4.3.1. Influence of size and shape on the mass transfer

Some research has been done on the influence of size and shape on the mass transfer kinetics. The surface area to volume ratio has been shown to be the influencing factor with higher ratios favoring better osmotic dehydration rates. Islam and Flink (1982) reported that the size and geometry of the food has some influence on the extent of final solute concentration, especially during short dehydration times; at such times, dehydration was primarily a transport phenomenon related to surface area. Lerici et al. (1985) compared osmotic drying of apple slices of four different shapes of (i.e slice, stick, ring and cube) and reported that the solids content increased with a decreasing surface

area/volume ratio, but that the moisture loss was optimal for the ring shape. Van Nieuwenhuijzen et al. (2001) reported that moisture loss and solids gain increases as particle size is decreased under same processing conditions.

4.3.2. Type of osmotic agent

The type, molecular weight and ionic behavior of osmotic agents are strongly affected by the kinetics of water removal. The most commonly used osmotic agents are carbohydrates (sucrose, sorbitol, corn syrup, glucose, and fructose) or salts (NaCl, $CaCl_2$) or their mixtures. In most published literature, sucrose is used for fruits and sodium chlorides for vegetables, fish and meat. The size and molar concentration of the ionized salts are different with unionized sugars; therefore, the smaller salt ions can more easily diffuse through the cell membrane resulting in a gain in higher solids, and a reduction in water loss as the osmotic potential gradient is reduced. However, larger molecules such as sugar cannot easily diffuse through the cell membrane (Ponting et al., 1966). Although sucrose is very effective, convenient and produces a desirable flavor, it promotes a greater solids uptake. Maltose can preserve cell structure and color stability, and also it causes lower solids gain, enhancing a positive impact on nutritional and sensory profiles (Forni et al., 1997; Ferrando and Spiess, 2001). Moreover, sucrose can be used in a binary system in order to reduce the cost of osmotic agents and improving the effectiveness of osmosis (Hawkes and Flink, 1978; Islam and Flink, 1982). Heredia and Andras (2008) reported that the use of ternary solutions in osmotic dehydrations of tomatoes could be more appropriate than the use of binary solutions with the aim of maximizing water loss and minimizing solutes gain. The low molecular weight of sugars such as glucose is more effective in the transfer of water than the higher molecular weight due to limiting solids uptake of food material. Invert sugar has twice as many molecules per unit volume, and is more effective than sucrose. During osmotic dehydration, leaching the acid from the fruit into the syrup leads to accelerated hydrolysis of sucrose to glucose and fructose, resulting in increasing water removal (Bolin et al., 1983). It is recommended using osmotic dehydration less than 50% weight reduction due to the decrease in the osmosis rate with time (Torreggiani, 1993). It is reported that water loss mainly occurs during the first two hrs and the maximum solid gain within 30 min (Conway et al., 1983). Lazarides et al. (1995) showed that under the same osmotic process conditions, using corn syrups as osmotic agents result in lowering sugar uptake.

4.3.3. Contact time

The contact time of food with the osmotic solution is an important variable during osmotic dehydration. During osmotic dehydration, increasing the time of the osmotic treatment results in decreasing the rate of mass transfer while weight loss in food so treated is increased (Fasina et al., 2002). In terms of the contact time, the rate of both moisture loss and solids gain is the highest within the first hour of osmosis followed by progressively lower rates for the rest of the time. On average, moisture loss rates drop to about 20% of the initial rate during the first hour of dehydration and nearly level off at about 10% of the initial rate within three hrs. Solid gain rates show a similar decrease trend. Rapid loss of water in the beginning is due to the large osmotic driving force between the dilute sap of the fresh fruit and the surrounding hypertonic solution.

4.3.4. Temperature of the solution

The temperature of the osmotic treatment is the most significant factor that influences the process of osmotic dehydration. The positive effect of temperature on the removal of water from the food during osmotic treatment has been shown by several researchers (Raoult-Wack et al., 1994; Lazarides and Mavroudis, 1996). Higher process temperatures generally promote faster moisture loss through better mass transfer characteristics on the surface due to lower viscosity of the osmotic medium. High temperatures, i.e. over 60°C, modify the tissue characteristics so favoring impregnation phenomena and thus the solid gain; however, above 45°C, enzymatic browning and flavor deterioration begins to take place (Lenart and Flink, 1984a). The best processing temperature depends on the food: for example, for green beans, 20°C gives better results, while 40°C is too high a temperature (Biswal et al., 1991).

4.3.5. Agitation and food/ solution ratio

Agitation of the osmotic solution is an important aspect of the osmotic treatment. The agitation ensures that the concentrated solutions are restored around the particle surface and that a concentration difference favorable to mass transfer is recreated. The ratio of osmotic solution to fruit is an important consideration and often influences the production logistics, since it dictates the mass transfer momentum and the equilibrium concentrations. High solution/fruit ratios maintain constant solution concentration, and prevent dilution. On an industrial scale, the ratio needs to be as low as possible to restrict plant size and costs of solution regeneration. On the other hand, use of a low ratio leads to significant transient changes in the solution composition. Most development studies are carried out with a large excess of osmotic solution to ensure minimal changes in solution concentration during test runs. The weight ratio of solution to product most often used is between 4 and 10.

4.4. ENHANCEMENT OF OSMOTIC DEHYDRATION

Osmotic dehydration is relatively slow so acceleration of mass transfer would be advantageous. There are various methods to increase the mass transfer, such as application of ultrasound, high hydrostatic pressure, high electrical field pulses, vacuum and centrifugal force and microwave

4.4.1. Application of ultrasound during osmotic dehydration

Ultrasound in the food industry is relatively new and it has not been explored in-depth until recently (De Gennaro et al., 1999). Ultrasound has been applied in the food industry to determine food properties due to low-frequency, high-energy ultrasound. It can travel through a solid medium; therefore, it can influence mass transfer. A phenomenon known as acoustic cavitation is generated during the application as ultrasonic waves can generate minute vapor-filled bubbles that collapse rapidly or generate voids in liquids. Consequently, rapid pressure fluctuations are induced within the wet material by the ultrasonic waves. Ultrasound can be carried out at ambient temperature as no heating is required for reducing the potential of thermal degradation (Rodrigues and Fernandes, 2007). It can influence mass transfer through structural changes, such as "sponge effect", and microscopic channels (Carcel et al., 2007). Applying ultrasound dur-

ing osmotic treatment has a significant effect on the kinetics of water loss, sugar gain, and firmness loss, as well as on the microstructure of osmotically dehydrated different products and processes in liquid–solid system, such as osmotic dehydration of apples (Carcel et al., 2007). Water effective diffusivity increases with the use of ultrasound and decreases the amount of sugar in the fruit to produce a dried low-sugar fruit (Rodrigues and Fernandes, 2007). Gallego-Juarez et al. (1999) used high-intensity ultrasound to accelerate the osmotic dehydration rate of apples. Duan et al. (2008) used ultrasound pretreatment to improve the freeze- drying rate.

4.4.2. Application of blanching as a pretreatment

Hot water or steam blanching is a pretreatment before osmotic dehydration with the purpose of enzyme inactivation, and also to promote gas removal from surfaces and intercellular spaces; oxidation, discoloration, and off-flavor development and microbial growth are thereby prevented (Rahman and Perera, 1999). Blanching has been applied prior to drying of fruits and vegetables, however blanching has some drawbacks such as causing changes in the chemical and physical state of nutrients and vitamins as well as having an adverse environmental impact on large water and energy usage (Rahman and Perera, 1999). Water blanching (85–100 °C) usually results in loss of nutrients such as minerals and vitamins (Akyol et al., 2006).

4.4.3. Application of high hydrostatic pressure as a pretreatment

High-pressure treatments have been tested for their effectiveness as an alternate to thermal blanching (Eshtiaghi and Knorr, 1993) because they can be applied to liquid and solid foods, with or without packaging, at pressures between 100 and 800 MPa (Eshtiaghi et al., 1994). Akyol et al. (2006) showed that high hydrostatic pressure (HHP) with the combination of mild heat treatment can be used for blanching purposes to inactive peroxidase (POD) and lipoxygenase (LOX) in carrots, green beans, and green peas. In addition, high pressures cause permeabilization of the cell structure (Eshtiaghi et al. 1994) leading to the enhancement of mass transfer rates during osmotic dehydration. Rastogi and Niranjan (1998) reported that the application of HP on pineapples damaged cell wall structure, leaving the cells more permeable with a reduction in intercellular material. Taiwo et al. (2001) report that high pressure may be considered during osmotic dehydration when product formulation through sugar uptake is desired.

4.4.4. Application of vacuum as a pretreatment and during osmotic dehydration

Application of vacuum impregnation (VI) simultaneously with osmotic treatment for a short period of time has been widely studied (Fito, 1994). Vacuum impregnation is widely used simultaneously with osmotic treatments to enhance mass transfer and promote more homogeneous concentration profiles in the fruits (Fito et al., 2001). The total transport of water and solute during vacuum pulse osmotic dehydration is caused by two mechanisms: the hydrodynamic mechanism (HDM) and pseudo-fictions mechanism. HDM is promoted by pressure gradients and penetration into the pores of plants over a short time period and the pseudo-fiction mechanism is driven by activity gradients over longer time frames (Fito, 1994). During vacuum impregnation especially in porous products, the action of hydrodynamic mechanisms (HDM) is combined by diffu-

sional phenomena to promote mass transfer (Fito et al., 2001). When a vacuum pulse is applied in the system, the gas and liquids in the internal pores of the product are replaced by the external liquid, and the impregnation process is completed practically by the external solution, resulting in changing the mass transfer behavior in the product due to its porosity reduction (Fito, 1994). When VI is applied, the mass loss is reduced as compared with the process carried out at atmospheric pressure. Moreover, the process yield is increased due to less mass loss in comparison with atmospheric pressure. In addition, the products enrich are enriched with nutrients, vitamins, minerals, incorporate additives; in many cases, the sensorial properties of the product are improved (Chiralt et al., 2001a). Vacuum impregnation has a great influence on product characteristics such as the internal ratio, water loss and solid gain (Barat et al., 2001b; Chafer et al., 2001).

Deng and Zhao (2008) reported the significant effect of pulsed-vacuum on depressing aw, titratable acidity, and in improving L value of the osmo-dehydrated apples. Vacuum osmotic dehydration (VOD) and pulsed-vacuum osmotic dehydration (PVOD), reduces the process time and energy costs (Deng and Zhao, 2008). Laurindo et al. (2007) developed a device for measuring the dynamics of the vacuum impregnation (VI) process. The device can measure the net force emitted by a food and transfer it to the VI process by a load cell. Determination of water in this system during the VI process is not required which increases the accuracy of the results. The experimental device can satisfactorily quantify the influence of the vacuum level, something that is very important for food process design. Vacuum impregnation (VI) processes reduced the process time (approximately 85%) and the weight loss (approximately 48%), increasing yield (Larrazabal-Fuentes et al., 2009). Furthermore, it is a minimally processed method in which the organoleptic characteristics of products and their shelf life are enhanced (Fito et al., 2001; Correa et al., 2010). Pulsed vacuum osmotic dehydration (PVOD) is a new method which is applied for a short (normally 5 min) vacuum treatment to a fruit dipped in an osmotic solution, and after that the osmotic dehydration is done at atmospheric pressure. The benefit of this method is that it reduces energy costs (Panadés et al., 2006). Castelló et al. (2010) investigated the effect of osmotic dehydration on the mechanical and optical properties of strawberry halves by applying (PVOD) and adding calcium. They reported that calcium addition and PVOD treatments had beneficial effects on the maintenance of the sample texture during storage. In addition, the sample porosity was greater due to the treatment (vacuum impregnation) results in modifying the color of strawberries. According to (Fito et al., 2001; Barat et al., 2001a; Chafer et al., 2003; Giraldo et al., 2003) higher effective diffusivity values are obtained with the application of the vacuum pulse and with a decrease in the osmotic solution concentration. Correa et al. (2010) reported higher weight loss of osmotically dehydrated guavas during application, higher sucrose solution concentrations and the vacuum pulse. They report that solid uptake was favored by vacuum application. Increasing the osmotic solution concentration induces an increase in the mass transfer (Barat et al., 2001a; Giraldo et al., 2003; Panadés et al., 2006; Ito et al., 2007).

4.4.5. Application of pulsed electrical field as a pretreatment

The pulsed electric field (PEF) as a non-thermal method has been reported to increase permeability of plant cells with positive influence on mass transfer in further

processes. The potential of PEF during osmotic dehydration for the first time was demonstrated by Rastogi et al. (1999). This finding has created more research looking into the ability of PEF as pre-treatment during osmotic dehydration of plant foods. The Pulsed Electric Field as a non-thermal method can cause permeable cells to whiten a short time (μs to ms range) while keeping the product matrix unaltered, thereby positively accelerating mass transfer during osmotic dehydration (Ade-Omowaye et al., 2001). Taiwo et al. (2001) studied the effect of high-intensity electric field pulses (HELP) pretreatment on the diffusion kinetics of apple slices. They reported that HELP has a very minimal effect on solids gain; and application of HP is advantageous when moisture reduction and minimal alteration in product taste are desired. Moreover, firmer texture, brighter color, and better retention of vitamin C are the advantages of applying HELP with osmotic dehydration. Lazarides and Mavroudis (1996), Ade-Omowaye et al. (2001) and Taiwo et al. (2001) reported that PEF pre-treatment might be a better alternative to processing at high temperatures.

4.4.6. Application of microwave during osmotic dehydration

Microwave-osmotic dehydration is a novel technique with a good potential for more efficient osmotic drying of fruits and vegetables. Carrying out osmotic drying in a microwave environment enhances moisture removal when moist food is immersed in a concentrated solution of an osmotic agent (Li and Ramaswamy, 2006c). The osmotic concentration gradient effect existing between the solution and food, which is the driving force for the removal of moisture from the food into the osmotic medium, is enhanced under the microwave field. This is due to selective absorption of microwave energy by the water molecules resulting in increased moisture outflux, which also has the tendency to limit the simultaneous transfer of solute from the solution into the food. Li and Ramaswamy (2006a.b,c) investigated the mass transport coefficients under microwave-osmotic dehydration (MWOD, immersion medium) and compared it with the conventional osmotic dehydration process (COD). They reported that MWOD significantly increased the rate of moisture loss and decreased the rate of solids gain. They also found that the osmotic dehydration under microwave heating made it possible to obtain a higher diffusion rate of moisture transfer at lower solution temperatures. In their experiments, they immersed the apple slices in the osmotic solution placed within the microwave field. In such an immersion medium, because the sample is surrounded by a large volume of the solution, the absorption of microwaves by the sample itself will be limited, thus reducing the moisture outflux effectiveness of the microwaves. This finding has provoked new research. Microwave osmotic dehydration under continuous flow medium spray conditions was developed and shown to provide a means of effecting moisture loss and limiting solids gain that was far superior to three other techniques under similar continuous-flow conditions (Azarpazhooh and Ramaswamy, 2010a). It was clearly demonstrated that spray mode heating enhanced the efficiency of the system. This is likely due to the direct and more efficient exposure of the sample to the microwave field. As opposed to the large volume of solution that surrounds the sample in the MWOD immersion system, the spray mode only uses a thin layer of osmotic solution that is continuously flushed down due to the rapidly flowing medium and gravity. The spray mode also eliminates the problem of sample floating, which can restrict the application of immersion mode (Azarpazhooh and Ramaswamy, 2010a). Microwave drying has the

specific advantage of rapid and uniform heating due to the penetration of microwaves into the body of the product. The most important characteristic of microwave heating is volumetric heating, which refers to the material absorbing microwave energy directly and internally and converting it into heat. Heat is generated throughout the material, leading to faster heating rates (compared to conventional heating, where heat is usually transferred from the surface to the interior) and producing rapid and uniform heating (Gowen et al., 2006). Microwave heating, causing a positive outflux of moisture from the product, not only results in greater moisture loss but also a higher solids gain. Immersion of the fruits in syrup in the MWODI mode limits the exposure of fruits to the MW field because of the surrounding syrup. However, in the MWODS mode, the same treatment provides a more direct exposure of the fruit to MW because as the continuous spray trickles down the fruit bed, it only retains a thin layer of the syrup at the fruit surface. It is interesting to note that applying spray can also overcome one of the problems with osmotic dehydration- the floating of the fruit in the solution.

4.5. MODELING OF THE OSMOTIC DEHYDRATION

Although considerable efforts have been made to improve the understanding of mass transfer in osmotic dehydration, fundamental knowledge about predicting mass transport is still a gray area (Raoult-Wack et al., 1991). Modeling of the osmotic dehydration process is necessary for optimizing the osmotic dehydration and subsequent drying processes, in order to achieve the highest possible quality at minimum energy costs (Saguy et al., 2005). The unusual features come from the interaction between the solution and materials of biological origin. Mass transfer in osmotic dehydration of cellular plant foods, such as fruit and vegetables, involves several physical effects due to the complex morphology of plant tissues. These can be described, in an ideal way, as osmosis, diffusion and hydrodynamic mechanism (HDM) penetration (Fito and Pastor, 1994). Two basic approaches can be used to model osmotic processes (Ramaswamy, 1982; Salvatori, 1998). The first one, the macroscopic approach, assumes that the tissue is homogeneous and the modeling is carried out on the cumulated properties of cell walls, cell membranes and cell vacuoles. The second one, the microscopic approach, identifies the heterogeneous properties of the tissue and is based on cell microstructure (Fito et al., 1996).

4.5.1. Macroscopic approaches

Macroscopic analysis has been carried out on pseudo-diffusion, square root of time, irreversible thermodynamic and other approaches (Fito et al., 1996) Very little work has been developed from the microscopic point of view (LeMaguer, 1996). The analysis of the concentration profiles developed throughout mass transfer processes, using a macroscopic approach, can be useful to clarify the mass transfer mechanisms and their coupling, especially if data are correlated with micro-structural features (shape, size and geometry changes in cell and intercellular spaces, cell wall deformation and relaxation changes, etc.) observed by a microscopic technique (Alzamora et al., 1996). However, concentration profiles allow us to calculate mass transfer kinetics (Lenart and Flink, 1984b). Mathematical modeling may provide a useful insight into the underlying mechanisms and several mathematical models have been proposed based on a cellular

structure approach that assumes water transport as a trans-membrane movement or Fick's second law with estimation of diffusion coefficients for both water loss and sugar gain (Azuara et al., 1992; Fito et al., 1996; Yao and LeMaguer, 1996) also including hydrodynamic mechanisms (Fito et al., 1996; Salvatori, 1998). In addition, empirical and semi-empirical models are often applied (Barat et al., 2001b).

A number of investigators have used Fick's unsteady state law of diffusion to estimate the water or solute diffusivity, simulating the experiments with boundary conditions to overcome the assumptions involved in Fick's law (Barat et al., 2001b; Fasina et al., 2002). There are two parameters required in Fick's law; these are sample dimensions and the effective diffusion coefficient. The effective diffusion coefficient can be obtained by finding numerical or analytical solutions to experimental data, calculating the relation between the slope of theoretical diffusion curve and the slope of experimental mass transfer ratio (Rastogi et al., 2000a; Rastogi et al., 2002), and applying linear and nonlinear regressions (Akpinar, 2006). Much of the literature considers any finite food geometry as infinite flat plate configuration, neglecting the diffusion in the other directions. Of these studies, only a few have considered unsteady state mass transfer during osmotic dehydration (Escriche et al., 2000; Rastogi and Raghavarao 2004).

Modeling of diffusion is a combination of physical and empirical approach. Mass transfer studies in food rehydration are typically founded on Fick's 1st and 2nd laws:

$$V\frac{\partial W}{\partial t} = D\frac{\partial^2 W}{\partial x^2} \tag{3}$$

$$J_x = -D\frac{dW}{dx} \tag{4}$$

where: Jx, flux (g H2O/m² s); W, moisture content (g H_2O/m³); x, spatial coordinate (m); t, time (s); D, diffusion coefficient (m²/s); V, volume (m³).

This allows the estimation of the diffusion coefficients for both water loss and solids gain individually or simultaneously. The mass transfer is assumed to be unidirectional and the interactions of the other components on the diffusion of the solute are negligible. Analytical solutions of the equation are available for idealized geometries, i.e. spheres, infinite cylinders, infinite slabs, and semi-infinite medium. For these analytical solutions of the unsteady state diffusion model to exactly apply, it is necessary either to keep the external solution concentration constant or to have a fixed volume of solution. The resistance at the surface of the solids is assumed to be negligible compared to the internal diffusion resistance in the solids. Biswal et al. (1991) and Ramaswamy and Van Nieuwenhuijzen (2002) used a rate parameter to model osmotic dehydration of green beans as a function of solution concentration and process temperature. The parameter was calculated from the slope of the straight line obtained from bean moisture loss and solid gain vs. the square root of time (Biswal et al., 1991).

Azuara et al. (1992) developed a model based on mass balances of water and sugar to predict the kinetics of water loss and solids gain during osmotic dehydration. The model is related to Fick's second law of unsteady state one-dimensional diffusion through a thin slab in order to calculate the apparent diffusion coefficients for each con-

dition. Correlative models have been proposed, either to compute the time required for a given weight reduction as function of the processing temperature and of the solution concentration or to estimate the dehydration parameters. Nsonzi and Ramaswamy (1998b) studied osmotic dehydration kinetics of the blueberry and further modeled moisture diffusivity and soluble solids diffusivity with quadratic functions of temperature and concentration. Azuara's model has the advantage of allowing the calculation of the equilibrium values (MLe and SGe) (Ochoa-Martinez et al., 2007).

4.5.2. Microscopic approach

The mass transfer phenomena occurring in plant tissues during osmosis involves complex mechanisms, most of them controlled by the plant cells. During osmotic dehydration of cellular material, mass transfer inside the cellular material depends on both processing variables and micro-structural properties of the biological tissue. There is a naturally wide variation in the physical nature of raw food material. When biological cellular material undergoes osmotic dehydration, mass fluxes in the system imply changes in structural and transport properties (volume, dimension, viscosity, density, porosity, etc.). As a result, these changes affect the mass transfer fluxes. The changes of material tissue volume and porosity promote the action of non-diffusional driving forces, such as a pressure gradient associated with the relaxation of a deformed cell network to release the structural stress (Mayor and Sereno, 2004), and changes in mechanical properties and color changes (Krokida et al., 2000). Knowledge of and predictions about these changes are important because they are related to quality factors and some aspects of food processing, such as food classification, process modeling and design of equipment. Most of these changes, although observed at a macroscopic level, are caused by changes occurring at the micro-structural/cellular level. In this way, the study of the micro-structural changes during dehydration is important because it can allow us to understand and predict the changes occurring in the physical–chemical properties at higher levels of structure. Mass transfer (and eventually heat transfer) phenomena result in changes at microscopic and macroscopic levels and consequently variations in the physical properties of the food system. These changes also produce alterations in mechanisms and kinetics in the transport phenomena (Fito and Chiralt, 2003).

4.6. COMPLEMENTARY DRYING METHODS

Osmotic dehydration is a pretreatment which can improve nutritional, sensorial and functional properties of food without changing its integrity (Torreggiani, 1993). Drying is a major part of osmotic dehydration, and the impact of it on complementary air drying requires special attention.

Osmotic dehydration is generally used as a preliminary step for further processing such as freezing (Ponting et al., 1966), freeze drying (Hawkes and Flink, 1978), vacuum drying (Dixon and Jen, 1977), microwave heating and processing applications (Nelson and Datta, 2001), and air drying (Mandala et al., 2005). Abundant information is available on the application of an osmotic treatment before a conventional drying (Lemus-Mondaca et al., 2009). Sharma et al. (1998) studied the influence of some pretreatment parameters such as steam blanching and sulfur dioxide treatment on product quality after osmo-air dehydration processing of apples. They found greater retention of ascor-

bic acids in treated samples with sulfur dioxide followed by osmotic dip and vacuum drying than in non-treated samples. Riva et al. (2005) observed that vitamin C was retained higher by osmo-air dried apricot samples than by non-treated air dried samples. They reported this phenomena as a lower phenolase activity and the protective effect of the sugar specially sorbitol. Several authors have reported that the texture, flavor, and color stability in dried fruit and vegetables are improved. This is especially important since color may be a decisive factor in the consumer's acceptance of a food (Krokida et al., 2000).

4.6.1. Impact of osmotic dehydration on quality properties

Osmotic treatment of fruits and vegetables preceding convective drying may strongly affect properties of the final product (Lewicki and Lukaszuk, 2000; Lewicki and Pawlak, 2003). During osmotic dehydration, many aspects of cell structures are affected such as alteration of cell walls, splitting of the middle lamella, lysis of membranes (plasmalemma and tonoplast), tissue shrinkage (Alvarez et al., 1995) which could strongly influence the transport properties of the product during processing. All these phenomena cause changes in the macroscopic properties of the sample, such as optical and mechanical properties, which are related to the product appearance and texture, respectively. All these changes greatly affect organoloptic properties of the osmo-dehydrated plant due to solute uptake and leaching of natural acids, color, and flavor compounds out of osmo-dehydrated plant tissue; as a result, natural composition of the product is modified (Lazarides et al., 1995). Although compositional changes may have a positive and negative effect on the final product, rehydration of osmotically dried fruit is lower than in the untreated fruit due to the rapid impregnation of a subsurface tissue layer with sugar (Nsonzi and Ramaswamy, 1998a); moreover, if the osmosis takes more time, the rehydration rate would be lower.

4.6.1.1. Impact of osmotic dehydration on color

Many investigators demonstrated that the quality (color, texture and rehydration capacity) of air, freeze or vacuum- dried fruits and vegetables could be improved by a prior osmotic step (Flink, 1975; Hawkes and Flink, 1978; Lerici et al., 1985; Nsonzi and Ramaswamy, 1998a). There have been numerous research studies on the application of color change during osmotic dehydration. The color of the products is measured by lightness (L* value), redness or greenness (a* value) and yellowness or blueness (b* value), during or after drying. Falade et al. (2007) reported transparency and that the color of the fruit may alter favorably due to physical and chemical changes during osmotic dehydration. They evaluated L*, a*, b* values of osmosed and osmo-oven dried watermelon, and reported that color parameters increase with an increase in osmotic solution concentration. Osmotic dehydration improves fruit quality by stabilizing color parameters and allows less color loss of fruit by enzymatic oxidative browning due to infusion of extensive sugars. In addition, reducing the water activity of samples also decreases the non-enzymatic browning reaction (Krokida et al., 2000).

Osmotic dehydration limits or reduces the use of preservatives such as sulfur dioxide in fruits. In addition, substantial amount of air from the tissue is removed; therefore blanching prior to osmotic dehydration also can be omitted (Torreggiani, 1993; Lenart,

1996). The sugar uptake is owing to the protective action of the saccharides (Ponting et al. 1966).

4.6.1.2. Impact of osmotic dehydration on texture

Texture is a significant quality attribute of fruits and vegetables. During osmotic dehydration, the rheological properties of osmo-dehydrated products are changed due to physical and chemical modifications occurring in the cell structure (Lewicki, 1998). Properties of the cell wall and middle lamella and the turgor pressure are the most important factors to determine the texture of plant tissue (Jackman and Stanley, 1995; Chiralt et al., 2001b). Plant tissue is affected by size and shape of the cell, volume of the vacuole, intercellular spaces volume, presence of starch granules and chemical composition. The majority of foods have visco-elastic behavior; that is why, during osmotic dehydration, the viscous natures of fruits and vegetables increase while their elasticity decreases due to the sugar uptake (Mayor et al., 2007). Osmotic dehydration weakens the texture of apples and makes apple tissues softer and more plastic than those of raw apple (Monsalve-GonaLez et al., 1993). Although there are numerous reports dealing with the effect of some sugars on the structural properties of osmo-treated plant material (Marcotte and LeMaguer, 1991; Maltini et al., 1993; Barat et al., 2001b), only a few reports talk about the structural changes at the cellular level which are only accessible through microscopic observations (Saurel et al., 1994; Martinez-Monzo et al., 1998). Puncture force is usually used to measure the textural properties of dehydrated products which is the measure of the hardness of the product surface, and presents the extent of case hardening during drying (Lin et al., 1998). During osmotic treatments, the main changes that affect the mechanical behavior of plant tissue are changes in the air and liquid volume fractions in the sample, the size and shape of the sample (Fito, 1994), loss of cell turgor, alteration of middle lamella (Alzamora et al., 1996), alteration of cell wall resistance, establishment of water and solute concentration profiles and compositional profiles in osmotically dehydrated samples (Salvatori, 1998). Differences in mechanical behavior of the dried samples must be related to the differences induced in the composition of the soluble water phase and in the solid matrix during treatments. Contreras et al. (2007) reported that soluble pectin is increased during drying which is altered cell bonding zone results in changing the solid matrix consistency. Osmotic dehydrated products have a softer texture due to leaching of calcium into the osmotic solution which in turn results in lowering the concentration of calcium content ions inside the tissue (Prothon et al., 2001).

4.6.1.3. Impact of osmotic dehydration on rehydration properties

There is a need for understanding the rehydration process due to the wide variety of dehydrated foods which are available today to consumers. Of particular concern are meeting quality specifications and conserving energy. Dehydrated products are usually rehydrated by immersion in water or other liquids, such as fruit juices, sucrose or glucose solutions. Restoring the properties of the fresh product by immersing dehydrated products in a liquid phase is an important aspect during rehydration. Rehydration can reflect the physical and chemical changes that have occurred during osmotic dehydration, and can therefore be used as a quality index. In other words, any pretreatment to which the products have been subjected are modified by the composition of the samples.

The rehydration process is typically composed of three simultaneous steps: absorption of water into the dry material, swelling of the rehydrated product, and loss or diffusion of soluble components (Lee et al., 2006). It is reported that increasing the rehydration temperature in the range of 40–80 °C for many fruits and vegetables, including bananas, carrots, apples, potatoes, tomatoes, and yellow, red, and green peppers markedly increase the volume of the product (Krokida and Marinos-Kouris, 2003). In order to design and optimize rehydration, different mathematic models can be used to describe how certain process variables affect water transfer. Some researchers have assumed simple least-squares adjustment to models based on exponential models or capillary absorption theory, while others have used Fick's diffusion laws, and demonstrated that a model based on first-order kinetics can properly describe the gain of water during rehydration (Krokida and Marinos-Kouris, 2003; Giraldo et al., 2006; Lee et al., 2006). There are three methods to estimate rehydration characteristics of dehydrated products: (1) water absorption capacity, WAC, which is the capacity of a matrix to absorb water that replaces the water lost during drying (2) dry mass retention capacity, DHC, which is the material ability to retain soluble solids after rehydration, and (3) rehydration ability or capacity, RA, which is the ability of a dehydrated product to rehydrate, and which shows total damage to tissues caused by drying and impregnation during rehydration (Maldonado et al., 2010).

4.7. CONCLUDING REMARKS AND FUTURE RESEARCH NEEDS

Nowadays there is a heightened motivation that explains many recent advances in the area of osmotic dehydration. Food applications of the osmotic dehydration process provide a potential to apply energy efficient procedures on an industrial scale to produce mildly processed, high quality products. Osmotic dehydration has a tremendous market potential for producing high quality food with different variety. It can also develop fruit and vegetable ingredients with functional properties. However it is difficult to define a general predictive processing model due to great variability of plant materials (species, cultivar, maturity stage, etc.). In addition there is lack of adequate responses to problems related to the management of the osmotic solutions (reconcentration, reuse, microbial contamination, reutilization, and discharge of the spent solution, etc.), and developing continuous processing equipment. It is noteworthy that the application of microwave osmotic dehydration viscous sugar solution makes the food pieces float; agitation of the solution is therefore necessary. Lack of knowledge relevant to microbial development in both medium and processed product has been also mentioned.

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Chapter 5
Foam Mat Drying of Fruit and Vegetable Products

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Contents

5.1. INTRODUCTION

Foam- mat drying is a promising new development in the field of drying aqueous foods. This method offers a wide scope for application in vegetable puree and fruit juice processing industry as it enables the dehydration of heat sensitive foods or which are difficult-to-dry, sticky, and viscous under relatively mild conditions without undue quality change. This technology is finding an increasing application and importance on commercial scale mostly in the drying of liquids that tender a high quality concentrate such as milk, fruit, juices, soluble coffee, etc.

The foam-mat drying is a process in which the transformation of products from liquid to stable foam follows air drying at relatively low temperatures to form a thin porous honey-comb sheet or mat which is disintegrated to yield a free-flowing powder. The dried product obtained from foam-mat drying is of better quality, porous and can be easily reconstituted. Concentration of the material prior to conversion into stable foam may or may not be an essential requirement and will depend on surface tension and consistency of the product. In spite of the fact that a large volume of gas present in the foamed mass impedes the higher rate of heat transfer, drying rate is comparatively high because of enormous increase in liquid-gas interface. The advantages of the foam-mat drying process include relatively fast drying, easy reconstitution and better quality product. The renewed process is of potential interest in foam-mat drying for developed and developing countries for its simplicity, rapid drying at lower temperature, suitable for all type of juices, retention of nutritional quality and cost effective for producing easily reconsitituble juice powders.

5.1.1. History

In 1950 Eddy reported that process of production of free flowing powders of fruits and vegetables by spray drying or drum drying is facing great difficulties. To overcome these problems he recommended the use of methylcellulose for the preparation of spray dried grapefruit and orange juice powders.

Foam mat drying originally was developed by Morgan et al. in 1959 at the Western Regional Research Laboratory of the U.S. Department of Agriculture. The foam-mat process involves drying thin layers of foamed material in heated un-dehumidified air at atmospheric pressure and is reported to be considerably cheaper than vacuum, freeze and spray drying methods.

5.1.2. Process

The essential steps in foam-mat drying are as follows:

(a) Pre-treatment of the raw material and preparation of liquid concentrate;

(b) Conversion of the concentrate into a stable foam by incorporating air or other gases and a suitable foaming agent;

(c) Exposing the foam in the form of a thin sheet to a current of hot air until it is dehydrated; or by hot water conduction method; and

(d) Conditioning and grinding of the dried porous mass into an easily reconsitituble powder in water.

Process of foam mat drying as developed by Morgan involves drying of liquid or semi liquid food concentrate in the form of a stabilized foam prepared by the addition of a stabilizer and a gas to the liquid food in a continuous mixer and drying it in heated air at atmospheric pressure. Stable gas-liquid foam is the primary condition for successful foam drying. For natural foams, such as egg whites, pineapple juice etc., there is no need to add any foaming agents. Vegetable proteins (e.g., solublized soya protein), gums and various emulsifiers (e.g., glycerol monostearate propylene glycerol monostearate, carboxy methyl cellulose, trichlorophosphate) are typically added to juices, pulps, purees, or concentrate as foaming agents. Mixtures are whipped to form foams using suitable blender or specially designed device. The foam thus formed is spread as a thin mat or sheet and exposed to stream of hot air or hot water conduction surface method until it is dried to required moisture level. The dehydrated product is milled and converted into powder. Foam-mat drying of the foamed product in the form of thin layer (0.1 to 0.5mm) is generally carried out between 65 and 85°C for a very short duration, as the foam reduces drying time many fold. A continuous belt tray dryer as well as a slightly modified spray dryer can also be used for this process. As such no complete foam-mat drying system is readily available in the world. Many organization / researches are working on this aspect and Central Institute of Post Harvest Engineering and Technology (CIPHET) an ICAR institute, Ludhiana India is one of them.

Good quality tomato powder can be produced using this technique. The optimal initial concentration of food solids is in the range of 39% for tomato pulp. The cost of such a drying process will be less than spray or drum drying, vaccum and freeze-drying. Three methods are generally used in the formation of food foams. In one method gas is bubbled through a porous sparger such as sintered glass into an aqueous solution of low protein concentration (0.01-2% w/v). The liquid may be completely converted to foam if a large amount of gas is introduced.

Secondly, foams can be formed by whipping (beating) an aqueous solution containing a foaming agent in the presence of a bulk gas/ air phase. Whipping can be carried out in a variety of devices that vigorously agitate the liquid and its interface with a bulk gas /air phase. The method has been preferred for most of the “functional tests” of proteins, as it is the standard means of gas introduction in most aerated products. The process of bubble formation and the history of a single bubble are not defined. The whipped foam is well mixed throughout its formation, so the stratifications often found in bubbled foam column are not observed. Compared to sparging whipping results in more severe mechanical stress and shear action and a more uniform dispersion of the gas/air. The severe mechanical stress affects both the coalescence and formation of bubbles. The volume of air included usually goes through a maximum with increasing intensity of beating (severe mechanical beating is a standard method of foam breaking). Hence, the observation of maximum levels of gas incorporation during whipping reflects a much more real dynamic equilibrium between mechanical formation and destruction of bubbles. In addition, mechanical stresses can break up bubbles formed earlier into several smaller ones.

A third procedure for forming foam termed as shaking has been used only rarely. Foam formation by shaking tends to be slower than by bubbling or whipping under similar conditions, which is due to the relative efficiency if the process in producing gas

bubbles. The maximum foam volumes obtained by shaking are also rather lower than that in the other two methods. The flow chart of the process is as given in **Figure 5.1.**

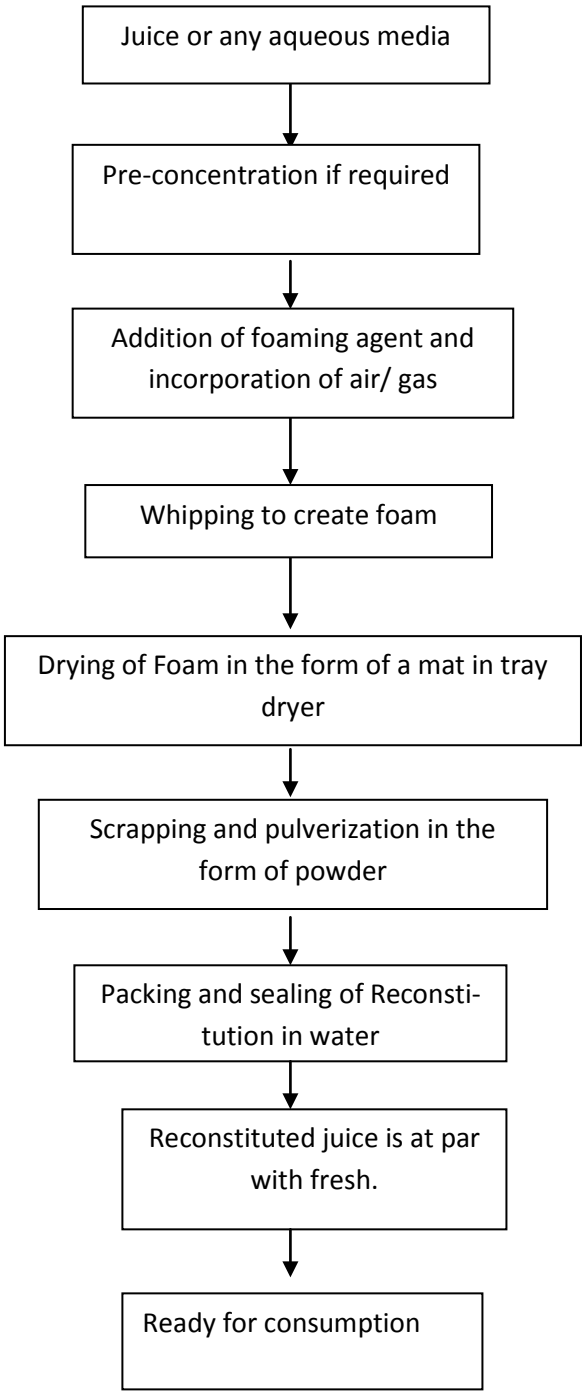

Figure 5.1. Process flow chart of Foam-Mat drying

5.2. FOAM CHARACTERISTICS

The most desirable characteristics of a foam honey comb is that it should consist of a large number of small and uniform bubbles which should retain their honeycomb structure during drying. Foam bubbles usually burst because of air and thus surface energy of the resulting drops is smaller than that of the original system. Adequate amounts of sta-

bilizers are added to provide stability to the foam, which would otherwise collapse before all the moisture has been removed during drying. Foam stabilizers might be surface-active agents, hydrophilic colloids or a mixture of both.

The key step in foam-mat drying is the preparation of stable foam. Whip ability, the capacity to form stable foams with air, is an important functional property of proteins for applications in food products. The term "whip ability" and "foam ability" are used interchangeably in the literature although whip ability usually suggests that tests were conducted using a household-type mixer with a whipping arrangements, while foam ability refers to the intensive shaking/agitation of a protein solution in a cylinder or the bubbling of air through a protein solution via a fritted disc. Foaming methods require less protein and are measured under milder and more controlled conditions. The mixing method for whipping is a simple one and gives more reproducible results, which can be easily translated from laboratory bench to pilot plant.

The characteristics of the foam are measured in terms of two parameters i.e. foaming ability and foam stability. Foaming ability is the initial height of foam in the column immediately after formation. Foam stability is the rate of subsidence of these foams. In other words, stability of a foam or whip is its ability to retain its maximum volume and is usually measured by the rate and/or amount of leakage of fluid from the foam.

As explained above the primary requirement for the process of foam mat drying is preparation of stable foam. Two important characteristics required for a stable foam preparation are consistency. The film forming components, used in the drying of fruits and vegetables are glycerol monostearate, soluble soya protein, polypropyleneglycol monostearate etc. Most suitable stabilizers are egg albumin, fatty-acids, monglycerides, mix of mono & diglycerides fatty esters of sucrose at levels of about 1% of the dry solids in the products helps in forming the stable foam.

In foam-mat drying of tomato paste and apple sauce certain methylcellulose such as methecol is the most effective stabilizer, as Methecol develops very stable foam and at faster rate due to its compatibility characteristics and low gel point.

5.3. FACTORS AFFECTING THE FOAM CHARACTERISTICS

The factors which greatly influence are two parameters, viz., foaming power and foam stability are the total solids contents of sample, temperature during foaming, whipping time and type and concentration of foaming agent and foam stabilizer. Foam stability is greatly influenced by soluble solids content of the sample, and type and concentration of the added foam inducer. Pulp content of the sample and mixing time has negligible effect on stability of the foam. In general, when the content of soluble solids in the sample is low, more amounts of foaming agent and stabilizers are required to be added. If the sample food is relatively free of pulp, the foam must be whipped to a very low specific gravity in order to acquire the necessary stiffness.

The concentration of the additive necessary to produce a given density of the foam depends on the characteristics of the material being foamed in addition to the other external variables. The foam-mat drying of some tropical fruits using two types of foam inducers, namely, modified soybean protein (D-100) and glycerol monostearate (GMS)

as foam inducers was less than 0.25% of D-100 adequate to produce foam of a density 300-400kg m-3 for most of the systems studied with or without the use of foam – stabilizer. Similarly, 0.5% GMS is able to produce foam of density 330-360 kg m -3 in some system (papaya puree), but, on the other hand, it is impossible to foam this puree with normal quantities of soya protein. The foam density and stability was reported to be increased with the increase in the soluble solids content of the juices.

The effect of whipping time in the preparation of grapefruit foam using GMS as the foaming agent increasing the whipping time from 6.5 to 15 min did not result in significant change in bubble size. However, after 15 min some break down occurs at a very slow rate and even after 30 min of whipping, foam still posed a good bubble size. The concentration of surfactant (foaming agent) in the range of 1 to 3% showed a decrease in bulk density till 8 min of stirring time after which the foam structure collapsed resulting in an increase in the foam density. A criterion for good foam stability was its uniformity and the lack of fluid drainage in 60 minutes after its preparation. These characters can be observed in foams with bulk densities below 300 kg m-3. In general, best results can be obtained when the smaller amount of surfactant is added, and for the shortest stirring, to obtain a bulk density of 260 kg m-3. Foams prepared under these conditions will show stability to drainage for over 1 hour.

The influence of mechanical mixing, gas input rate and a gas sparger (hole diameters) dependent on the gas flow rate under steady state condition. Also rotational speed from 1000 to 2000 rpm improves the foaming capacity without any adverse effect on foam density. Foam expansion is not influenced by changes in pH of the material but stability decreased with its increase during functional properties of sunflower seed protein. An increase in protein concentration increases both the expansion as well as stability of the foam. Similarly, higher stirring time did not appreciably affect foam expansion but increased the foam stability, whereas higher stirring speed increases foam expansion significantly but foam stability only slightly.

5.4. TYPES OF FOAMING AGENTS

Foam-mat drying requires stiff stable foams which are not readily made from many food concentrates especially food with low protein content, unless there is an addition of a small quantity of foaming agents or foam stabilizers. Foam stabilizers are added at different levels to varying composition of the food concentrate, and their performances could be measured by their foaming, reconstitution, and sensory attributes.

Many types of agents are used for production of foams and each of them offers certain distinct advantages. One of the most commonly used is the monoglyceride, or fatty-ester type. This agent has the capacity to produce extremely fine foams which enable thorough and efficient moisture removal under milder conditions than could be used with some other agents. Hence this agent is particularly useful with the more heat-sensitive materials. It is probably for this reason that most commercial foam-mat dried products have utilized monoglyceride agents. Orange, lemon and tomato powders of this type have been produced commercially. By adding a small amount of edible foam stabilizer such as monoglycerides or a modified soyabean protein with methyl cellulose to liquid stiff foam is produced by whipping. Monoglyceride agents, however, impart to the

dried powder certain physical properties, especially during reconstitution, which are detrimental to its commercial appeal. For example, upon reconstitution of juices from monoglyceride type powders a very white, milky, unnatural appearance often results. This is due to dispersion of microscopic bubbles of gas distributed throughout the solution. The monoglyceride acts as a very effective emulsification agent forming a thoroughly dispersed "air sol." This effect has been reduced by the use of a "warm-rolling", technique which increases the bulk density of the powder. This technique was not completely effective in eliminating the unnatural appearance, however, and has the added disadvantage that it impedes solubility. Another undesirable effect in solution of monoglyceride powders is the formation of a layer or "head" of foam after the juice has been reconstituted. In solutions which do not exhibit the milky initial appearance there are often sufficient small bubbles dispersed throughout the solution that 15 minutes or more after reconstitution a layer of light colored material accumulates at the top and the solution becomes unsightly. This effect occurs in almost all solutions made from powders using glyceride-ester type foaming agents. Although the densification procedure improves the initial appearance, it does not have much effect on diminishing this "layer" of foam.

5.4.1. Foam Expansion

$$\text{Foam Expansion (\%)} = \frac{V_1 - V_0}{V_0} \times 100$$

Where V_1 is Final volume of foamed product in cm^3

And V_0 is the initial volume of the product in cm^3

5.4.2. Foam Stability

Foam stability is determined by measuring the reduction in foam volume at definite intervals of time by using the following relationship

$$\text{Foam stability} = V_0 \frac{\Delta t}{\Delta V}$$

Where ΔV is the change in volume of foam occurred during the time interval.

5.4.3. Foam density

The density of the foamed material (Juice/ pulp) can be determined in terms of mass by volume and represented as g/cm^3.

$$\text{Foam density} = \rho \frac{V_0}{V_1}$$

Where, ρ is the density of the material (Juice/ pulp)

5.5. DRYING OF FOAMS

In order to dehydrate the foams, different drying techniques like vacuum foam drying, foam spray drying, foam-mat drying including crater techniques are in practice worldwide. Development of a belt-type foam-mat dryer and production of free flowing, rehydratable powders from tomato juice, milk, coffee extract orange juice, pineapple

juice, mango juice etc. is a major researchable issue, subsequently several basic forms of foam-mat dryers including the laboratory type adiabatic dryer. A belt-type foam-mat dryer consists of an endless steel or Teflon-coated belt which alternatively passes over the heating and cooling drums. The foamed material is spread over the moving belt and temperature of air flowing across the material through the ports is controlled in the range of 65º C to 21º C. The drying in such process takes about one hour time depending upon the characteristics of the material being dried. The difficulty with such dryers, however, is the removal of the product from belt in certain cases.

Tray and crater-type foam-mat drying have been used by various researchers for the production of fruit/vegetable powder. The tray dryer is an improved design over the belt dryer. In this, a layer of foam is spread over metal trays and dried. In the crater technique, perforated metal trays are used on which the foam is spread. A controlled air blast is directed nozzles direct thin flat jets of air up through the tray perforations to pierce the foam and pile it in volcano-shaped craters around each hole.

Foam-mat drying using crater technique has several added advantages. Because of the large surface exposed to the air, most of the water is removed from the material in a very short time. However, the capacity of such dryers is very low. Tray drying of foams as mats is simple and cheap in comparison to the crater technique. Foam-mat drying of tomato paste upto 2% moisture content using crater technique can be done within 2 to 18 minutes depending upon the paste characteristics and drying conditions. About 70-90% of the moisture can be removed in the first few minutes.

The effect of concentration of foam stablizers significantly reduces the drying time on drying characteristics of citrus concentrates and soymilk powder. Physical characteristics and reconstitution properties of the powder prepared from foamed citrus juice, soymilk etc. were found to be better than that from the unfoamed. The final moisture content attained in the foamed samples is lower than that of the unfoamed sample.

Foam-mat drying of tomato, mango, pineapple, lemon, banana and guava etc. juice/pulp can be done to produce easily reconstitutable powder. The foams are spread on plain aluminum trays in the form of thin sheet and dried in a cross-flow hot air dryer at 80ºC for 30 min followed by 30-90 min drying at 65-70ºC The dried foams are cooled to room temperature in a dry atmosphere to prevent caking due to highly hygroscopic nature of powder prepared by this novel method. Color flavor and texture of the dried product are good and uniform.

5.6. ADVANTAGES OVER TRADITIONAL METHODS

This method offers wide scope for drying of other difficult-to-dry sticky, viscous and heat sensitive materials like glue, gelatin, pigments Varnishes etc. Any fluid material that needs to be dried gently could be dried by the foam-mat method provided it is capable of forming stable foam. The main advantage of foam is that the structure provides a large surface at which water may rapidly evaporate. Water vapor produced below the already dry outermost portions diffuses through the thin, warm walls of these outer parts, and not through the thick, dense skin, which would result from shrinkage of an unfoamed mat. The same structure ensures rapid rehydration of the dry product. The water travels along the web of solid material, like ink onto blotting paper. Formation of a gummy cap-

sule is avoided by the small gas inclusions, which do not escape until the solids outside have dissolved or dispersed. When the foams are sufficiently stable, the dry product is uniform and has foam structure. When the foam bubbles are sufficiently small, the dried product may be subdivided fairly finely without losing the advantages of foam structure. From the point of view of rehydration, foam structure provides the advantages of natural porosity.

Over the past decade, this relatively old technology, known as foam mat drying, received renewed attention because of its added ability to process hard-to-dry materials, obtain products of desired properties (e.g., favorable rehydration, controlled density), and retain volatiles that otherwise would be lost during the drying of non-foamed materials. Foam-mat dried vegetables or fruit powders have less heat induced changes in color and flavor as compared to conventional spray-dried or drum-dried products. A product with density less than that in a conventional dryer is obtained. The product density is about equal to the density of instantized or agglomerated powder.

The dehydrated powder / flakes are superior to drum dried and spray dried products because of its honey comb structure and better reconstitution properties. Selected fruit pulps such as mango, star fruit, papaya and banana have been dried to produce flakes by using foam mat drying technique.

The thin layer drying study on foamed mango pulp concluded that the mango pulp treated with egg albumen (10%) and methyl cellulose (0.5%), dried at 60ºC with one mm foam thickness retained significantly higher biochemical contents than that of other foaming and drying treatments. In general, drying of foamed materials is faster than that of non-foamed ones, although certain foams such as the ones from soymilk or starfruit exhibit higher drying rates in the beginning of foam mat drying whereas for other materials such as tomato paste, bananas, and mango drying rates are greatly accelerated at the end of drying.

Foam-mat drying allows processing of hard to-dry materials such as tomato paste and a variety of fruit pulps and juices. Preferential product quality stems from accelerated drying at generally lower drying temperatures. Reduced density of foamed materials leads, however, to a decreased dryer load, which has to be compensated for by shorter drying time to maintain the dryer throughput.

Besides accelerated transport of liquid water to the evaporation front, drying experts have repeatedly pointed to the increased interfacial area of foamed materials as the factor responsible for reduced drying time. Because density of foamed materials is lower than that of non-foamed ones and extends from 300 to 600 kg/m3, the mass load of the foam-mat dryer is also lower. However, shorter drying time can not only offset the reduced dryer load but also increase the dryer throughput. Shorter drying time per unit mass of foamed materials might not always bring about lower energy consumption and better process economics.

5.7. COMMERCIAL APPLICATIONS

The process has been under study for some time and several commercial operations are developed. The process has evolved in several basic forms including drying on a Tef-

lon-coated fiberglass belt, on perforated stainless steel trays, and on an endless stainless steel belt. Lemon powders are presently being produced by a commercial concern on a perforated tray or "crater" type dryer, and a number of fruit and vegetable products are produced on an endless stainless steel belt dryer which uses high belt speed and very short drying time. Over the years, foam-mat drying has been applied to many fruits including tomato paste mango, soymilk, star fruit, cowpea and bananas Pineapple, Lemon, Citrus (Kinnow), Sapota, apple etc.

Addition of soy protein in a solid form at the 10 g/100 g level is very effective foam inducer, foam mat drying of banana to produce free flowing powder reducing the density of the banana puree to 0.5 g/ml after 12 min of whipping. The drying behaviour of the banana foam mat is strongly affects the physical characteristics of the foam, i.e. the density and thickness, while increasing the air temperature markedly reduced the drying time, even at 75°C and 90°C. Neither the air flow conditions nor the sugar content of the foam mats as obtained through osmotic pre-treatment had a profound effect on drying, although forced convection conditions were better than drying by natural convention.

The drying of foamed syrups of different fruits like orange, lemon, grapefruit, tomatoes, strawberry, guava and apple were carried out in a solar energy augmented drying unit.. The results showed that foaming decreased the time of drying by 30.8–41.5% in the case of direct sun drying and by 47.1–73.2% in the case of solar drying compared to the drying time of unfoamed syrup. So it was concluded that solar-augmented foam-mat drying technique proves to be of sufficient efficiency and acceptability to replace spray drying which is a highly complicated and energy-consuming technique.

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Chapter 6
Product Quality Evolution During Drying of Foods, Vegetables and Fruits

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Contents

6.1. INTRODUCTION

The processing of a food products involves several stages and drying is one such operation that is commonly used in a food manufacturing plant. Quality changes and food spoilage might occur during drying due to environment that is not always conducive for processing the food products. Conventionally, food products should be dried below the level susceptible to growth of microorganism, typically at water activity level of less than 0.6. Apart from this, product quality is often related to various physical and chemical parameters, which in many cases, are decided upon by consumers whom will eventually purchase and consume it. The governing criteria could be due to taste, colour, texture, size, shape and the functionality associated with the product. In addition to that, food manufacturers should also conform to the microbiological and nutritive aspects of quality control during manufacture.

The aim of this chapter is to provide some general aspects of product quality attributes associated with the drying of food, vegetable and fruits. The effect of various drying parameters on product quality is also discussed based on published literature.

6.2. PRODUCT QUALITY ATTRIBUTES

The quality attributes of a dried food product can be classified into physical, chemical, biological and nutritional (Perera, 2005; Sablani, 2006). The specification of dried food products also largely depends on these quality attributes. In general, improper processing conditions results in higher nutritional loss and poorer product quality (Rahman, 2005).

6.2.1. Physical

6.2.1.1. Colour

Colour is perhaps the most important attribute, apart from product appearance, that will determine the level of acceptance by consumers. Colour pigments, Maillard reactions and enzymatic browning play significant roles in the colour changes of the product during drying (Marty-Audouin and Rocha-Mier, 1999). Very often temperature and pH play an important role during processing as shown in **Table 6.1**.

Evaluation of colour can be carried out by using destructive or by non-destructive methods. Destructive method is carried out by evaluating the extracted colour pigments spectrophotometrically or by using high performance liquid chromatography. Alternatively, the non-destructive method can be used and it is favoured by most researchers. Using the CIELAB colour space ($L^*a^*b^*$), the parameters L^*, a^* and b^* values represent light-dark spectrum with a range from 0 (black) to 100 (white), the green-red spectrum with a range from -60 (green) to +60 (red), and the blue-yellow spectrum with a range from -60 (blue) to +60 (yellow), respectively (Abbot, 1999).

Table 6.1. Factors contributing to colour changes during drying

Components	Compounds	Effects of drying
Pigments	Chlorophylls	Changes from green to yellow or to red colours
	Carotenoids	Oxidation of carotenoid pigments by oxygen in air
	Anthocyans	Quite stable during processing at low pH
	Betalaines	Very sensitive to pH, degraded to brown compound at neutral pH
Reactions		
Maillard reactions	Reducing sugars, amino acids, proteins	Formation of brown or black pigments, melanoidins and other scented compounds
Enzymatic browning	**Phenolics**	Transformation of phenolics compounds to brown or black polymers

The following parameters (Equations 6.1-6.3) can be further defined for the purpose of colour evaluation:

$$\text{Hue angle}\,(H^*) = \arctan\left(\frac{b^*}{a^*}\right) \tag{6.1}$$

$$\text{Chroma}\,(C^*) = \sqrt{a^{*2} + b^{*2}} \tag{6.2}$$

$$\text{Total colour change}\,(\Delta\Delta E = \sqrt{(L^* - L^*_{ref})^2 + (a^* - a^*_{ref})^2 + (b^* - b^*_{ref})^2} \tag{6.3}$$

High value of hue angle indicates less browning and vice versa while chroma is a measurement of the strength of colour such as the intensity or saturation. **Table 6.2** shows the descriptive levels of colour change as determined from the ΔE values (Chen, 2008). In most cases a large difference in ΔE is not desirable as consumers tend to prefer product that resemble the colour of the fresh product before drying. A very large ΔE value could indicate higher degree of browning which could be unattractive in appearance.

Table 6.2. Descriptive levels of colour change

Level	ΔE range
Trace level difference	0 – 0.5
Slight different	0.5 – 1.5
Noticeable difference	1.5 – 3.0
Appreciable difference	3.0 – 6.0
Large difference	6.0 – 12.0
Very obvious difference	> 12.0

The kinetics of colour changes in food materials during drying can be modeled by using zero order or first order degradation model (Kong et al., 2007; Kahyaoglu and Kaya; 2006). The following equations (6.4-6.5) were used:

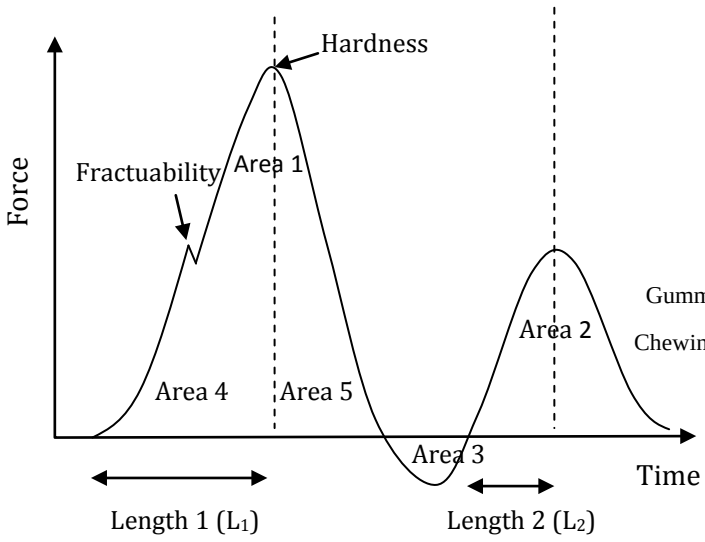
Zero order: $Y = Y_0 \pm kt$ (6.4)

First order: $Y = Y_0 \exp(\pm kt)$ (6.5)

The constant k refers to the kinetic constant, Y is the measured colour scale ($L^*a^*b^*$) and (±) indicate the formation and degradation of the any quality parameter. The purpose of modeling is to relate the kinetic of colour changes to the moisture content reduction and product temperature evolution during drying.

6.2.1.2. Texture

Structural collapse in food due to moisture removal from the food product results in significant changes in texture. This causes shrinkage and change in porosity of the dried product. Texture attributes such as hardness, fracturability, springiness, chewiness, gumminess, cohesiveness and resilience can be determined by texture profile analyses (TPA). This can be carried out by subjecting the sample to two compression test cycles, which typical TPA profile is shown in **Figure 6.1**. The hardness and fracturability can be determined readily from the force-time curve as the first maximum peak and the first significant break, respectively. Other texture attributes that can be determined from the curve are such as springiness, resilience, cohesiveness, adhesiveness, gumminess and chewiness, which the formulas are given in Figure 6.1



$$\text{Springiness} = \frac{L_2}{L_1}$$

$$\text{Resilience} = \frac{A_5}{A_4}$$

$$\text{Cohesiveness} = \frac{A_2}{A_1}$$

$$\text{Adhesiveness} = A_3$$

$$\text{Gumminess} = \text{Hardness} \times \text{Cohesiveness}$$

$$\text{Chewiness} = \text{Hardness} \times \text{Cohesiveness} \times \text{Springiness}$$

Figure 6.1. A typical force-time curve generated from TPA

These attributes are useful for comparison of textural quality of food product including dehydrated food subjects to various drying methods. Results from TPA are influenced by sample size, shape, compression speed and extent of compression (Rahman, 2005). These attributes can be correlated with several sensory properties as perceived by human being (Szczesniak, 2002).

The kinetics of textural changes can be determined using the following equation:

$$\frac{dF}{dt} = \pm kF^n \tag{6.6}$$

where F is the textural attribute, t is the time, k is the rate constant and n is the kinetic order of textural changes.

The value of n can be determined from linear regression analyses by assuming a zero order, half order, first order and second order kinetics (Lau et al., 2000). A more comprehensive model can also be used that takes into account the specific disappearance rate of the raw and soft tissue (Figure 2) analogous to two irreversible series reactions (Troncoso and Pedreschi, 2007).

$$\text{Raw tissue} \xrightarrow{k_1} \text{Soft tissue} \xrightarrow{k_2} \text{Hard tissue}$$

6.2.1.3. Shrinkage

When moisture is removed within the solid network of a food product during drying, a pressure unbalance is produced between the inner and external part of the food material, generating contracting stresses that lead to material shrinkage, changes in shape and sometimes product cracking (Mayor and Sereno, 2004). Visual appeal is affected too should severe shrinkage is experienced by the product. Typically, shrinkage increases proportionally with the volume of water removed during drying. Under ideal shrinkage condition the volume of water removed is equivalent to the reduction in sample volume. Sometimes, this could be untrue especially at low moisture content where transition from the rubbery to the glass state occurs. At this stage the rate and extension of shrinkage decreases significantly.

Mayor and Sereno (2004) and Ratti (1994) gave an extensive review of shrinkage of food materials during drying. Shrinkage of food products during drying can be modeled using empirical or fundamental relationships. In empirical modeling, shrinkage (volume, area or thickness) is a function of moisture content (or moisture ratio) in most models. Empirical models are suitable for materials with very low porosity or materials with uniform porosity development during drying. In contrast, the fundamental models are derived based on mass balance, density and porosity. **Table 6.1** shows some examples of empirical and fundamental models used in modeling food shrinkage.

The measurement of shrinkage is carried out based on the displacement methods to determine its apparent volume. Comparison of shrinkage measurement methods during drying of banana, pineapple and mango slices was reported by Yan et al. (2008) using (i) displacement with glass beads, (ii) liquid displacement, (iii) liquid pycnometer and (iv) Archimedes principle. The Archimedes method using solvent n-heptane was recommended based on the lowest coefficient of variation. The greater difference between the density of the solvent and sample enables n-heptane to distinguish the finer difference of sample's weight between in the air and solvent.

Table 6.3. Examples of food shrinkage model

Type of model	Geometry	Reference
Empirical:		
$V_r = aX+b$	Cylinder Sphere	Ratti (1994) Mclaughlin & Magee (1998)
$V_r = a + bX + cX^2 + dX^3$	Cylinder	Ratti (1994)
$V_r = a\exp(\frac{bX}{X_o})$	Cylinder & slab	Mayor & Sereno (2004)
Fundamental:		
$\frac{A}{A_o} = \left(\frac{V}{V_o}\right)^{\frac{2}{3}}$	Cube	Suzuki et al. (1976)
$V_r = \frac{1}{(1-\varepsilon)}\left[1 + \frac{\rho_o(x\text{-}x_o)}{\rho_w(1+x_o)} - \varepsilon_o\right]$	Cylinder	Mayor & Sereno (2004)

where Vr = volume ratio, A = area (m2), V = volume (m3), X = moisture content (dry basis), ρ = density (kg m-3) and ε = porosity.

6.2.1.4. Porosity

Porosity is a measurement of pore or empty spaces of a material to that of the total volume or simply it can be defined as the volume fraction of air in the food product (Equation 6.7).

$$\varepsilon = 1 - \frac{V_a}{V_t} \tag{6.7}$$

where Va = volume of air (m^3) and Vt = total volume (m^3).

Transport, mechanical and textural properties are affected by porosity (Hussain et al., 2002; Chen, 2008). Therefore, the formation of pores can be categorized into one with an inversion point and another without an inversion point based on experimental evidence (Rahman, 2000). **Figure 6.2** (a) shows pores collapsed at a critical value but further drying causes formation of pores (smooth line) and vice versa (dotted line) while **Figure 6.2** (b) shows pore sizes increased (dotted line) or decreased (smooth line) with moisture content.

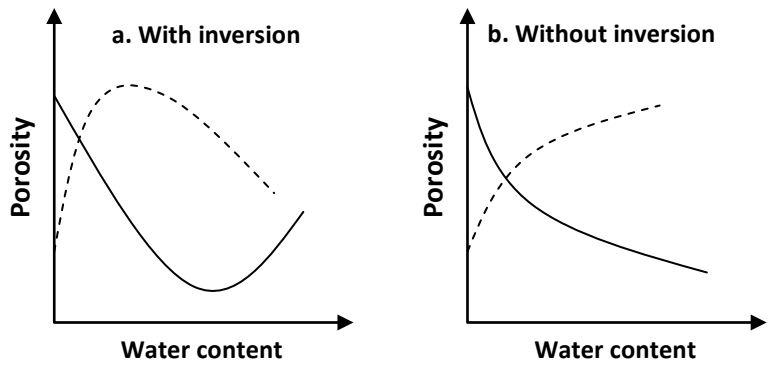


Figure 6.2. Change of porosity as function of moisture content (Rahman, 2000)

Glass transition theory is one of the concepts that is used to explain changes in porosity during drying. Generally, structural collapse is negligible (more pores) if the food

material is processed below glass transition temperature (T'_g). The higher the difference between the process temperature and the glass transition temperature, the higher is the collapse (Rahman, 2001). This explains why freeze dried material ($T < T'_g$) is generally more porous with negligible shrinkage as compared to hot air dried material. However, this is not applicable when the drying product experiences case hardening and crust formation as these will impede porosity development. In addition, surface tension, structure, environment pressure and mechanisms of moisture transport equally play significant roles in porosity development. Correlations that relates porosity with moisture, density and shrinkage based on fundamental relationship was developed by Martynenko (2008). The correlations are given in the following equations (6.8-6.10).

Porosity as function of shrinkage and moisture content:

$$\varepsilon = 1 - \alpha\left(\frac{1+\beta X}{1+\beta X_o}\right)\cdot\left(\frac{1}{\xi}\right) \tag{6.8}$$

Porosity as a function of shrinkage and density:

$$\varepsilon = \left(1-\frac{\rho}{\rho_l}\right)+\left(\frac{\alpha(\beta-1)}{1+X_o}\right)\cdot\left(\frac{1}{\xi}\right) \tag{6.9}$$

Porosity as function of moisture content and density:

$$\varepsilon = 1-\frac{\rho}{\rho_s}\cdot\left(\frac{1+\beta X}{1+X}\right) \tag{6.10}$$

Where α, β = density ratio coefficient, X = moisture content (kg kg^{-1} dry basis), ξ = bulk shrinkage, ρ = bulk density (kg m^{-3}) and subscript 0 = initial, s = solid and l = liquid.

These equations allow porosity to be calculated based on one of the two measureable variables (moisture content, shrinkage and density). No additional information is needed about the kinetics or spatial distribution of these variables.

6.2.1.5. Rehydration

Most dried food products are rehydrated prior to consumption. It is considered as the percentage of the original weight gained by dried samples during rehydration for a given time at a given temperature in water which depends greatly on the porosity of the material (Perera, 2005). Rehydration of dried products typically composed of the imbibition of water into dried product, swelling of the rehydrated product and leaching of solubles (Lewicki, 1998). It is generally accepted that the degree of rehydration is dependent on the degree of cellular and structural disruption (Krokida and Philippopoulus, 2005).

A first order kinetic model was used by Krokida and Marinos-Kouris (2003) to model the rehydration kinetics of various dried fruits and vegetables (Equation 6.11). The water temperature was found to influence the rehydration rates and the equilibrium moisture content in a positive way.

$$-\frac{dX}{dt} = k_r(X - X_e) \tag{6.11}$$

where X = moisture content and kr = rehydration rate (s^{-1}).

6.2.2. Chemical

6.2.2.1. Flavour

Flavour is the primary concern to consumers irrespective of the texture, shape and colour of a dried product. Flavour of food consists of various food aroma compunds that constitute the taste and odour of the food. Some flavour compounds are volatile and these are carried away during moisture removal process. The change in shape and texture influence the microstructure of the food product and controls the release of flavour during processing and consumption. Flavour properties of a food product can be analysed via chemical analyses (e.g. by chromatography method) or sensory evaluation. Chemical evaluation is able to provide the quantitative details of the aroma compounds but no indicative on the acceptance in terms of taste as perceived by human beings. Therefore, sensory evaluation plays an ultimate role in deciding the final acceptability of the food product. This is done by comparing the test product to a reference sample and rating is given during evaluation.

Undesirable flavour can also be produced due to product spoilage. Dried food with high fat content can easily become rancid due to fat oxidation. Oxygen level below 1% is effective in delaying rancidity, staleness and other deteriorative activities in dried food product (Perera, 2005). High fat content dried food could also pick up foreign odour easily such as from smoke exhaust, drying with other strong odour materials, contaminated packaging bags and etc.

6.2.2.2. Water activity

The removal of moisture content reduces the water activity of the product during drying. In general, the water activity (a_w) in most dried food is relatively low, typically less than 0.6, which is the recommended level for safe storage. Low water activity inhibits the growth of various microorganisms and prevents oxidation and enzymatic reactions. **Table 6.4** shows typical water activity values to prevent growth of some common microorganisms (Rahman, 2005).

Table 6.4. Critical water activity to inhibit microorganisms

Microorganisms	a_w (Critical range)
Bacteria	< 0.85 – 0.86
Yeasts and moulds	< 0.62

6.2.2.3. Shelf life

Storage and packaging play an important role in affecting the shelf life of a dried product. Typically the optimum relative humidity for dried product storage is 55 – 70% at moisture content ranging from 2 to 20% (Perera, 2005). Packaging should be moisture proof and able to prevent the transfer of oxygen into the product and cause off flavour formation. Alternatively, modified atmosphere packaging technique can be used to extend the shelf life of the dried products (García-Esteban et al., 2004).

In general, under ideal condition, the shelf life of a food product can be predicted based on microbial growth (Equations 6.12-6.13).

$$N = N_0 \exp[k(t - t_L)] \quad (6.12)$$

$$t_s = \ln(N_s / N_0)/k + t_L \quad (6.13)$$

where N_0 is the initial microbial load, N is the microbial level at time t, N_s the microbial level at the end of shelf life, t_s is the shelf life at constant temperature, k and t_L are the specific growth rate and lag time at constant storage temperature (Fu and Labuza, 1993).

6.2.3. Nutritional aspects

6.2.3.1. Food nutrients

Food nutrients degrade during drying and the magnitude of change depends on the foodstuff and the drying conditions. Losses of nutrients can be minimized by applying suitable pretreatments, selection of appropriate dying methods and optimization of drying conditions (Sablani, 2006). Generally, nutritional loss increases with the severity in the process conditions during processing (Rahman, 2005). **Table 6.5** shows the typical nutritional changes that could occur during drying (Perera, 2005).

Table 6.5. Nutritional changes during drying of food

Type	Possible changes
Colorie content	Does not change, but is concentrated into a smaller mass as moisture is removed
Fiber	No change
Vitamin A	Fairly well retained under controlled heat methods
Vitamin C	Mostly destroyed during blanching and drying of vegetables
Thiamin, riboflavin and niacin	Some losses during blanching but fairly good retention if the water used to rehydrate is also consumed
Minerals	Some maybe lost during rehydration if soaking water is not used. Iron is not destroyed during drying.
Protein	Can undergo heat denaturation, susceptible to light oxidation and may undergo enzymatic degradation
Lipids	May undergo enzymatic hydrolysis in the initial phase of drying. At low water activity auto-oxidation of unsaturated fatty acids causes rancidity
Carbohydrates	Maillard browning and changes in flavour under high heat. Sugar can be caramelized and give darker colour to dried product.

The degradation of a nutrient during drying can be described using a first order reaction model (Benali, 2004). The degradation model (Equation 6.14) can be expressed by:

$$\text{Degradation rate} = \frac{d[N]}{dt} = \frac{d([N]_0 - [N]_x)}{dt} = -k([N]_0 - [N]_x) \quad (6.14)$$

Where $k = k_0 \exp^{\frac{-E_a}{RT}}$ (6.15)

The constant k is known as the degradation rate constant which follows the Arrhenius temperature dependency equation (Equation 6.15). The term E is the activation energy while R is the universal gas constant (8.314 J/mol-K).

6.2.3.2. Antioxidants

Most fruits and vegetables contain various antioxidants which are beneficial to human health such as in lowering incidence of degenerative diseases i.e. cancer, arthritis, arteriosclerosis, heart diseases, inflammation, brain dysfunction and ageing process (Lim et al., 2007). This is due to the ability of the antioxidants to scavenge free radicals in human body and thereby decrease the amount of free radical damage to biological molecules like lipids and DNA (Wu et al., 2004). Antioxidants from plant chemical are such as Vitamin C, Vitamin E, carotenoids, polyphenols, melanoidins and indoles (Manarch, et al., 2004). Drying causes nutritional losses and hence some antioxidants are destroyed, probably due to thermal degradation, depending on the drying condition and techniques used. **Table 6.6** and **Table 6.7** list some of the common methods that are used to determine the antioxidant capacity and the antioxidant photochemical in food products.

Table 6.6. Determination of antioxidant capacity

Method	Analytical assay	Unit	Sample	Reference
ABTS cation radical-scavenging assay	2,2'-azinobis-(3-ethylbenzothiazoline-6-sulfonic acid)	µmol/g AEAC	Fruit seeds	Soong and Barlow (2004)
Trolox equivalent antioxidant capacity (TEAC) assay		mmol/L	Fruits and vegetables	Pellegrini et al. (2007)
Oxygen radical absorbance capacity (ORAC)	2,20-azo-bis, 2-amidinopropane (AAPH) dihydrochloride solution	µmol TE/g	Fruits Date	Patthamakanokporn et al. (2008) Maisuthisakul et al. (2007)
DPPH free radical-scavenging assay	1,1-diphenyl-2-picrylhydrazyl assay	IC_{50}, AEAC	Fruits	Lim et al. (2007)
		DPPH radical scavenging activity (%), EC_{50}, A_{AR}	Plant extracts	Maisuthisakul et al. (2007)
		µmol BHT equivalents/ g sample FW	Strawberries	Pinto et al. (2008)
Ferric-reducing antioxidant power assay (FRAP)	Ferric-TPTZ (2,4,6-tripyridyl-s-triazine) reagent	µmol/g FRAP	Fruit seeds	Soong and Barlow (2004)
		µmol TE/g	Fruits	Patthamakanokporn et al. (2008)
		µmol /g DW	Apple peel	Łata (2008)

Ferrous ion chelating activity (FIC)	Iron (II)-ferrozine complex	Chelating effect (%)	Fruits	Lim et al. (2007)

AEAC = L-ascorbic acid-equivalent antioxidant capacity, GAE = Gallic acid equivalents, TAE = Tannic acid equivalents, TE = Trolox equivalents, EC50 = amount of extract necessary to decrease DPPH radical concentration by 50%, AAR = 1/EC50 (antiradical activity), BHT = butylhydroxytoluene

Table 6.7. Determination of antioxidant phytochemicals

Antioxidant phytochemical	Analytical method	Unit	Sample	Reference
Total phenolic content	Folin–Ciocalteu reagent	GAE mg/g	Fruit seeds Plant extracts	Soong, Y.Y. and Barlow (2004) Al-Farsi et al. (2005)
		TAE/g dw	Pistachio hull extract	Goli et al. (2005)
		mg FAE/ 100 g of fresh weight	Date	Al-Farsi et al. (2005)
		(+)- catechin equivalents (mg/L)	Orange	Rapisarda et al. (2008)
		g p-coumaric acid/ kg DW	Pepper fruits	Navarro et al. (2006)
Total flavonoid content	Colorimetric assay - Aluminum chloride	RE mg/ g DW (rutin equivalents)	Plant extracts	Maisuthisakul et al. (2007)
		mg QE/100 g fresh matter	Fruits and vegetables	Pellegrini et al. (2007)
Flavanone glycosides	HPLC	Hesperidin equivalents (mg/L)	Orange	Rapisarda et al. (2008)
Hydroxycinnamic acids (*p*-coumaric, ferulic, caffeic and sinapic acids) – polyphenols	HPLC	Mg/kg FW	Fruits and vegetables	Pellegrini et al. (2007)
Total Anthocyanins	pH-differential method	mg cyanidin 3-glucoside equivalents/ 100 g of fresh weight	Date Blueberries	Al-Farsi et al. (2005)
	Spectrophotometer	Cyanidin-3,5-diglucoside chloride	Apple peel	Łata (2008)
Total Caroteno-	Spectrophotometer	mg/ 100 g fresh weight	Date	Al-Farsi et al. (2005)

ids		mg Lycopene/ kg DW mg β-Carotene	Pepper fruits	Navarro et al. (2006)
Ascorbic acid	HPLC	Mg/100 ml	Orange	Rapisarda et al. (2008)
	Titration method - indophenol solution	Percent of anhydrous citric acid (%)	Fruits	Lim et al. (2007)

RE=Rutin equivalents (a flavonoid type compound)' FAE=Ferulic acid equivalents, QE=quercetin equivalents

6.2.4. Biological aspects

Microbial growth on food product is a critical issue that cannot be tolerated. Information on microbiological specifications (Mould and yeast, E. coli, Salmonella and etc…) can be obtained from government and health related authorities (WHO, FAO and ICMSF etc.) but specifications may vary among countries. Failure to comply with these specifications could cause fatality upon consumption of the food product.

Another aspect of food safety that is a serious concern to human health is contamination of mycotoxins in food products. Mycotoxins have been shown to be potent carcinogens, mutagens and tetratogens. The most important groups of mycotoxins present in food are aflatoxins, ochratoxins, trichothecenes, zearzlenone and fumonisins. The occurrence of these toxins can be traced prior to harvest and also during storage if moisture exceeds the critical value for mould growth (a_w=0.65). The most common mycotoxin-producing fungi are Aspergillius flavus, Aspergillius parasiticus, Aspergillius ochraceus, fusarium verticillioides, Fusarium graminearum and Penicillium spp. (Kumar et al., 2008).

The current EU standard for total aflatoxins in all food is 4 ng/g (other than peanuts) and 15 ng/g in peanuts (Wu, 2008). Many countries have regulatory standards on mycotoxins in food products and vary among countries.

6.2.5. Sensory properties

Sensory evaluation is another aspect of food quality control that needs to be emphasized in food product development. It comprises of appearance, odour, flavour and texture of the food products. It is a method of accurate measurement of human responses to foods with minimal biasing effects. A successful product must meet the physical, chemical and microbiological parameters as well as the sensory expectations as demanded by consumers. Elortondo (2007) proposed a general approach for the development of an accredicted sensory method for the quality evaluation of food and beverages. **Figure 6.3** shows examples of some of the common sensory attributes for food products. Reference sample is given with pre-defined intensity scores associated with the product during evaluation. Therefore, the selection of the sensory attributes is crucial and it should cover the essential favour notes of the food product.

Most sensory attributes can be correlated to the physical and chemical properties of the food product. Szczesniak (2002) correlated sensory and instrumental ratings for hardness, chewiness, adhesiveness, brittleness, gumminess and viscosity. Acidity and

astringency have been correlated to the content of volatile acids and polyphenols in cocoa beans (Jinap and Zeslinda, 1995; Luna et al., 2002). Theobromine and caffeine contribute to bitterness during sensory evaluation (Ney, 1992). The presence of aldehydes, alcohols and ketones could produce several odours to rice such as fruity, woody, green, pungent, sweet, citrus, spicy, fragrant and etc (Sunthonvit et al., 2003).

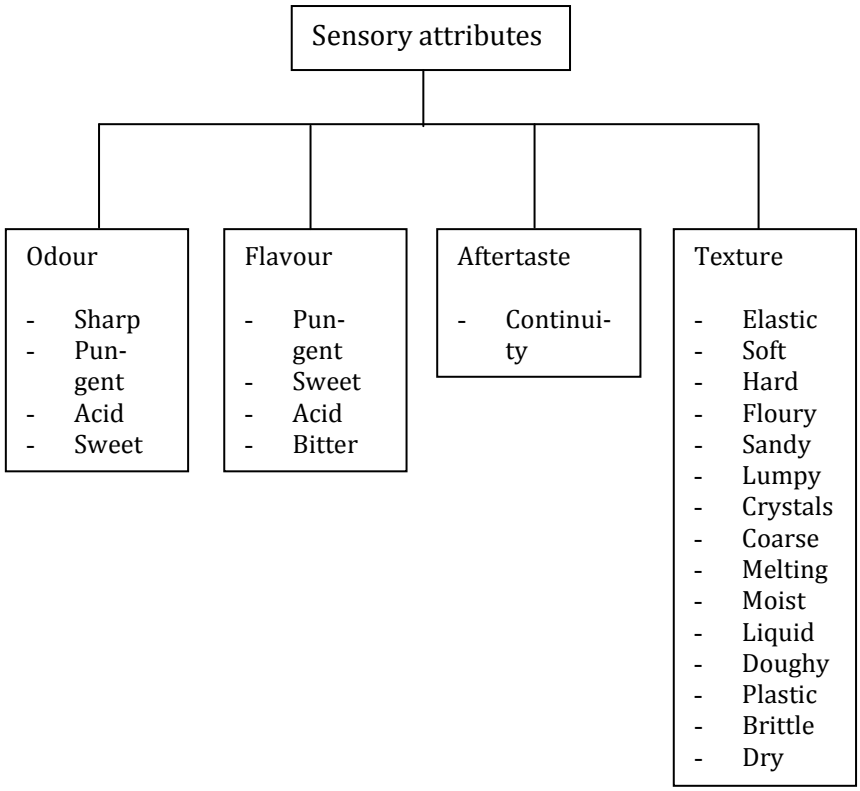


Figure 6.3. Some selected sensory attributes of food products

6.3. EFFECT OF DRYING ON PRODUCT QUALITY

All food quality attributes (e.g. texture, colour, flavour and nutrients) are affected by drying conditions and processing parameters. In recent years various emerging drying technologies and strategies have been developed to improve product quality such as by using spray freeze drying (Leuenberger et al., 2006), intermittent drying (Chua et al., 2002), microwave assisted drying (Orsat et al., 2007) and superheated steam drying (Devahastin and Suvarnakuta, 2004).

Several papers have provided comprehensive review on the effect of drying on product quality (Mayor and Sereno, 2004; Santos and Silva, 2008; Sablani, 2006; Perera, 2005; Rahman, 2005). **Table 6.8** shows some selected examples of effect of drying parameters on product quality.

Table 6.8. Selected examples on the effect of drying on product quality

Quality attributes	Products	Findings	References
Various	Fish mus-	Size reduction in length (5-10%), width	Pinto and Tobinaga

physical attributes	cles	(15-30%) and thickness (60-75%)	(2006)
	Chicken meat	Shrinkage at 50-71% and less shrinkage in superheated steam – heat pump drying	Nathakaranakule et al. (2007)
	Apple slices	Microwave and infrared drying showed 11-12% lower shrinkage, 30-34% lower volume, 18-23% lower density and porosity 25-28% higher than the convection method	Witrowa-Rajchert and Rząca (2009)
Rehydration	Vegetables	Temperature increment increases the rehydration capacity. Rehydration ratio ranges between 1 to 4 for all the examined materials	Krokida and Marinos-Kouris (2003)
Texture	Chempedak	Hardness, cohesiveness and chewiness increased with temperatures. Springiness decreased	Chong et al. (2008)
Colour	Chempedak	L^* and b^* decreased but a^* increased with temperature	Chong et al. (2008)
Sensory	Banana	Banana dried at 60°C were better accepted due to softer texture and better colour	Leite et al. (2007)
Nutritional	Various fruits and vegetables	Freeze drying preserved the highest retention of vitamins. Low oxygen level reduced loss of nutrients. Pretreatment improved nutrients retention	Sablani (2006)
	Figs	Pretreatments caused micro wounds on fruit peel and enhanced water removal	Piga et al. (2004)
	Banana and Guava	Step-down drying reduced colour degradation without compromising on drying time	Chua et al. (2002)
	Vegetables	Retention of vitamin C and total carotenoids were better under inert drying environment.	Ramesh et al. (1999)
	Sweet potatoes	Steamed freeze dried purple-fleshed sweet potatoes showed 40% higher ORAC antioxidant activity than fresh freeze dried powder and 20% higher than steam air-dried powder	Yang and Gadi (2008)

6.4. CLOSING REMARKS

The processing of dried food products involved several processing variables that determine the final quality of the dried products. Removal of moisture causes physical and chemical changes that influence both the quality attributes (e.g. colour, texture, shrinkage, porosity, rehydration, flavor and nutrients) and the level of acceptance of the product by consumers. Important quality criteria should be fulfilled for successful market acceptance as well as to ensure safe consumption. Appropriate means should be used to monitor and evaluate these quality attributes. The use of new raw materials, changing consumer pattern, demands for novel food products and health conscious awareness pose a challenge not only to conventional but also to emerging drying technologies.

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Chapter 7
Energy Efficiency and Energy Saving in Drying

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Contents

7.1. INTRODUCTION

Thermal drying operations are found in almost all industrial sectors and are known, according to various estimates, to consume 10-25% of the national industrial energy in the developed world. As energy cost is increasing in recent years, operating cost of energy intensive operations such as thermal drying is escalating as well; whilst, greenhouse gas emissions are correlated with energy consumption. With the global emerging economies rapidly industrializing, the energy consumed for thermal drying and the resulting adverse environmental impact of the greenhouse gas emissions will inevitably increase over time. This gives pressure to the energy intensive industry to look for energy efficient technology and to find ways to reduce energy consumption. Since drying is an energy intensive operation, energy consumption of an industrial dryer is huge and this in turn makes the unit operation costly.

The most effective solution to this growing problem is to develop and utilize highly energy-efficient drying technologies that will reduce net energy consumption and mitigate the environmental impact. Conventional industrial dryers usually operate at 30-70% efficiency levels. Hence, industrial drying is definitely an area that is desperate for energy efficient technology.

7.2. WHY CONVENTIONAL DRYERS HAVE LOW ENERGY EFFICIENCY

Generally, conventional dryer are operated at low energy efficiency due to poor design and lack of understanding of drying fundamental and science. Moreover, these dryers were designed when energy was abundant and low in cost. To date, the scenario has changed tremendously where energy cost is a major concern not only from the point of view of economy but also environmental impact. The inefficiency of conventional dryers is due to the factors given in **Figure 7.1**.

7.2.1. Low contacting efficiency

Most conventional dryers are convective direct dryer where drying medium makes contact directly with drying material for heat and mass transfer. However, drying material itself is a resistance to the flow of the drying medium and hence, drying medium tends to bypass the drying material through the empty space between the drying chamber and the drying material. This results in low contacting efficiency between the drying medium and the materials.

In this regard, fluidized bed drying has been recommended to improve the contacting efficiency. As the bed of solids is fluidized in the fluidizing gas stream, the gas makes contact with the bed of solids at a larger degree to enhance heat and mass transfer between the two phases. With reference to this, spouted bed, pulsating bed, agitated bed also have the advantage of improving the contacting efficiency between drying medium and drying material. Readers are to refer to the Handbook of Industrial Drying, Guide to Industrial Drying and other chapters in this book for more details about the respective types of dryer.

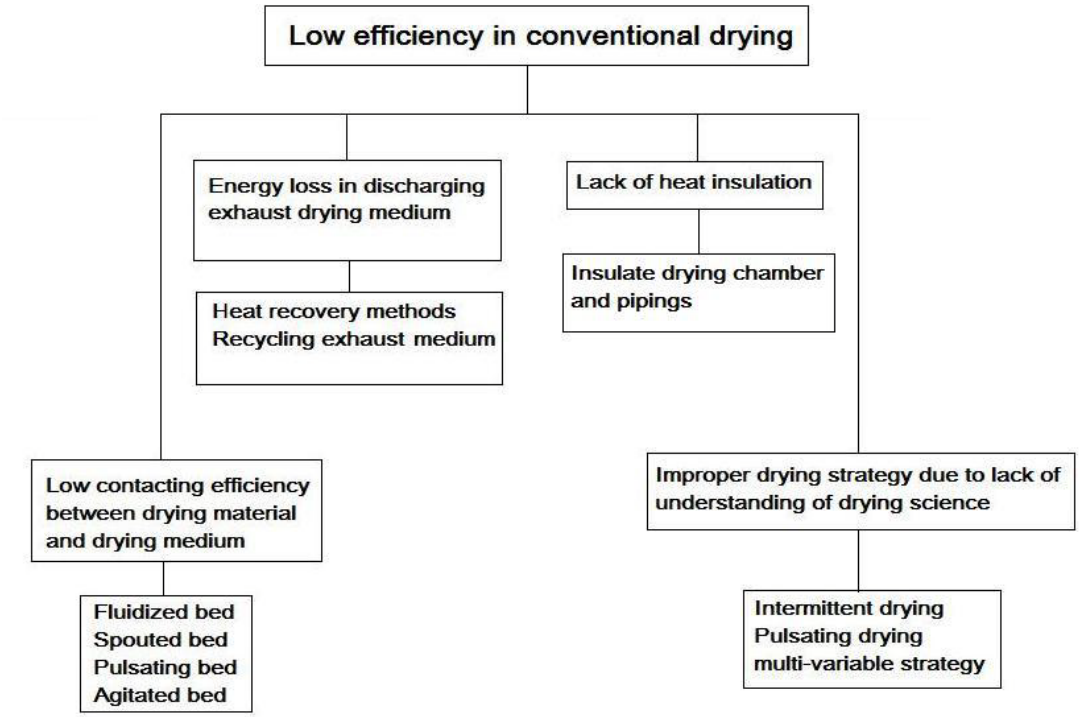

Figure 7.1. Factors that cause low energy efficiency in conventional drying and the respective drying techniques and drying strategy to improve the energy efficiency

7.2.2. Energy loss resultant from discharging of exhaust gas

In conventional convective drying, hot air is typically generated by heating the atmospheric air at room temperature to a desirable temperature. After passing through the drying material in drying chamber, it becomes humid and still hot. Thereafter the humid hot air is discharged into the atmosphere. Toward the end of drying, the exhaust gas is typically not humid and its temperature is typically a few degrees lower than the inlet hot air. There is a huge loss of energy occurs when enthalpy in the exhaust air is vented without partial recycle or heat recovery. This is even more significant if the flow rate of the exhaust air is high.

In this regard, waste heat recovery has been proposed to increase the energy efficiency of a drying system. A heat exchanger can be installed to transfer the heat in the exhaust air to the inlet prior to the heating of inlet air. This in turn saves the energy cost for heating the inlet air to desirable temperature. In addition, the waste heat can be stored in a phase change material and the heat is then transferred to the inlet air immediately or when the heat source is not available for the case of sun drying.

7.2.3. Lack of heat insulation

Poor insulation in dryers causes appreciable loss of energy to the environment. In this regard, drying chamber and air duct or piping can be insulated to minimize energy loss to the environment.

7.2.4. Improper drying strategy due to lack of understanding of drying science

Drying generally involves removal of surface moisture as well as internal moisture unless the drying material is rigid and contains only surface moisture. The removal of

these two types of moisture is dependent on different mechanism. Hence a technique that is efficient in removing surface moisture might not be suitable for removing internal moisture.

Conventional dryers tend to apply constant operating conditions where operating temperature and hot air flowrate are kept constant throughout the entire drying process. High temperature and fast flowrate may enhance the rate of moisture removal, however, these two parameters do not play an important role in removing internal moisture especially toward the end of drying process. Keeping the operating temperature and flowrate as high as the initial stage is merely a waste of energy, the internal moisture transport is governed by internal diffusion. In this case, external temperature and air flowrate does not promote the diffusion of internal moisture.

Recent developments in drying technology has revealed that intermittent drying, pulsating drying, multi-variable strategy and etc. can be applied to save energy. Intermittent drying enables active drying to be conducted periodically where the process is idle in between two active drying. During inactive drying, internal moisture slowly migrates from the internal to the surface of the drying material. The subsequent active drying remove higher amount of surface moisture which in turn enhances the drying rate Moreover, the operating cost is reduced significantly as drying is idle in intervals which save noticeable amount of energy.

7.3. ENERGY EFFICIENCY

Specific energy consumption Es, which is normally expressed in GJ/t water evaporated, is the measure commonly used to quantify the thermal efficiency of a dryer.

There are a number of energy efficiency indexes to measure the energy performance of a dryer. Kudra (2004) pointed out that there are inconsistencies in the definition of various terms that are used to measure energy efficiency, drying efficiency and etc. among users and researchers. This chapter adopts the definitions given by Kudra (2004).

Energy efficiency (η) measures the percentage of total input that is used for the evaporation of moisture.

$$\eta = \frac{E_{ev}}{E_{in}} \tag{7.1}$$

Here E_{ev} is the energy that is used for moisture evaporation and E_{in} is the total energy supplied to the dryer.

If heat capacity of air is constant, e.g. low humidity and low temperature convective drying, energy efficiency can be approximated by thermal efficiency (η_T).

$$\eta = \frac{T_1 - T_2}{T_1 - T_0} \tag{7.2}$$

Here T_1 is the inlet temperature, T_2 is the outlet temperature and T_o is the ambient temperature.

Since the outlet temperature, T_2 is impossible to reach the ambient temperature, T_o; thus the thermal efficiency according to eq (2) will never be 100%! Therefore, to im-

prove the thermal efficiency, one needs to recover the waste heat in the exhaust air to further reduce the outlet air temperature before it is discharged into the atmosphere.

Since drying is not a steady state process, outlet air temperature, amount of moisture removed vary at different drying time; thus energy efficiency varies throughout the entire drying process. In this regard, instantaneous energy efficiency (given in eq 3) can be measured at a particular drying time and the average efficiency can be calculated based on the instantaneous energy efficiency from equation (4). Energy efficiency (eq 1 and 2) is useful when comparing the efficiency of different types of dryer whereas instantaneous energy efficiency is useful when analyzing a drying process or a dryer configuration.

Instantaneous energy efficiency, ε_E

$$\varepsilon_E = \frac{Energy\ required\ for\ evaporation\ at\ time\ t}{input\ energy\ at\ time\ t} \tag{7.3}$$

Average energy efficiency within time = 0 until time t

$$\overline{\varepsilon_E} = \frac{1}{t}\int_0^t \varepsilon_E(t)\,dt \tag{7.4}$$

Drying efficiency on the other hand evaluate the percentage of energy transferred to the dryer for the evaporation of moisture. It is defined as:

$$\varepsilon_D = \frac{Energy\ required\ for\ evaporation\ at\ time\ t}{(input\ energy - exhaust\ energy)\ at\ time\ t} \tag{7.5}$$

$$\overline{\varepsilon_D} = \frac{1}{t}\int_0^t \varepsilon_D(t)\,dt \tag{7.6}$$

significant with reference to the input energy, drying efficiency is not a good indicator to reflect the energy efficiency; simply because the energy efficiency is low although the drying efficiency might be high. As such, both energy efficiency and drying efficiency may provide insight on energy aspect and efficiency aspect of a drying system. **Table 7.1** shows the various scenarios with reference to energy efficiency and drying efficiency variations and area for improvement with regard to the respective scenario.

Table 7.1. Area for improvement with reference to low energy efficiency and low drying efficiency

Energy efficiency	Drying efficiency	Area for improvement
Low	Low	Loss of energy to the atmosphere. May consider insulation to improve drying efficiency.
Low	High	Loss of energy in exhaust air. May consider to recover waste heat

7.4. METHODS TO IMPROVE ENERGY EFFICIENCY

Over the past few decades, tremendous developments and improvements in drying technology have been reported in the literature. Readers may refer to review papers on the latest development and advancement in this area (Mujumdar & Pasos, 2000; Mujumdar, 2001; Mujumdar, 2006; Mujumdar, 2007; Law et al., 2008). Suffice it to say that

the developments and advancements which are related to energy efficiency of industrial drying can be classified into the subtopics given in **Figure 7.2**.

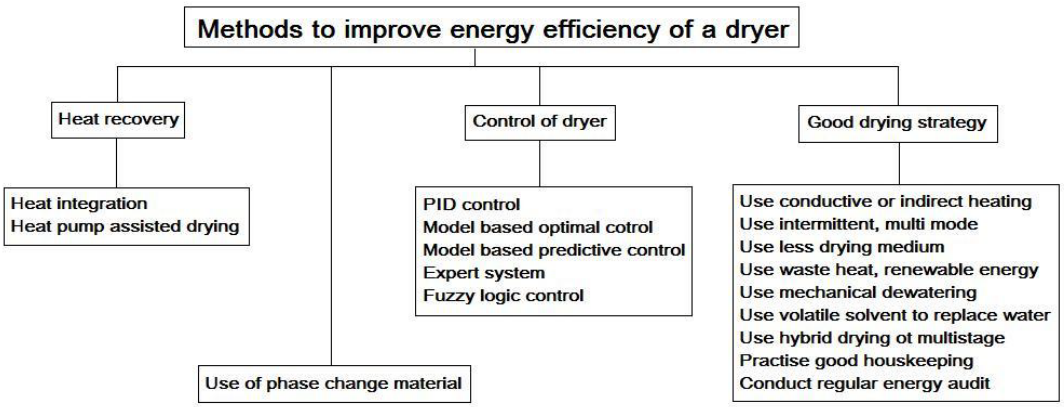

Figure 7.2. Methods to improve energy efficiency of a dryer

7.4.1. Heat Recovery

Recovering waste heat in the exhaust air can be realized by heat recovery or heat Recovering waste heat in the exhaust air can be realized by heat recovery or heat integration. Heat recovery is simpler as it only involves heat exchanger for heat transfer between the exhaust air and the inlet air; or a mixing T and purging system for recycling exhaust air directly with the inlet air.

Both direct and indirect heat recycle methods enable the recovery of part of the enthalpy of the hot and humid exhaust air to maximize the energy efficiency. It is especially important for drying processes that are operated at high air velocity and have short contact time between drying medium and drying material. This is due to the fact that the contacting efficiency is generally low.

Heat integration is typically complex and therefore may increase the complexity of start-up and shutdown operations; it also limits the flexibility of the process. Generally heat integration gives higher energy efficiency as compared to conventional heat recovery methods. Kemp (2005) gave a few examples of using heat integration to maximize energy efficiency and commented that this technique is especially useful for minimizing energy consumption of a drying operation in sites that have combined heat and power (CHP) system. Further, the effectiveness of heat integration is affected by initial product moisture content which is dependent on the upstream processes rather than the dryer itself. Therefore, the entire process should be looked into when heat integration is performed.

With reference to heat recovery, there are a few factors that one needs to consider:

- Costs associated with recycle ducting and reduction in driving potential
- Problems of condensation if the exhaust air is near to the saturation point
- Dust in the exhaust air when it is directly recycled may cause surface abrasion, and pose dust explosion hazard

Heat pump assisted drying recovers latent heat and thus gives higher energy efficiency. Details of heat pump dryer can be obtained elsewhere in this book and references mentioned in the introduction of this chapter. It is operated in a closed system

where humid air is recycled to extract its moisture and thereafter heated up to reduce its relative humidity. Heat pump dryers generally have high performance (COP ranging from 5 to 7). Likewise, recycling of exhaust superheated steam in superheated steam drying can also increase the energy efficiency significantly.

7.4.2. Use of Phase Change Material (PCM)

PCM can be used to store waste heat in the exhaust air. It is a good thermal energy storage agent which can be placed in exhaust duct of a batch dryer to capture the residue heat of the exhaust air. The PCM then changes from solid to liquid (in molten form) after receiving thermal energy. The heat stored in the PCM is then recovered later by passing ambient air over the exchanger with molten PCM. Supplementary heat can be supplied if the heat transfer from the PCM does not meet the total heat requirement of a drying system. This idea requires further exploration.

7.4.3. Control of dryer

Good control strategy can be applied in a drying system to reduce energy consumption and reduce operating costs. It has been reported that optimization of grain drying could reduce the cost significantly by optimally tuning the air flows (Ryniecki & Nellist, 1991a) as well as optimal tuning the heater power (Ryniecki & Nellist, 1991b). In addition, installation of an on-line optimal controller in a grain dryer was reported to reduce drying time by 18% which in turn saved 6.4% in fuel consumption, and 1.3% in total (Mc Farlane & Bruce, 1996). The application of a model based predictive controller in a beet sugar processing facility could reduce the energy costs by 1.2% (equivalent to £18,900/year) and decrease the downstream energy cost by £14,000/year (CADDET, 1997, 2000a, 2000b). Further to this, installation of a PI controller in a rotary dryer has been reported to decrease energy consumption by 7% compared to manual control (Iguaz et al., 2002).

Dufour (2006) gave a comprehensive dryer control strategy. There are two types of control strategies, namely open loop and close loop. Open loop control strategies include model-based optimal control, genetic algorithm which is a data-based method; whereas close loop control strategy includes PID control, model-based optimal control, model-based predictive control, expert system and fuzzy logic control.

Readers may refer various works published elsewhere, for instance the application of Multiscale Computational Model to reduce energy consumption in wood drying: (Perre´ et al., 2007).

7.4.4. Development of mathematical modeling

The development of mathematical modeling of a drying system or a dryer may help a design engineer to design an energy efficient dryer by simulating the profiles of moisture content, temperature, determination of heat and mass transfer as well as specific energy consumption. **Table 7.2** shows the recent findings on using mathematical modeling to improve energy efficiency of a dryer.

Table 7.2. Recent research findings on applying mathematical modeling to improve energy efficiency

Drying system / dryer	Findings	Reference
Plug flow fluidized bed using mathematical models in different drying periods	25-27.5% saving in thermal power by upgrading insulation and adjusting inlet air temperature or flow rate in order to avoid overdrying.	Baker & Lababidi, 2010
Wood drying using multiscale computational model	Vacuum drying of spruce using suitable drying schedule could give 10% savings in total energy consumption	Perre et al., 2007
Through drying of tissue paper using a dynamic model for through drying combined with static model for air system	3.3% reduction in total operating cost by reducing initial fabric moisture ratio.	Weineisen & Stenstro¨m, 2008
Spray drying using simulation program	14% of fuel oil saving if 60% of exhaust air is recycled	Velic et al., 2003

7.4.5. Drying strategy for energy savings

Apart from heat recovery, heat integration and applying control scheme to drying, there are several drying strategies which can be applied to improve energy utilization and save energy cost:

- Use conductive heating or indirect heating (such as IR) to avoid loss of energy in exhaust air, where possible and this strategy is generally cost-effective
- Use intermittent, multi-mode heating to optimize the heat input and moisture transport, where possible for batch drying
- Use less air and higher temperature where possible to avoid loss of energy in exhaust air
- Use waste heat, renewable energy (such as solar, wind energies etc.), where feasible
- Use mechanical means such as filtration, ultra-centrifugation to remove water without phase change, etc and use evaporation (for dilute liquids) to reduce the water content prior to drying
- Use solvent with low heat of vaporization and high vapor presence to displace water from drying material
- Apply hybrid drying or multistage drying to intensify energy utilization during drying.

A dryer type may have many different variants. Each dryer variant can involve different levels of energy consumption, for example fluidized bed dryer has more 30 different variants. Reader may refer to Law and Mujumdar (2004, 2007) for the descriptions of various types of fluidized bed dryer (FBD). Conventional FBD uses high airflow and thus it requires higher energy consumption. With the use of immersed heat exchanger, it can save ~30-50% of energy usage. Vibrated / pulsed fluid bed on the other hand, can save ~20-40% energy by using lower airflow rate. Whereas, spouted bed consumes

more energy but it is used when particles cannot be fluidized in a conventional fluidized bed.

Table 7.3 gives some of the recent research findings on energy saving of multi-stage drying, hybrid drying, heat pump drying and application of heat recovery method

Table 7.3. Please provide the caption here

Drying system / dryer	Findings	Reference
Two-stage zeolite dryer	10-15% higher in energy efficiency than single stage zeolite dryer 30% higher in energy efficiency compared to conventional dryer	Djaeni et al., 2009
Two-stage freeze drying followed by microwave vacuum drying	54.02% saving in invalid energy. Invalid energy is the portion of total energy (a large portion) that is not used for removing moisture.	Huang et al., 2009
Heat pump assisted dryer	Specific moisture extraction rate (SMER) is three times higher than hot air dryer	Lee & Kim, 2009
Fluid bed dryer and hybrid fluid dryer	Fluid bed dryer gives high energy efficiency for drying which occurs in constant rate period. Fluid bed – conveyor may be used in falling rate period	Menshutina et al., 2004
Longan drying using heat recovery method, wood as fuel, applying thermal insulation and better temperature and humidity control	20% improvement in thermal efficiency and 80% reduction in fuel cost	Tippayawong, 2008

Hybrid drying or multistage drying has been reported to reduce energy consumption compared to conventional drying. For instances, hybrid 6 hour freeze drying followed by microwave vacuum drying could reduce energy consumption by 54.02% compared to conventional freeze drying (Huang et al., 2009). More information on energy aspects in drying technology can be found in Strumillo et al. (2007).

7.5. CONCLUSION

Energy analysis and minimization of energy consumption should be performed on the entire flowsheet of a process rather than targeting on an individual unit operation such as a dryer alone. Pre-drying, such as mechanical dewatering, filtration and etc. as well as post-drying such as cooling, granulation, blending and etc. should be considered in the overall strategy to save energy. However, it should be noted that the best energy option does not produce the optimal product quality. Therefore, optimization should be conducted to obtain the best drying strategy to meet requirements from various aspects such as energy and product quality.

Performance of a dryer type is dependent on its sub-classification, geographical location, ambient condition, operating conditions, maintenance etc. Thus, copying flowsheets from other plants elsewhere done at different times should be avoided since it does not guarantee the same drying performance. Selection of energy efficient dryer is dependent on the properties and quality of feed / product; relative cost of fossil fuel / electricity; ability to model / control dryer and possibility of using new technique, e.g. heat pump drying; dielectric drying; pulse combustion drying; superheated steam drying, etc. In addition, various methods can be applied to minimize the energy consumption of a dryer such as applying heat recovery methods, use of phase change material, use of appropriate drying strategy etc. Further to this, good housekeeping such as good insulation or elimination of leakage, etc as well as energy audit should be practiced to minimize heat loss.

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Chapter 8
Statistical Analysis/Design of Experiments: Application in Drying of Foods

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Contents

8.1. INTRODUCTION

Scientific experiments are important in research laboratories of universities and also in the engineering laboratories of industries. Experiments in processing companies are often conducted in a series of trials or tests which produce quantifiable outcomes. For continuous improvement in product/process quality, it is fundamental to understand the process behavior, the amount of variability and its impact on processes (Mason et al., 2003).

Quality and productivity with process economics are characteristic goals of industrial processes, which are expected to result in superior goods that are highly sought by consumers and that yields profit for firms that supply them. Recognition is now being given to the necessary link between scientific study of industrial drying process and the quality of dried products produced. The stimulus for this recognition is the intense international competition among companies selling similar dehydrated products to a limited consumer group. Competition demands that a better product need to be produced within the limits of economic realities. Better food products are initiated in academic and industrial research laboratories, made feasible in pilot studies and new-product research studies, and checked for adherence to design specifications throughout processing stages (Mason et al., 2003). All of these activities require experimentation and the collection of data. Experimental design is a critically important tool in the food engineering world for improving the performance of a dehydration or formulation process. It also has extensive applications in development of novel drying techniques.

Design of Experiments (DOE) is a statistical technique introduced in the 1920s by Sir Ronald Fisher in London. His initial experiments were concerned with determining the effect of various fertilizers on different plots of land. The final condition of the crop was not only dependent on the fertilizer but also on a number of other factors (such as underlying soil condition, moisture content of the soil, etc.) of each of the respective plots. Fisher used DOE which could differentiate the effect of fertilizer and the effect of other factors. Since then DOE has been widely accepted and applied in many research disciplines (Antony, 2003).

The applications of experimental design techniques in process development can result in

1. Improved process yields and product quality.
2. Reduced variability and closer performance to target requirements.
3. Reduced number of steps and development time.
4. Improved process economics.
5. Increased understanding of the relationship between key process inputs and output (s). (Montgomery, 2003)

An experiment is a series of tests, called runs, in which changes are made in the input variables in order to identify the reasons for changes in the output response (Box et al, 2005). The term scientific study indicates a process of objective investigation which makes sure that valid conclusions can be drawn from experimental study. **Figure 8.1** signifies that statistics is imperative in every step of data collection and analysis, from initial problem recognition and definition of objectives to the drawing of final conclusions. **Figure 8.1** distinguishes two types of studies: experimental and observational. In experimental studies the variables of interest often can be controlled and fixed at predetermined values for each test run in the experiment. In observational studies many of

the variables of interest cannot be controlled, but they can be recorded and analyzed. Data collection is at the center of experimental and observational studies (Mason et al., 2003; Antony, 2003; Cox & Reid, 2000).

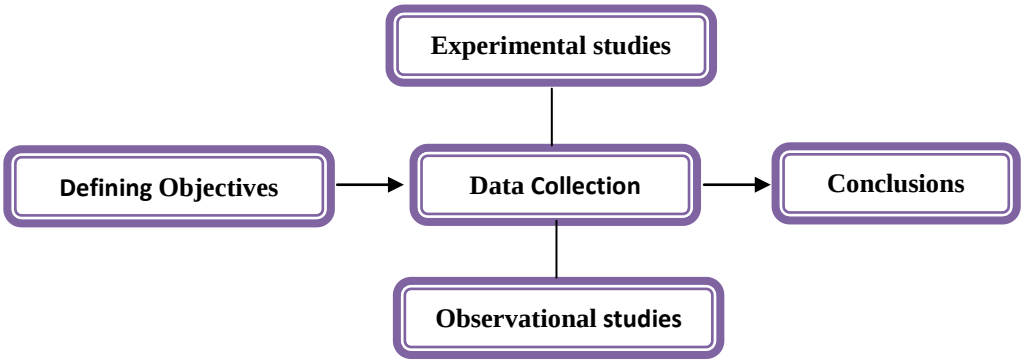

Figure 8.1. Important stages of statistical input in scientific investigations

8.2. STATISTICS IN EXPERIMENTATION

Statistical experimental design will be shown to be effective in eliminating known sources of bias, guarding against unknown sources of bias, ensuring that the experiment provides precise information about the responses of interest, and guaranteeing that excessive experimental resources are not needlessly wasted through the use of an uneconomical design. Design of experiments in statistics works on assumption that, measurements are subject to variation. The study of variation includes the construction of experimental designs and the development of models which describe variation. The term measurement encompasses both qualitative responses as well as quantitative measurements. In most industrial drying processes there are numerous sources of possible variation. Frequently studies are conducted to investigate the causes of excessive variation. These studies could focus on a single source or simultaneously examine several sources. Consider, for example, dehydration of strawberries on industrial scale that involves procurement of raw materials from different sources and the dehydration which is performed by several operators. Variation could occur because the operators systematically differ in their method of operation. Variation also could occur because one or more of the operators do not consistently adhere to the drying procedures, thereby introducing uncontrolled variability to the measurement process. To investigate sources of variability for a dehydration studies, an experiment should be statistically designed and analyzed to ensure that relevant sources of variation could be identified and measured (Mason et al., 2003).

8.3. ROLE OF STATISTICS IN EXPERIMENTATION

In general, there are three basic steps in the statistical design and analysis of experiments as depicted in **Table 8.1**.

Table 8.1. Function of Statistics in Experimentation

Function of Statistics in Experimentation
Planning Phase • Problem recognition and formulation. • Selection of response or quality characteristic. • Selection of process variables or design parameters. • Classification of process variables. • Determining the levels of process variables. • List all the interactions of interest.
Design Phase • Control known sources of variation • Allow estimation of the size of the uncontrolled variation • Permit an investigation of suitable models
Analysis Phase • Make inferences on design factors • Determine the design parameters or process variables that affect the mean process performance. • Determine the design parameters or process variables that influence performance variability. • Determine the design parameter levels that yield the optimum performance. • Determine whether further improvement is possible. • Guide subsequent designs • Suggest more appropriate models

8.3.1. Planning Phase

Statistical considerations should be included in the project planning & designing phase of any experiment. At this stage of a project one should consider the nature of the data to be collected, including what measurements are to be taken, what is known about the likely variation to be encountered, and what factors might influence the variation in the measurements.

8.3.2. Design Phase

In this phase, one may select the most appropriate design for the experiment. Experiments can be statistically designed using classical approach advocated by Fisher, orthogonal array approach advocated by Taguchi or variables search approach promoted by Dorian Shainin. In Fisher approach, choice of full factorial, fractional factorial or screening designs such as Plackett-Burmann design can be used (Antony, 2003). The size of the experiment is dependent on the number of factors and/or interactions to be studied, the number of levels of each factor, budget and resources allocated for carrying out the experiment, etc. During the design stage, it is quite important to consider the confounding structure and resolution of the design.

A statistical design should be selected that controls variation from known sources. The design should allow the estimation of the magnitude of uncontrollable variation and the modeling of relationships between the measurements of interest and factors (sources) believed to influence these measurements. Uncontrollable variation can arise

from many sources. Two general sources of importance to the statistical design of experiments are experimental error and measurement error. Experimental error is introduced whenever test conditions are changed. For example, dryer settings are not always exact enough to be fixed at precisely the same value or in case of microwave vacuum dryer, vacuum chamber pressure changes with respect to atmospheric temperature & humidity if the chamber pressure is not set. Dehydration batches of same Sapota fruit do not always show exactly the same drying nature and quality due to different initial composition. Measurement errors arise from the inability to obtain exactly the same measurement on two successive test runs when all experimental conditions are unchanged.

8.2.3. Analysis Phase

A statistical analysis of the experimental results should allow inferences to be drawn on the relationships between the design factors and the measurements. This analysis should be based on both the statistical design and the model used to relate the measurements to the sources of variation. If additional experimentation is necessary or desirable, the analysis should guide the experimenter to an appropriate design and, if needed, a more appropriate model of the measurement process (Mason et al., 2003).

Thus, the role of statistics in food engineering and scientific experimentation can be described using three basic categories: project planning, experimental design, and data analysis.

8.4. DIFFERENT TERMINOLOGIES USED IN EXPERIMENTAL DESIGN

The words and phrases used in experimental design are not uniform across disciplines or even, in textbooks. For this reason statistical experimental design with a brief definition of terms is compiled as below. **Table 8.2** contains definitions of many terms which are in common use.

A response variable is an outcome of an experiment. It may be a quantitative measurement such as the percentage of moisture removed in batch drying process, the drying time or it may be a qualitative result such as extent of color changes in drying of certain food product for example. A factor is an experimental variable that is being investigated to determine its effect on a response. It is important to understand that a factor is controllable by the experimenter; that is, the values, or levels, of the factor can be determined prior to the beginning of the test runs and can be executed as planned in the experimental design. To give an example, in hot air drying of Garlic slices experiments, if a response is retention of Allicin (the principle constituent of garlic), the factors would be drying time, drying temperature and slice thickness then the possible levels for a factor drying temperature would be 40, 50 and 60°C. However, one will try to avoid higher drying temperature as it may result in unacceptable product quality. An experimental region, or factor space, consists of all possible levels of the factors that are considered for inclusion in the design. For quantitative factors, the factor space is often defined by lower and upper limits for the levels of each factor. Additional variables that may affect the response but cannot be controlled in an experiment are called covariates. Covariates are not additional responses; that is, their values are not affected by the factors in the experiment. Rather, covariates and the experimental factors jointly influence the re-

sponse. For example, in many hot air drying experiments both temperature and humidity affect a response, but the laboratory equipment can only control temperature; humidity can be measured but is difficult to control. In such experiments temperature would be regarded as an experimental factor and humidity as a covariate. A test run is a single factor-level combination for which an observation (response) is obtained. Repeat tests are two or more observations that are obtained for a specified combination of levels of the factors. Repeat tests are conducted under as identical experimental conditions as possible, but they need not be obtained in back-to-back test runs. Repeat tests should not be two or more analytical determinations of the same response; they must be two or more identical but distinct test runs.

Table 8.2. Experimental-Design Terminology

Terminology	Definition
Block	Group of homogeneous experimental units.
Confounding	One or more effects that cannot unambiguously be attributed to a single factor or interaction.
Covariate	An uncontrollable variable that influences the response but is unaffected by any other experimental factors.
Design (layout).	Complete specification of experimental test runs, including blocking, randomization, repeat tests, replication, and the assignment of factor–level combinations to experimental units.
Effect	Change in the average response between two factor–level combinations or between two experimental conditions.
Experimental region (factor space)	All possible factor–level combinations for which experimentation is possible.
Factor	A controllable experimental variable that is thought to influence the response
Homogeneous experimental units	Units those are as uniform as possible on all characteristics that could affect the response.
Interaction	Existence of joint factor effects in which the effect of each factor depends on the levels of the other factors.
Level	Specific value of a factor
Noise	The natural variations that occur in a process when all conditions are maintained at the same level
Repeat tests	Two or more observations that have the same levels for all the factors
Replication.	Repetition of an entire experiment or a portion of an experiment under two or more sets of conditions.
Response	Outcome or result of an experiment.
Test run	Single combination of factor levels that yields an observation on the response.
Unit (item).	Entity on which a measurement or an observation is made; sometimes refers to the actual measurement or observation

Replications are repetitions of a portion of the experiment (or the entire experiment) under two or more different conditions, for example, on two or more different days. Experimental responses are only comparable when they result from observations taken on homogeneous experimental units. Homogeneous experimental units do not differ from

one another in any systematic fashion and are as alike as possible on all characteristics that might affect the response. While there is inherent random variation in all experimental units, the ability to detect the effects of important factor and to estimate these effects with satisfactory precision depends on the degree of homogeneity among the experimental units.

If all the responses for one level of a factor are taken from experimental units that are produced by one manufacturer and all the responses for another level of the factor are taken from experimental units produced by a second manufacturer, any differences noted in the responses could be due to the different levels of the factor, due to the differences in design from two manufacturers, or to both. In this situation the effect of the factor is said to be confounded with the effect due to the manufacturers. Confounding variation can occur when using dryers from two different fabricators for same response.

When a satisfactory number of homogeneous experimental units cannot be obtained, statistically designed experiments are often blocked so that homogeneous experimental units receive each level of the factor(s). Blocking divides the total number of experimental units into two or more groups or blocks (e.g., raw materials) of homogeneous experimental units so that the units in each block are more homogeneous than the units in different blocks. Factor levels are then assigned to the experimental units in each block. The natural variation that occurs in a process, even when all conditions are maintained at the same level, is termed as noise. When the effect of a particular factor on a process is studied it becomes extremely important to distinguish the changes in the process caused by the factor from noise.

The terms design and layout often are used interchangeably when referring to experimental designs. The layout or design of the experiment includes the choice of the factor-level combinations to be examined, the number of repeat tests or replications (if any), blocking (if any), the assignment of the factor–level combinations to the experimental units, and the sequencing of the test runs (Mason et al., 2003; Antony, 2003 & Montgomery, 2003).

8.5. SELECTING A STATISTICAL DESIGN

To avoid various potential pitfalls during experimentation, several key factors should be considered. Important design considerations for selecting a statistical design are as follows.

8.5.1. Consideration of Objectives

Defining conceptual terms is prerequisite to understand and quantify outcome of experiment. Concept definition and determination of observable variables influence both the experimental design and the collection of information on uncontrollable factors. Consider an example, in case of drying of carrots, it is prerequisite for experimenter to be clear about response outcome such as colour retention, β carotene retention (principal ingredient in Carrots) etc. To design such an experiment it is important to know different physical properties of β carotene in order to retain maximum content. So concept definition is important in order to select the experimental conditions for quantifiable outcome. Consideration of the nature of anticipated conclusions can prevent unexpected complications when the experiment is finished and the result is being written.

(The experimental design is different if the goal of a particular study is to evaluate the effect on various colour attributes during dehydration and may well be entirely different if goal of a same particular study is to study the effect on all dehydration properties during dehydration) So the experiment should be design in a way keeping in mind the final response.

8.5.2. Factor Effects

A second important criterion in the selection of an appropriate statistical design is likely effect of the factors. Inclusion of all relevant factors, when experimentally feasible, is necessary to ensure that uncontrolled systematic variation of these factors will not bias the experimental results. An accounting for uncontrollable systematic variation through the measurement of covariates is necessary for the same reason. Anticipated factor effects also influence the choice of a statistical design through their expected relationships with each another. If each factor is believed to affect the response independently of any other factor or if joint effects of the factors are of secondary interest, screening experiments can be used to assess the effects of the factors. If the effect of one factor on the response depends on the levels of the other factors, a larger design is needed. In general, an experimental design should allow the fitting of a model so that the salient features of the response and its relationships with the factors can be identified. For example, the design should permit polynomial terms in the quantitative factors to be included in the fitted model so that the response function can be assessed. The design should permit an assessment of the adequacy of the fitted model. If the fitted model is judged to be an inadequate representation of the response function, the design should form the basis for an expanded design from which more elaborate models (e.g., higher-order polynomials) can be fitted. When assessing factor effects it is important to explore the entire experimental region of interest. The combinations of factor levels used in a statistical design should be selected to fill out the experimental region. If a factor is only studied over a narrow portion of the experimental region, important effects may go undetected (Mason et al., 2003; Antony, 2003 & Montgomery, 2003).

8.5.3. Precision & Efficiency

Precision refers to the variability of individual responses or to the variability of effects that measure the influence of the experimental factors. Precision is a property of the random variables or statistics and not of the observed values of those variables or statistics. For example, an (observed) effect is said to be sufficiently precise if the standard deviation of the statistic that measures the effect is suitably small. In its simplest form, an effect is simply the difference between two averages.

An observed effect is then said to be sufficiently precise if the standard deviation (or, equivalently, the variance) of this statistic is sufficiently small. In practice, the value of the standard deviation can be estimated from the data.

Blocking, repeat tests, replication, and adjustment for covariates can all increase precision in the estimation of factor effects. Blocking increases precision (decreases variability) by controlling the systematic variation attributable to non homogeneous experimental units or test conditions. Adjustment for covariates increases precision by eliminating the effects of uncontrolled factors from the variability that would otherwise be attributed to random error.

8.5.4. Randomization

Randomization of the sequence of test runs or the assignment of factor-level combinations to experimental units protects against unmeasured sources of possible bias. Randomization also helps validate the assumptions needed to apply certain statistical techniques. The protection that randomization affords against unknown bias is easily appreciated by considering the common problem of instrument drift or deviation. If during an experiment, dryer drift builds over time, the later experimental measurements will be biased because of the drift. If all tests involving one level of a factor are run first and all tests involving the second level of a factor are run later, comparison of the factor levels will be biased by the instrument drift and will not provide a true measure of the effect of the factor. Randomization of the test runs cannot prevent instrument drift but can help to ensure that all levels of a factor have an equal chance of being affected by the drift. If so, differences in the responses for pairs of factor levels will likely reflect the effect of factor levels and not the effect of the drift. It should be noted that, the design criteria discussed here may not be comprehensive. The discussion is presented as a guide to some of the more important considerations that must be addressed in the planning stages of most experiments. (Mason et al., 2003; Antony, 2003 & Montgomery, 2003).

8.6. DESIGNS FOR QUALITY IMPROVEMENT

Dehydration procedures in scientific and engineering experiments are frequently guided by established protocol and subjective considerations of practicality. While such experimental procedures may be viewed as economical in terms of the number of test runs that must be conducted, the economy of effort can be deceiving for two reasons. First, economy is often achieved by severely limiting the number of factors whose effects are studied. Second, the sequence of tests may require that only one of the factors of interest be varied at a time, thereby preventing the evaluation of any combined effect of the experimental factors. The effective use of the statistical principles in design of experiments ensures that experiments are designed economically, that they are efficient, and that individual and joint factor effects can be evaluated.

Statistical experimental design is then motivated by an examination of problems that frequently arise when statistical principles are not used in the design. Special emphasis is placed on the investigation of the joint effects of two or more experimental factors on a response. Statistical methodology for quality improvement can be divided into two main categories: on-line and off-line statistical measurement procedures. In the past, on-line statistical quality control techniques were used for assurance of product quality, currently off-line investigations using engineering design techniques and statistical design of experiments used for quality improvement and increased productivity (Mason, 2003). Off-line experiments are performed in academic laboratories, pilot plants, and preliminary dehydration runs, prior to the complete implementation of formulation or dehydration process operations. Hence, it can be stated that statistical design of experiments is an integral component of off-line quality-improvement studies. Once a target has been determined, based on product quality, consumer preferences and manufacturing capabilities, quality improvement relies on achieving the target value and on reducing variability.

A number of statistical methods available for effective designs of the experiments are as follows:

8.6.1. Full factorial design

A factorial design is an experimental strategy in which design variables are varied together, instead of one at a time. The factorial experiments in which all combination of levels of the factors is run are referred as full factorial experiments. In the full factorial design it is prerequisite to define the lower and upper bounds of each N design variables. The allowable range is then discretized at different levels. To construct an approximation model that can capture interactions between N design variables, a full factorial approach (Montgomery, 1997) may be necessary to investigate all possible combinations. If each of the variables is defined at only the lower and upper bounds (two levels), the experimental design is called 2N full factorial. Two level factorial experiments are those in which each factor is investigated at only two levels. The early stages of experimentation usually involve scrutinizing the vital factors from a large number of potential factors. Two level factorial experiments are used during this stage to quickly filter out unwanted effects so that attention can then be focused on the more important ones. The design matrix for 2^2 designs is shown in **Figure 8.2**. Full factorial two level experiments are also referred to as 2^k designs where k denotes the number of factors being investigated in the experiment. A full factorial two level design with k factors requires 2^k runs for a single replicate.

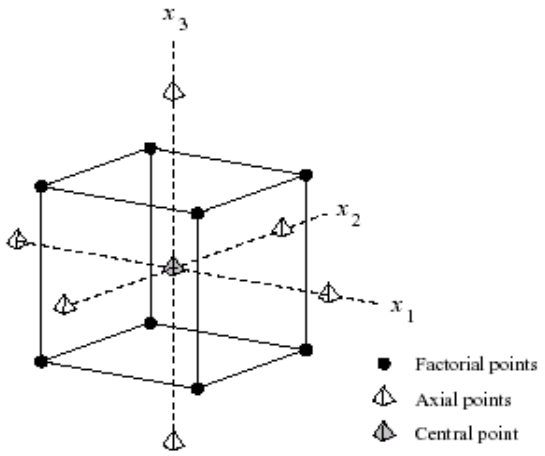

Figure 8.2. 2N Factorial Design

For example, a two level experiment with three factors will require 2^3= 8 runs. The choice of the two levels of factors used here depends on the factor itself. Some factors naturally have two levels. For example, if gender is a factor, then male and female are the two levels. For other factors, the limits of the range of interest are usually used. For example, if drying temperature is a factor that varies from 45°C to 65°C then the two levels used in the 2^k design for this factor would be 45°C to 65°C. The two levels of the factor in the 2^k design are usually represented as -1 (for the first level) and 1 (for the second level).

The 2^3design is a two level factorial experiment design with three factors (say factors A, B and C). This design tests three (k = 3) main effects A, B and C; three two factor interaction effects AB, BC, AC and one three factor interaction effect, ABC. The design

requires eight runs per replicate. The eight treatment combinations corresponding to these runs are - (abc), a, b, ab, c, ac, bc and abc. It should be observed here that the treatment combinations are designed in such order that factors are introduced one by one with each new factor being combined with the preceding terms. This order of writing the treatments is called the standard order or Yates' order. The design matrix for the 2^3 design is shown in **Figure 8.3**. The design matrix can be constructed by following the standard order for the treatment combinations to obtain the columns for the main effects and then multiplying the main effects columns to obtain the interaction columns.

The full factorial design is the most popular first-order design, in which every factor is experimentally studied at only two levels. Due to their simplicity and relatively low cost, full factorial designs are very useful for preliminary studies or in the initial steps of optimization, while fractional designs are almost mandatory when the problem involves a large number of factors. However, since only two levels are used, the models that can be fit to these designs are somewhat restricted. Consequently, if a more sophisticated model is required, as for the location of an optimum set of experimental conditions, then one must resort to designs for second-order models, which employ more than two factor levels to allow fitting of a full quadratic polynomial (Ferreiraa et al, 2007a).

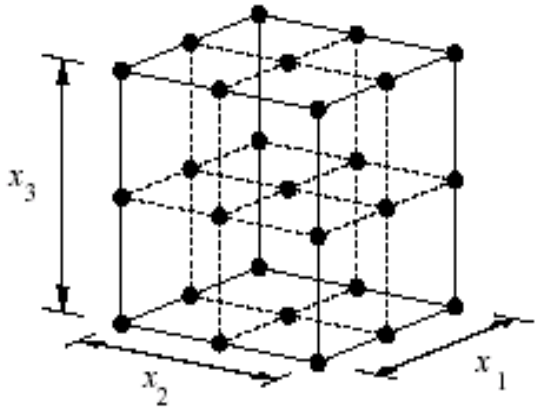

Figure 8.3. 3N Full Factorial

8.6.2. Fractional Factorial Designs

As the number of factors in a factorial design increases, the number of runs for even a single replicate of the 2^k design becomes very large. For example, a single replicate of an eight factor two level experiment would require 256 runs. Fractional factorial designs can be used in these cases to draw out valuable conclusions from fewer runs. The basis of fractional factorial designs is the scarcity of effects principle. The principle states that, most of the time, responses are affected by a small number of main effects and lower order interactions, while higher order interactions are relatively unimportant. Fractional factorial designs are used for screening experiments during the initial stages of experimentation. At these stages, a large number of factors have to be investigated and the focus is on the main effects and two factor interactions. These designs obtain information about main effects and lower order interactions with fewer experiment runs by confounding these effects with unimportant higher order interactions. As an example, consider a 28 design that requires 256 runs. This design allows investigation of 8 main effects and 28 two factor interactions. However, 219 degrees of freedom are devoted to

three factor or higher order interactions. The full factorial design can prove to be very inefficient when these higher order interactions can be assumed to be less important. Instead, a fractional design can be used here to identify the important factors that can be investigated more thoroughly in subsequent experiments. In unreplicated fractional factorial designs, no degrees of freedom are available to calculate the error sum of squares.

The fractional factorial experimental design is useful for the responses affected by two significant factors. If the response is influenced by three or more factors at a time then factorial design is unable to interpret the complex interaction between the factors affecting the same response. For this, higher order model can be employed.

8.6.3. Response surface methodology

Response surface methodology (RSM) is a collection of mathematical and statistical techniques that are useful for designing experiments, building models, evaluating the effects of factors and searching for the optimum conditions, modeling and analysis of problems in which response of interests is influenced by several variables and objectives (Montgomery, 2003, Kalil et al., 2000). By design of experiments, the objective is to optimize a response (output variable), which is influenced by several independent variables (factors). RSM can be used to evaluate the relative significance of several affecting factors even in the presence of complex interactions.

Once the important factors have been identified, the next step is to determine the settings for these factors that result in the optimum value of a response. This optimum value can either be a maximum value or a minimum value, depending upon the product or process in consideration. For example, if the response in a drying experiment is the retention of micronutrients, then the objective would be to find the settings of the factors for maximum retention of micronutrients. On the other hand, if the response in an osmotic dewatering experiment is the solid gain, then the goal would be to find the setting that minimizes the solid gain.

The multivariate approach in RSM reduces the number of experiments, improves statistical interpretation possibilities, and indicates interaction among different parameters. Combinatorial interactions of drying parameters with the quality of dehydrated product and the optimum processes may be developed using an effective experimental design procedure. Two steps are necessary, the definition of an approximation function or response and the design of the plan of experiments. These methods are exclusively used to examine the "surface" or the relationship between the response and factors affecting the response. RSM can be used for approximation of both experimental and numerical responses. Regression models are used for analysis of the response, as the focus is on nature of the relationship between the response and the factors, rather than identification of the important factors.

Response surface methods usually involve the following steps:

I. The experimental design is shifted from the current operating conditions to the vicinity of the operating conditions where the response can be optimum. This is either done by the method of steepest ascent (for maximizing the response) or the method of steepest descent (for minimizing the response).

II. Once in the vicinity of the optimum response the design needs to fit a more elaborate model between the response and the factors. Special experimental designs, referred to as RSM designs are employed. The fitted model is used to arrive at the best operating conditions that result in either a maximum or minimum response.

III. It is possible that a number of responses may have to be optimized at the same time. For example, in a drying experiment the goal may to optimize drying temperature, product quality parameters like rehydration ratio, % retention of active nutrient etc. The optimum settings for each of the responses in such cases may lead to conflicting settings of the factors. Hence, a balanced selection has to be found that will give the most appropriate values for all the responses. Desirability functions are the ones used in these cases.

Overview of the Method

- Suppose y = y (a, b, c ...), where, y is the outcome or result or response which is to be optimized, and there are 'n' parameters, a, b, c ... which can be varied.

- In these notes, it is assumed that the optimum 'y' is the maximum 'y'. Similar analysis can be done for minimizing 'y'.

- The goal of RSM is to efficiently hunt for the optimum values of a, b, c ... such that 'y' is maximized or minimized.

The response can be represented graphically, either in the three-dimensional space or as contour plots that help visualize the shape of a response surface. Contours are curves of constant response drawn in any two variables' plane (x_i, x_j), keeping all other variables fixed. Each contour corresponds to a particular height of the response surface. Generally, the structure of the relationship between the response and the independent variables is unknown. The first step in RSM is to find a suitable approximation to the true relationship. The most common forms are low-order polynomials (first or second-order).

RSM is an important tool for optimization of a response from 3-4 important factors. Criteria for optimal design of experiments by response surface methodology are associated with the mathematical model of the process. Generally, these mathematical models are polynomials with an unknown structure, so the corresponding experiments are designed only for a particular problem. The choice of design of experiments can have a large influence on the accuracy of the approximation and the cost of constructing the response surface.

8.6.3.1. Central Composite Design

Central composite design (CCD) is the most widely used response surface design. Although rotatability is a desirable property of a central composite design where there is a difficulty in extending the star points beyond the experimental region defined by the upper and lower limits of each factor, a face-centered design can be used (Tsapatsaris & Kotzekidou, 2004). A second-order model can be constructed efficiently with central composite designs (CCD) (Montgomery and Douglas, 1997). CCD are first-order (2N) designs augmented by additional centre and axial points to allow estimation of the tuning parameters of a second-order model. **Figure 8.3** shows a CCD for 3 design variables. In **Figure 8.2**, the design involves 2N factorial points, 2N axial points and 1 central point. CCD presents an alternative to 3N designs in the construction of second-order models

because the number of experiments is reduced as compared to a full factorial design (for three variable system, 15 in the case of CCD compared to 27 for a full-factorial design). Generally, for a large number of variables, the number of experiments grows exponentially and becomes impractical. A full factorial design typically is used for five or fewer variables. Factorial designs and CCD can be used for fitting second-order models. A second-order model can significantly improve the optimization process when a first-order model suffers lack of fit due to interaction between variables and surface curvature. A general second-order model is defined as:

$$y = a_0 + \sum_{i=1}^{n} a_i x_i + \sum_{i=1}^{n} a_{ii} x_i^2 + \sum_{i=1}^{n}\sum_{i=1}^{n} a_{ij} x_i x_j \quad (i<j)$$

Andrade and Flores, 2004 have used RSM for optimization of spray drying of Roselle extract (*Hibiscus sabdariffa*). Optimization of spray drying process for Inulin obtained from chicory root extract was done by RSM by Nogueira et al. (2000). Brodhead et al. (1994) have suggested the use of multifactorial approach using factorial and or composite design because of the number of the effects involved in spray drying. **Table 8.3** lists some of the different application of CCD in Food dehydration (Mason et al., 2003; Antony, 2003; Montgomery, 2003).

Table 8.3. Applications of statistical designs for food dehydration in the literature

Reference	Design	Drying material & method	Factors & levels	Response
Koc et al, 2010	Central Composite rotatable design (CCRD)	Spray drying of yogurt for determination of optimum processing conditions	The inlet (150-180° C) and outlet air temperatures (60-90° C) and the feed temperature (4-30° C)	Maximum survival ratio of lactic acid bacteria, maximum overall sensory attributes, minimum color change, and acceptable moisture contents
Jadhav et al., 2010	RSM, central composite design	Optimization of pretreatment prior to solar cabinet drying of green peas.	Blanching time (1-5 min) and potassium metabisulphite (KMS) concentration (0.2-0.5%)	Color, hardness, rehydration ratio, shrinkage, overall acceptability
Han et al., 2010	RSM, orthogonal rotatable central composite design	Optimization of process parameters for microwave vacuum drying of apple slices	Microwave power (8-16 W/g) , vacuum level (0.075-0.095 MPa) , and initial moisture content (0.3-1 kg/kg db)	Drying time, sensory quality and porosity.
Giri & Prasad 2007	RSM	Optimization of microwave-vacuum drying of button mushrooms	Microwave power level (115 to 285 W), system pressure (6.5 to 23.5 kPa), and slice thickness (6 to 14 mm)	Color, texture, rehydration ratio, and sensory attributes
Birchal et al, 2005	Full factorial design	Optimization of conditions for spray drying of milk	feed flow rate, the atomization rotation and the inlet air temperature	Residual moisture content, tapped bulk density, cohesion force enhancement

				between particles, size distribution of agglomerate and its morphology
Medeiros et al, 2002	2^4 factorial design	Optimization of drying of pulps of tropical fruits in spouted bed and effect chemical composition of pulps on the spouted bed performance	Glucose, starch, pectin, citric acid, olive oil and Mango fibers.	Efficiency of powder production, Stable spout pressure drop and minimum spouting flow rate
Zakhia et al, 1995	RSM	Optimization of fish drying with combination of RSM and diffusional models	Temperature, relative humidity, velocity	Drying time, coefficient of internal diffusion and external diffusion
Corzo et al, 2008	RSM Rotatable CCD	Optimization of conditions for thin layer drying of coroba slices.	air temperature, air velocity and drying time	Final moisture content, drying rate, energy efficiency and energy efficiency
Hammami & Rene, 1997	RSM two factor quadratic model	Optimization of freeze drying conditions for strawberries	pressure and heating plate temperature	Product qualities such as appearance/shape, color, texture, rehydration ratio
Manivannan &Rajasimman, 2010	RSM, CCD	Optimization of osmotic dehydration of radish in sugar solution	Temperature (25 - 45°C), processing time (30-150 minutes), sugar concentration (20 - 60% w/w), solution to sample to ratio (5:1 - 25:1 w/w)	Water loss, solute gain, and weight reduction
Singh et al., 2010	RSM face centered CCD	Optimization of osmotic dehydration process of carrot cubes	osmotic solution concentration (5-15%w/v), temperature (35-55°C) , process duration (120-240. min)	water loss, solute gain, retention of colour, and sensory score
Granato et al., 2010	RSM	Physicochemical optimisation of soy-based desserts	soy protein (SP) (1%, 2%, 3%) and guava juice (GJ) (22%, 27%, 32%)	Water activity, physical stability, colour, acidity, pH, iron, and carotenoid contents
Kumar et al., 2010	RSM CCRD	Optimization of processing conditions for extruded products	Moisture content (17-21%), screw speed (270-310 rpm) and die temperature (110-130°C)	Lateral expansion, bulk density, water absorption index, water solubility index, hardness, sensory characteristics
YaGci & Gogus, 2009	RSM	Optimization of processing conditions for extrusion of fruit waste with hazelnut flour and durum flour	Moisture content of blend (12-18%), barrel temperature (150-175 ^{0}C), screw speed (200-280 rpm)	Radial expansion ratio, color, and textural and sensory properties
Saxena et al.,	RSM	Optimization of	osmotic concentra-	maximum water loss,

2009		osmotic dewatering conditions for Jackfriut	tion, temperature, and duration of immersion	overall acceptability, minimum solid gain
Farris and Piergiovanni, 2009	RSM	Optimization of manufacture of almond paste cookies	Weight of bamboo fiber, fructose/saccharose ratio (F/S), weight of egg white as ingredients, baking time, baking temperature	Product quality, texture, moisture content , color
Eren and Ertekin, 2007	RSM	Optimization of osmotic dehydration of potato	Temperature (20-60 °C), processing time (0.5-8 h), sucrose (40-60% w/w), salt concentrations (0-15% w/w)	water loss, solid gain , weight reduction, water activity
Huang et al., 2006	RSM	Optimization of operating conditions for extruded snack food with tomato powder	Screw speed, moisture content, tomato powder content	Radial expansion ratio , bulk density, degree of gelatinization, water , absorption index , hardness
Zhu and Pan, 2009	Factorial design (3 factors)	Optimization of infrared blanching and drying conditions for Apple slices	Radiation intensity, slice thickness and processing time	Heating and drying rates, product temperature, moisture reduction, residual polyphenol oxidase, peroxidase activities, surface color change
Ito et al., 2007	Fractional factorial design (2^{5-1})	Optimization of pulsed vacuum osmotic dehydration of mango slices	Temperature, Vacuum time, solution concentration, Osmotic recirculation, vacuum pressure	Water loss, solids gain, water activity, and the effective diffusivities of the water or solids
Madamba and Lopez, 2002	Fractional factorial design (3 level, 4 parameters)	Optimization of the osmotic dehydration of mango slices	Treatment time, temperature, sugar concentration , slice thickness	weight reduction , sugar gain , final moisture content, overall product acceptability
Lopes et al, 2006	Full factorial design	Optimization of operating conditions for drying of Mango pulp in spout fluidized bed	Process temperature, feed flow rate, spout, annular gas velocity	Efficiency of powder production, product moisture, feed, process time
Chegini and Ghobadian, 2005	Full factorial design	Optimization of spray drying conditions for Orange juice powder	Feed ratio, atomizer speed, inlet air temperature	Particle size, average time of wettablity, insoluble solids, bulk density and moisture content of the powder

8.6.4. Taguchi Design

One widely used Japanese quality-improvement philosophy, the Taguchi approach, has statistical design of experiments as its core. Once an optimum value of the response has been achieved, the next goal of experimentation is to make the optimum response value insensitive to the noise factors so that a consistent performance is obtained at all times. For example, if the yield from a spray drying process has been optimized at 95%,

then this value of yield should be obtained regardless of the variation in factors such as the quality of raw materials or fluctuations in humidity or other weather conditions. These factors, that are called noise factors, are beyond the control of the operator. Therefore, the product or process should be such that it is not affected by minor fluctuations in these factors. The process of making a system insensitive to noise factors is referred to as Robust Design. Robust design was pioneered by the Japanese industrialist Dr. Taguchi in the 1980s.

Taguchi's approach to achieve a high quality system consists of three stages, namely, system design, parameter design and tolerance design.

I. System design: The stage when ideas for a new system are used to decide upon the combinations of factors to obtain a functional and economical design.

II. Parameter design: The stage when factor settings are selected that make the system less sensitive to variations in the uncontrollable factors affecting the system. Therefore, if this stage is carried out successfully, the resulting system will have little variation and the resulting tolerances will be tight.

III. Tolerance design: The final stage when tolerances are tightened around the best value. This stage increases cost and is only needed if the required quality is not achieved during parameter design. Thus, using parameter design, it is possible to achieve the desired quality without much increase in the cost.

Taguchi divided the factors affecting any system into two categories control factors and noise factors.

a) Control factors: The factors affecting a system that are easily set or controlled by the experimenter. For example, if in a drying process the drying time is found to be a factor affecting the product quality, then this factor is a control factor since it can be easily manipulated and set by the experimenter. The experimenter will choose the drying time that improves the product quality.

b) Noise factors: The factors affecting a system that are difficult or impossible to control. For example, ambient temperature and humidity may also have an effect on the drying time of a fruit pulp, but ambient temperature and humidity could be a noise factor if it is beyond the control of the experimental settings. Thus, change in ambient temperature and humidity will lead to variations in the drying time but such variations are undesirable.

Taguchi studied the interaction between the control and noise factors using two experiment designs viz; Inner array and outer array. The inner array is essentially any experimental design that is used to study the effect of the control factors on the response. Taguchi then used an outer array for the noise factors so that each run of the inner array was repeated for every treatment of the outer array. The resulting experiment design, that uses both inner and outer arrays, is referred to as a cross array.

8.6.5. Box-Behnken designs

Box-Behnken designs (BBD) are response surface methodology rotatable second-order designs based on three-level incomplete factorial designs. It is used to study the quadratic effect of factors after identifying the significant factors using factorial experiments. The special arrangement of the BBD levels allows the number of design points to

increase at the same rate as the number of polynomial coefficients. For three factors, for example, the design can be constructed as three blocks of four experiments consisting of a full two-factor factorial design with the level of the third factor set at zero. The number of experimental points (N) is defined by the expression $N = 2k (k - 1) + C_0$, where k is the number of variables and C_0 is the number of center points.

Advantage of the BBD is that it does not contain combinations for which all factors are simultaneously at their highest or lowest levels. So these designs are useful in avoiding experiments performed under extreme conditions, for which unsatisfactory results might occur. Conversely, they are not to be used for situations in which the aim is to know the responses at the extremes, that is, at the vertices of the cube. BBD for four and five factors can be arranged in orthogonal blocks. Because of block orthogonality, the second-order model can be augmented to include block effects without affecting the parameter estimates, that is, the effects themselves are orthogonal to the block effects. This orthogonal blocking is a desirable property when the experiments have to be arranged in blocks and the block effects are likely to be large (Box and Behnken, 1960).

The Box-Behnken is a good design for response surface methodology because it permits:

- Estimation of the parameters of the quadratic model;
- Building of sequential designs;
- Detection of lack of fit of the model; and
- Use of blocks.

8.6.6. Evolutionary operation Approach

Evolutionary operation approach (EVOP) is used as an experimental strategy when only two or three factors can be varied at a time, and only small changes in the factor levels can be tolerated. As such, EVOP is a hybrid of on-line and off-line quality improvement techniques. Two-level factorial experiments around a center point are typically used. As operating conditions that lead to improved process characteristics are identified, the experimental region is moved to explore around this new set of conditions. This procedure is repeated until no further improvement is obtained (Mason, 2003).

However, certain risks are inherent due to exploring a limited experimental region and a small number of factors. A consequence of the EVOP approach for process improvement is that many repeat test runs are needed at each set of factor–level combinations. This large number of repeat tests is needed because factor levels can only be changed by small amounts so that existing quality levels will not be seriously degraded at some of the factor–level settings. Because of this requirement, there is a weak "signal" (change in the response) relative to the "*noise*" (experimental error or process variation). This usually results in the need to collect many observations so that the standard deviations of the statistics used to measure the effects are sufficiently small and statistically significant effects can be detected (Antony, 2003 & Montgomery, 2003).

8.6.7. Plackett-Burman design

Plackett-Burman design is used to determine the most influential factors on the process and their levels. Plackett-Burman orthogonal designs (Plakett and Burman,

1994) work at two levels, and can be constructed on the basis of fractional replication of a full factorial design. This design allows reliable short listing of a small number of ingredients for further optimization and allows one to obtain, unbiased estimates of linear effects of all the factors with maximum accuracy for a given number of observations, the accuracy being the same for all effects (Akhnazarova and Kafarov, 1982).

8.6.8. Doehlert design

Doehlert (1970) proposed an alternative and very useful experimental design for second-order models is the uniform shell. Doehlert designs are easily applied to optimize variables and offer advantages in relation to central composite and Box-Behnken designs. They need fewer experiments, which are more efficient and can move through the experimental domain. Despite these attractive features, it took some time until researchers started to take notice of Doehlert designs (Ferreira et al, 2004).

For two variables, the Doehlert design consists of one central point and six points forming a regular hexagon, and therefore situated on a circle. In three dimensions it can be viewed in different ways, depending on the geometric structure selected (Garcıa Campana et al, 1997). In Doehlert designs the number of levels is not the same for all variables. In a two-variable Doehlert design, for example, one variable is studied at five levels, while the other is studied at only three levels. This property allows a free choice of the factors to be assigned to a large or small number of levels. Different criteria can be used to assign the factors. As a general rule, it is preferable to choose the variable with the stronger effect as the factor with five levels, in order to obtain maximum information of the system.

The uniform shell design developed by Doehlert (1970) has the following characteristics:

i. Uniform distributions of the experimental points are allocated on the surface of a hypersphere.

ii. The number of experiments is given by N2 + N+1, where N is the number of variables under study.

iii. Each factor is analyzed at different number of levels. This particular characteristic is relevant when some factors have certain restrictions such as cost or instrumental constraints, so their study with a small number of levels is necessary

iv. Extension of the experimental matrix to another experimental domain may be done by using previous adjacent points.

Many of the papers reporting the use of a Doehlert matrix involve the optimization of a process controlled by only two variables, for which seven experiments are required (Ferreira et al, 2004). Doehlert design belongs to the category of simultaneous designs, whose basic idea is to record one or more selected experimental responses for a set of experiments carried out in a systematic way, in order to predict the optimum and the interaction effects using regression analysis (Araujo and Brereton, 1996). This design offers advantage in relation to other second order models such as central composite design (CCD) and Box Behnken design (BBD), as they need fewer experiments, which are easier and more efficient.

8.7. FREQUENT DESIGN TROUBLES

In the experimental design, statistical analyses of the results are often inconclusive or, misleading if statistical considerations are not incorporated. Below are few of many potential problems that can occur when statistical methodology is not used to design drying or food engineering experiments.

8.7.1. Experimental variation masking factor effects

Researchers often invest substantial project funds and a great amount of time and effort only to find that the research hypotheses are not supported by the experimental results. Many times the lack of statistical confirmation is the result of the inherent variability of the test results.

For example, color kinetics during drying of Sapota fruit there can either be a variation among different test runs due to experimental procedures or variation in the raw material source and even maturity of the fruit can change the color estimation. Experiments that are intended to study factor effects (e.g., drying time) on fruit color must be designed so that the variation in subjects and across time does not mask the effects of the experimental factors.

It should be noted that, the experimental error variation must be considered in the statistical design of an experiment. Failure to do so could result in true factor effects being hidden by the variation in the observed responses.

8.7.2. Uncontrolled factors compromise experimental conclusions

Sometimes researchers would intentionally ignore factors that are known to exert important influences on a response; there are many subtle ways in which failure to carefully consider all factors of importance can compromise the conclusions drawn from experimental results.

Consider, for example, an experiment conducted to compare color changes in L, a, b values during hot air drying of Sapota pulp. Suppose that an adequate experimental design has been selected, including a sufficiently large number of test runs. **Figure 8.4** exhibits actual results of such a test run. One of the important conclusions that can be drawn from an analysis of the experimental data is that the L, a, b values decrease slightly with respect to drying kinetics and then slight increase at the end of drying.

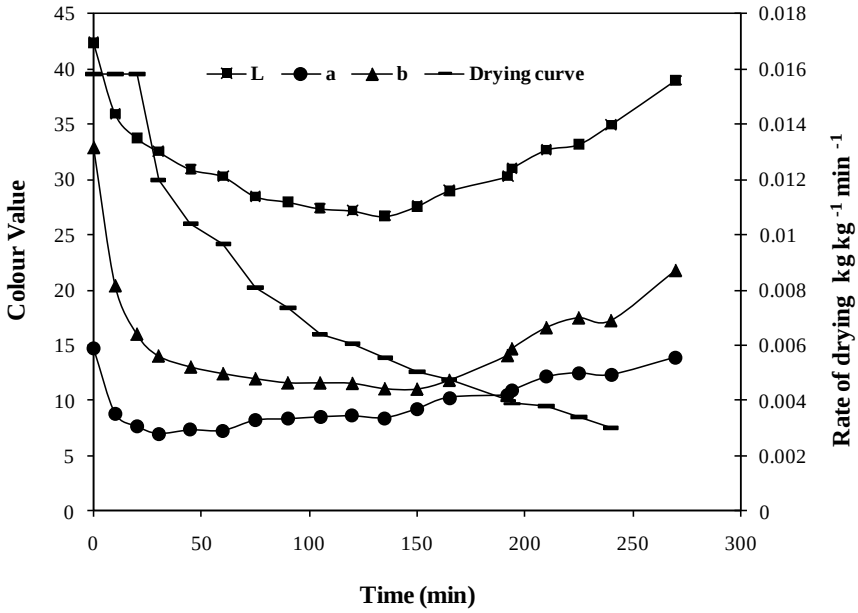

Figure 8.4. Effect of hot air drying on color values of Sapota pulp (Data from Chaughule and Thorat, Formulation, drying & nutritional evaluation of ready to eat sapota {Achras zapota} extrudes), submitted to IDS2010, proceedings)

Subsequent to a conclusion such as this, researchers often wish to determine which of several pulp properties (e.g., protein content, total sugars, etc) contribute to the reduction and slight increase in L, a, b values. The difficulty with such a determination is that the pulp properties of interest cannot all be specifically controlled in the dehydration of Sapota pulp. Because of this, many pulp properties that might subsequently be of interest simultaneously vary across the test runs, resulting in a confounding of their effects.

This experiment was specifically designed only to investigate the effects on L, a, b values during processing. Studies could be specifically designed to study some of the other product properties. In such studies the pulp properties would be varied in a systematic fashion and confounding among the properties could be eliminated by the choice of the design. Note that in this example it is the uncontrolled variation of the pulp properties that leads to the confounding of their effects on the response.

8.7.3. Incorrect principles of efficiency lead to unnecessary or inconclusive results

The aforementioned sapota pulp example demonstrates the need to construct designs in which factors of interest are systematically varied and need to consider the likely magnitude of the inherent variation in the test results when planning the number of test runs. In academic research sometime the desire to run economical experiments can lead to strategies that may in fact be wasteful or even fail to achieve the expected goals of the project. Time and cost efficiencies are always important objectives in experimental work. Occasionally efficiency becomes an overriding consideration and the project goals become secondary. If time or budgetary considerations lead to undue restrictions on the factors and levels that can be investigated, the project goals should be reeva-

luated relative to the available resources. This may lead to a decision to forgo the experimentation.

The problem of experiment efficiency is most acute when several factors must be investigated in an experiment. When guided only by intuition, many different types of designs could be proposed, each of which might lead to flawed conclusions. Some experimenters would choose to hold factors constant that could have important influences on the response whereas; other experimenters may allow many unnecessary changes of factors that are inexpensive to vary and few changes of critical factors that are costly to vary. Efficiency is achieved in statistically designed experiments because each observation generally provides information on all the factors of interest in the experiment. If each of the test factors had been investigated separately using the same number of test runs then large number of test runs would have been needed. It is neither necessary nor desirable to investigate a single factor at a time in order to economically conduct experiments. Because there is a prevalent view that one-factor-at-a-time testing is appropriate when there are several factors to be investigated (Mason, 2003).

8.7.4. Limitations of one-Factor-at-a-Time method

Most widely used experimental approach in many academic research laboratories is one factor at a time. In studies when multiple factors affect a same response this technique is very useful. Consider an experimental setting in which the goal is to determine the combinations of levels of several factors to optimize a response. The optimization might be to minimize the loss of active nutrient in a food drying process. It might be to maximize the color retention properties of the food material during drying. It might be to maximize the rehydration properties of the dehydrated food materials. In each of these examples the optimization is a function of several factors, which can be experimentally investigated. Because of the complexity of simultaneously investigating the influence of several factors on a response, it is common practice to vary one factor at a time in search for an optimum combination of levels of the factors.

The perceived advantages of one-factor-at-a-time testing are primarily two:

- The number of test runs is believed to be close to the minimum that can be devised to investigate several factors simultaneously.

- One can readily assess the factor effects as the experiment progresses, because only a single factor is being studied at any stage.

One-factor-at-a-time experimentation is not only used to determine an optimum combination of factors. Often this type of testing is used merely to assess the importance of the factors in influencing the response. This can be an impossible task with one-factor-at-a-time designs if the factors jointly, not just individually, influence the response.

The drawbacks of one factor at a time can be attributed to the single dimensional approach which is laborious and time consuming, especially for large number of variables, and frequently does not guarantee the determination of optimal conditions (Xu et al., 2003). In fact the optimal factor combinations may not be obtained when only one factor is varied at a time. Also, the combinations of levels that are tested do not necessarily allow appropriate models to be fitted to the response variable. Additional test

runs may have to be added if an estimate of experimental error is to be obtained. These limitations of one-factor-at-a-time optimization process can be eliminated by optimizing all the affecting parameters collectively by statistical experimental design (Mason et al., 2003; Dean & Voss, 1999).

8.8. STEPWISE PROCEDURE FOR EFFECTIVE DESIGN OF EXPERIMENTS

Optimization of a process is an ultimate goal in statistical design of experiment. In typical drying experiment, researchers are usually interested in determining which process variables affect the response (drying parameters). A logical next step is to determine the region of the important factors that leads to the best possible response. For example, if the response of a drying process is the retention of micronutrients then one would look for region of retention of micronutrients. Several authors reported optimization of experiments by various statistical drying process using full factorial, fractional factorial, response surface methodology and one factor at a time.

Figure 8.5 shows the steps involved in the process of optimization. Before starting any process, it is prerequisite to know the current operating conditions in the process. Commonly goal for the food drying process is based on maximum retention of micronutrients, color, texture, sweetness, principal constituents and minimum solid gain in the case of pretreatments like osmotic dewatering process. Once the response objectives are clear, various statistical tools can be employed to change the current factors settings or sometimes change of drying systems. By studying various techniques finally optimum settings can be obtained.

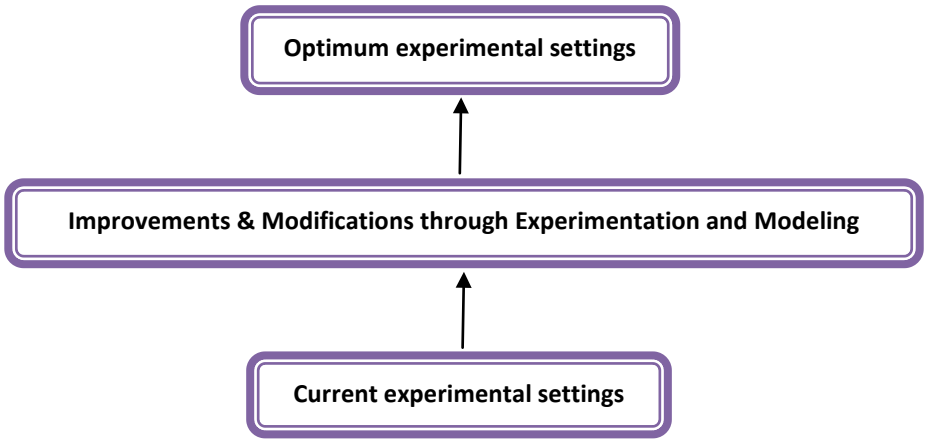

Figure 8.5. Steps in involved in optimization of a process

Figure 8.6 illustrates optimization scheme for any food, vegetable or fruit dehydration process. The first step is to study current operational settings. It is then important to select appropriate factors with most possible influential levels for the process. If the drying process is less complex and comprise of only two factors then factorial design or fractional factorial design can be employed. The first order model can be generated for the process to study the optimum. If the desired response is obtained then the process can be said to be approaching optimum. These designs are handy tool for optimizing less complicated process in short time. However, they are very cumbersome for the process affected by many factors at the same time and hence not practical. If the process is more

complex and many factors can influence the desired response then statistical tool like Plackett-Burman design can be useful. In food dehydration process, Plackett-Burman design can be used for screening of most influential factors on the response. If the process is not optimized by first order models various second order modeling designs such as Doehlert design, Taguchi design, Box Behnken design, response surface designs can be employed. The choice of the design can be made by characteristics of the desired response. Taguchi design is useful for minimizing noise factors i.e. the factors which are affecting the extent of response. For example in case of hot air drying of banana slices, if the response is optimized for certain values of air temperature and velocity. The fluctuation in relative humidity is the cause of variation in experimental settings then it is called as noise. For such problems Taguchi design is a useful tool. Response surface design is the most widely and popular design for optimization of multivariate systems. Usually processing processes affected by 3-4 factors are considered. Like all other design RSM suggests set of experiments for different levels of factors. Response surface plots can be obtained from the experimental data by fitting the second order polynomial equation. RSM plots show surface interactions amongst the factors for obtaining the desired response. However, RSM suffers from some drawbacks such as large variations in the factor levels can be misleading and can result in to error or bias. Sometimes critical factors may not be defined properly and sometimes over reliance on computer. Unlike RSM if the extreme levels for factors are not desirable then Box Behnken design can be applied. In EVOP two or more factors can be varied at a time, hence can be used in the complex systems influenced by many factors. In some cases Doehlert design may find application as it takes minimum number of experiments as compared to other second order model design. In case if one design does not satisfy the optimum point, different second order polynomial can be screened for desired optimum response.

There is no general rule for selecting a statistical design for drying of foods, vegetables and fruits. The choice of design in many cases is decided on response characteristics and feasibility of experimentation. Various DOE software are available commercially which can be employed for the above mentioned designs.

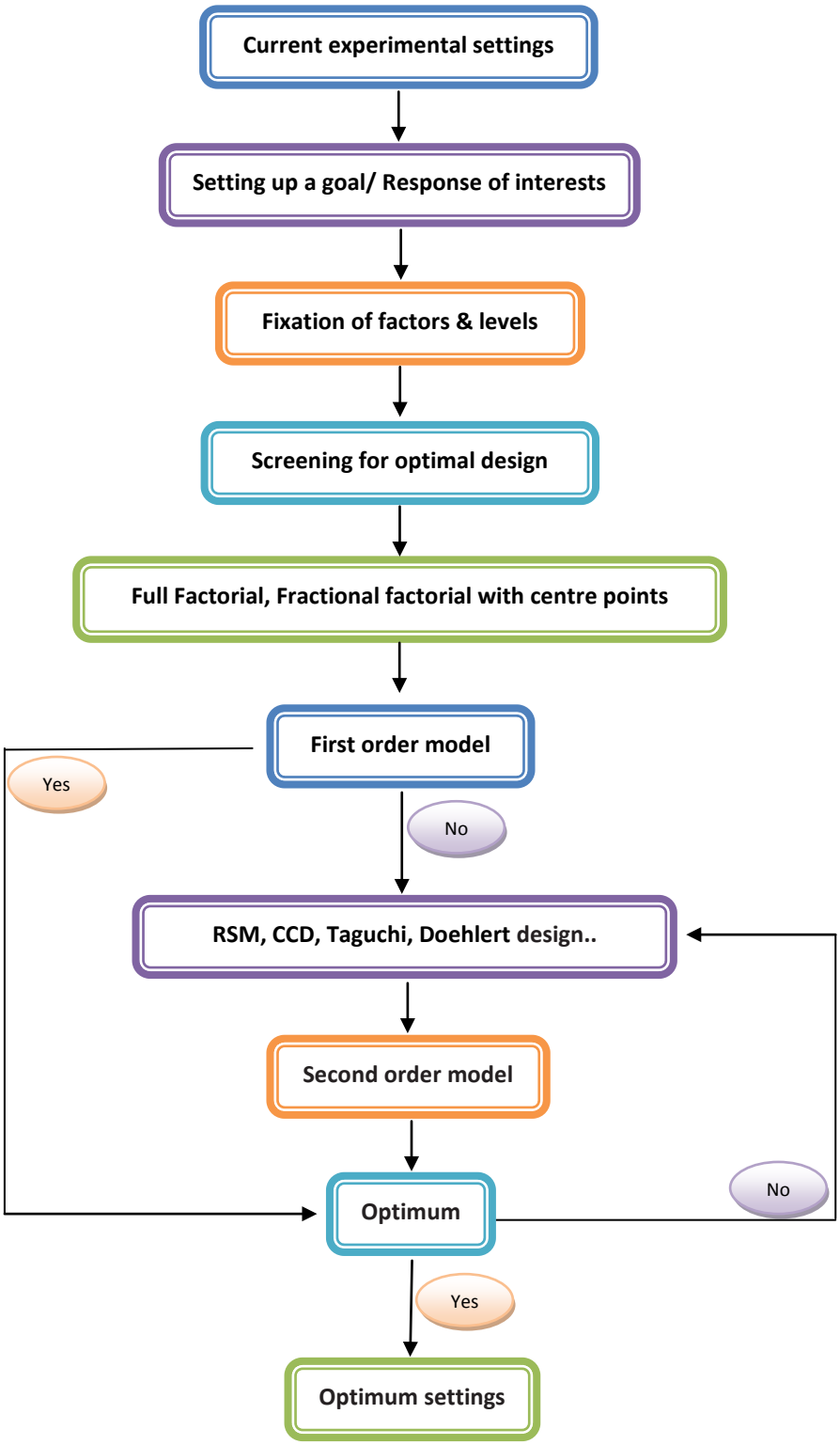

Figure 8.6. Optimization scheme

8.9. APPLICATIONS IN FOOD INDUSTRY

Intense ever increasing international competition and process economics with assurance of quality is the main driving force behind the study of industrial drying processes in food industries. Statistical design techniques can offer wide range of experimental designs to a broad range of industrial drying problems. **Table 8.3** enlists vari-

ous applications of statistical designs used in food dehydration so far available in the literature.

8.9.1. Case Studies

8.9.1.1. Optimization of spray drying of ginger extract

Jangam and Thorat (2010) have optimized conditions for spray drying of water extract of ginger. RSM with CCD was used to design the experiments. The design consisted of 30 experiments (interested readers please refer to Jangam and Thorat, 2010)with each factor varied over five levels. Air inlet temperature (120-160°C), air flow rate (40-60 Nm^3/hr), atomization pressure (1.5-2.25 kg/cm^2) and liquid feed flow rate (2.5-4 ml/min) were selected as independent variables. Moisture content, water activity, percentage retention of 6-gingerol, flowability and porosity of spray dried powder were the responses. The software used was Design expert 6.0.10.

Jangam and Thorat (2010) fitted the experimental data to a second order polynomial model and regression coefficients were obtained. The generalized second-order polynomial model used in the response surface analysis was as follows:

$$Y = B_0 + \sum_{i=1}^{4} B_i X_i + \sum_{i=1}^{4} B_i X_i^2 + \sum_{i=1}^{4} \sum_{j=i+1}^{4} B_{i,j} X_i X_j$$

Where, Bo, Bi and Bi,j are the coefficients of regression and Xi and Xj are the independent variables. The mathematical models for each response have been evaluated using multiple regression method. The significance of the equation parameters for each response variable has analyzed using the analysis of variance. Design expert software used for regression analysis, generated regression coefficients, analysis of variance and correlation coefficients for the model. The model adequacy can be checked on the basis of correlation coefficient (R^2). In the article, the optimization was carried out using numerical optimization tool, by setting the desired goal for each response variable. Optimized conditions were obtained for the criteria of minimum moisture content and water activity and maximum porosity, flowability and retention of 6-Gingerol by assigning same importance to all responses. **Figure 8.7** shows the effect of air temperature and air flow on flowability. It can be seen that there exists optima at the center for flowability. The inner circle shows the set of factor levels responsible for optimum response. Likewise, many response surface plots have been obtained for the different responses. Table Jangam and Thorat (2005) also have reported the R^2 values of the response studied which signified the accuracy of the models adapted.

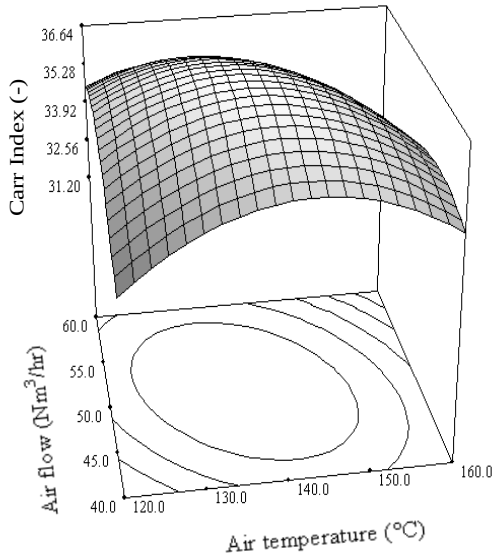

Figure 8.7. Combined effect of air flow and air temperature on Carr Index (Feed flow – 3.25 ml/min; atomization pressure – 1.88 kg/cm2)

{Adapted from Jangam and Thorat, Optimization of spray drying of ginger extract accepted for publication in Drying Technology, with permission}

8.9.1.2. Studies on Solar Cabinet Drying of Green Peas (Pisum sativum)

Jadhav et al, (2010) have optimized the pretreatment conditions for green peas prior to solar cabinet drying. Response surface methodology having a 22 factorial experimental design with four axial and five central points leading to 13 experiments were performed for the optimization of blanching time in hot water (96°C for 1-5 min) and KMS concentration (0.2-0.5%). Color and hardness of the dehydrated green peas were the responses. RSM was applied to the experimental data using a commercial statistical package, Design Expert version 7.0. The details about coded and actual levels of variables can be found elsewhere (Jadhav et al., 2010). RSM has given different combinations of different levels of the two factors studied. The optimum conditions of pretreatment before solar cabinet drying were reported as 4.24-min blanching time and 0.49% KMS concentration, resulting in 345.38 g hardness and 19.92mg/100 g color (Jadhav et al, 2010).

CLOSING REMARKS

The application of statistical designs for optimization of drying processes and their utility in drying R & D is still in its early years. An attempt is made here to compile statistical optimization designs for potential relevance in food processing R & D.

Optimization using factorial design is a rigorous and simple method to find the adequate experimental conditions to produce the best response of the drying system. Factorial designs can be used for screening purposes to identify the factors affecting the selected response and as a tool to explore and model this response as a function of these significant experimental factors. The use of multilevel designs allows an efficient exploration of the response in the experimental region and the estimation and optimization of

the response function. The second-order model is the most applied empirical model. This kind of model showing a suitable quality is required to obtain the response function. The most commonly applied designs are three-level factorial designs, central composite designs, Box-Behnken designs, and Doehlert matrixes. The choice of the response variable is an important step in the optimization.

Together these experimental designs can be used to determine process conditions for achieving the target value and to identify variables that can be controlled to reduce variation in key performance characteristics. It is important to note that these new philosophies and experimental strategies have been highly promoted primarily because of the renewed emphasis on product quality improvement as a means to attain competitive advantage.

All the procedures recommended, including screening experiments, factorial experiments, and specialized designs, can be used in suitable quality-improvement settings. The responses of interest in quality-improvement studies include both measures of product or process location and measures of dispersion. Many times the goal may not be to find optimal points (maxima or minima) in the response surfaces that coincide, but rather to locate flat regions that give stability of the responses. This is particularly true in product design (robustness) and process design (process control).There are various software commercially available for design of experiments such as start ease, statagraphics etc.

The reason for the recent popularity of these statistical and experimental strategies is the competitive environment of today's marketplace in many manufacturing and food process industries. The statistical design techniques discussed here in this chapter can be used to determine desired factor settings so that a process average or a quality characteristic of key product properties are close to the target (on aim) and the variability is as small as possible.

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Chapter 9
Current State of Global Research and Development in Drying

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Contents

9.1. INTRODUCTION

Given the diversity of the 50,000 or so materials that are dried commercially at various scales for a variety of reasons, the wide range of drying times required, the diverse physical forms of the materials dried and the multitude of quality constraints required to be met for the dried products, it is not surprising that literally hundreds of dryer types are in use today. Drying is a highly energy-intensive operation that also determines the quality of most products that are dried. It combines transport phenomena with material science. Since fossil fuels are commonly used as the energy source for dryers, drying also has important environmental implications. It is estimated that from 9-25% of the national industrial energy consumption is attributed to thermal dehydration in developed countries. This wide range is a result of the fact that different industrial sectors have widely varying demands as far as drying is concerned, ranging from a high of 35% in papermaking to just over 3% in the chemical process industries. Also, the thermal efficiencies of dryers in use today range from a low of around 20% to a high of 80%; the latter is difficult to achieve and is most common for indirect dryers which have so far limited industrial applications today.

It is interesting to note that about one ton equivalent of oil is consumed for, on average, six tons of water removed by thermal dehydration. Since it has already been shown that there is a positive correlation between the amount of water removed in industrial processing and the GDP (or standard of living) of the country it is clear that efforts must be made to improve the drying processes as the large developing economies of the world will soon make accelerating demands on fossil fuels to provide the energy for drying in various industrial sectors.

Drying is crucial to food preservation and agricultural processing. Thus, it is also at the heart of the nexus of food, water and energy. Combustion of fossil fuels leads to emissions of greenhouse gases (carbon dioxide, in particular) as well as noxious gases and odors. It is obvious that the environmental impact of drying must deserve attention of all governments and granting agencies in the immediate future. It is hoped that legislative requirements will be placed on thermal performance of industrial dryers in coming decade so dryer vendors and users will pay special attention to energy consumption just as consumers today look at energy consumption ratings of domestic appliances like TV, clothes dryers and washers. This will encourage R&D required to enhance dryer performance and discourage non-optimal operation of existing dryers. Carbon footprints of dryers per unit of water removed should be placed on boiler-plate so that the buyers are aware of the performance of the units they wish to install.

This chapter summarizes attempts, principally by the author, in the past thirty eight years to promote and encourage drying R&D across industrial sectoral as well as geopolitical boundaries and the results of these attempts. It is impossible to cover all aspects of the subject, however. Over 80 percent of the scientific, technological and engineering literature in the field of drying has appeared in the past two decades. There has been rapid growth in technical literature on drying during 1980- 1996 when it seems to have peaked. Fortunately, the publication rate has not subsided but reached a plateau. This implies that much is now known about various dryers and this knowledge has entered

the implementation phase since only generating new knowledge is not enough; it must be applied in practice for societal benefit.

What is remarkable about this development is that it has occurred over the whole world; indeed the slack in drying R&D experienced over the past decade in the western countries and Japan has been more than compensated for by increase in such activity in the developing economies of the world, with one notable exception of India. Still, over 250 patents are granted annually by the US Patent Office and about 100 by the European Community Patent Office. These numbers are a testimonial to industrial interest in drying technology development. The corresponding numbers for other unit operations which are more in vogue in academia, e.g., adsorption, crystallization, membrane separations, are each about an order-of-magnitude lower. The negative correlation between the academic activity and industrial patent activity is probably a result of lack of proactive interaction between industry and academia, which the author has termed in earlier publications as a "closed loop" model of academic research leading to "research by academics and for academics." For an applied discipline like drying technology lack of industry-academic interaction can have serious negative effects. Faculty members must be attuned to industrial needs to carry out relevant research and solve real- not imaginary-problems. Pie-in-the-sky curiosity-driven research projects are the realm of pure sciences which are funded independently; engineering and technological R&D must have practical relevance to justify continued support by tax-payers and industry. Impact of such research should be measured not by impact factors of journals papers are published in or the citation counts- not even the so-called over-hyped "h" factor-but by its real life applications. We need measures to assess engineering research and credit it properly.

9.2. A HISTORICAL PERSPECTIVE

It was early in the seventies that I carried out my first detailed literature search of on all aspects of drying. This was in itself a massive task as it involved long days and nights at the library and extensive snail mail correspondence even beyond the "iron curtain". I was perplexed by the lack of scientific literature in the English language at that time. Much of the scientific and engineering literature on drying appeared in Russian, Japanese, German, Polish, Hungarian and French. Despite the fact that drying is a key operation in almost all industrial sectors, consuming the most energy and often determining the quality of the product, it is astonishing that the academic research community worldwide, with some notable exceptions, had ignored drying as a research and development area worth pursuing. I also noticed that several industrial sectors shared common drying problems and indeed technologies but were happily unaware of the developments in other sectors. The need to bring together R&D personnel, technologists, vendors of drying equipment as well as academics under one umbrella was obvious. Vision is defined as the ability to see the invisible. To me the need for consolidated R&D in drying seemed too obvious to be considered as a "visionary development". I believe dryers were simply built rather than designed when the oil price was in lower single digits and no one worried about the finite extent of fossil fuel reserves the earth has. No one imagined the future needs of the most populated parts of the world which will strain

the reserves severely decades later. Certainly there was global scale lack of vision in this area.

The energy crisis of the early seventies gave real impetus to recognition of drying as a worthwhile R&D area by industry, especially in industries where drying was a key and costly operation e.g. in pulp and paper, wood, foods etc. This led me to develop and found the idea of providing a forum for exchange of ideas, research results as well as technology transfer between academia and industry. The idea was (and still is) to acquaint academics with industrial needs in the inter- and cross-disciplinary area and to familiarize the industry with current R&D. It also turned out to be an excellent forum for collaboration between researchers from various parts of the world. Much of the earlier work carried out in non-English speaking countries became widely accessible as a result and indeed the researchers from these countries became recognized in the western world as well – a direct consequence of this truly global forum.

The First International Symposium on Drying, its official title at the time, was announced in spring 1977 and held in August 1978 on the campus of McGill University in Montreal, Canada. Fortunately, despite the short induction time, it turned out to be a success, thanks to sponsorships by several large companies and several professional societies. Some 210 participants from 22 countries attended the meeting. A formal proceedings volume was published, it contained only about 40 papers although about twice as many were presented at the meeting; most of the remainder appeared in Drying'80, Vol. 1. A forum was held on R&D Needs and Opportunities which reflected strong industrial interest and accentuated the need for a forum devoted to exchange of information on drying regardless of geographical, disciplinary and industrial sectoral boundaries. Thus, the food or textile industry could benefit from advances made by the paper industry in drying of continuous sheets, for example. It was recognized then that drying is a truly inter- and multi-disciplinary field that can only advance by sharing the expertise in different disciplines and industries. Indeed, there is no major industry that does not utilize drying processes at some stage of their manufacturing sequences.

One unique feature of the first symposium was the fact that it attracted a greater number of participants from industry rather than academia (112 from industry and government laboratories and 98 from academic institutions). It was clear that industry was well aware of its drying R&D needs while the academic world was not quite active in the field probably as a result of years of traditional isolation from the industrial environment. Without exception academic participation exceeded the industrial one in all later IDS meetings. I believe a balanced participation is the key to success in effective technology and knowledge transfer and IDS must endeavor to correct this anomaly in the future. Curiously, IDS also stands for IDEAS. Indeed, in this respect IDS has been a remarkable success story involving over 50 countries. It is the only series of international symposia in a traditional area that has continued unabated-and indeed growing and multiplying- for over three decades. Most specialized conference series fold in about a decade as new areas emerge and supplant the old ones.

Subsequent evolution of the IDS series, as indicated in Table 1, clearly shows the rising interest in drying R&D by both academia and industry on a truly global scale. Participation by industry demonstrated the need for better understanding of various drying processes and the numerous challenging problems in drying. The academic community

benefited by being exposed to industrial needs so that they could develop new viable research programs. Cross-fertilization of ideas occurred as participants from different disciplines, different countries and different industries inter-mingled and readily appreciated the commonality of several drying problems they had thought to be the exclusive domains of their discipline or industry. This awareness also helped develop research collaborations and avoid unnecessary duplication of research efforts. Many vendors of drying equipment presented technical aspects of their new drying equipment while many academic researchers have put forward truly innovative new concepts for dryer design that the vendors should try to commercialize.

Without significant industrial participation there is a danger that academic researchers will follow what I call a "closed-loop" approach to research. Basically it leads to academic research by academics and for academics. In an applied field such as drying results of research are wasted if they are not used by industry in some fashion. In the closed loop approach one academic paper spawns another and this sequence continues indefinitely until, perhaps, research funds run out. While this does lead to a larger citation frequency the results are typically wasted. What we really need to assess drying research (and indeed any other applied research) is a "utilization index" and not a citation index since only another academic can typically cite a published paper. I believe that IDS provides an opportunity for the academic to interact with its industrial counterpart and familiarize himself/herself with real world problems awaiting effective solutions. It is hoped that dryer vendors will take advantage of the IDS and its sister series of symposia to obtain new ideas for design, optimization, control etc.

Table 9.1. List of IDS Series/Venues

Year	Event
1977	International Symposium on Drying announced in March
1978	**First Symposium held at McGill University, Canada**
1980	Second Symposium held also in Montreal
1982	Birmingham, UK – Symposium series goes global
1984	Kyoto, Japan – Term IDS used for first time
1986	Cambridge, USA – Major Awards initiated
1988	Versailles, France
1990	Prague, Czech Republic – First time IDS was part of a major international conference (CHISA'90)
1992	Back to square one: Montreal, Canada
1994	Gold Coast, Australia
1996	Krakow, Poland
1998	Halkidiki, Greece

2000	Noordwijkerhout, The Netherlands
2002	Beijing, China
2004	Sao Paulo, Barzil
2006	Budapest, Hungary
2008	Hyderabad, India
2010	Magdeburg, Germany

A careful reading of the technical programs of all the IDS events held so far clearly demonstrates a change in the themes and the relative significance of various topics in time and with the geographical location. While in early years energy savings and scale-up procedures for dryer design were prominent topics, in recent years it is quality aspects, optimization via mathematical models and development of novel drying techniques. It seems that modeling drying at the microscopic level has remained a formidable task over the past decade with only a few research groups around the world devoting serious attention to the subject.

Since energy and environment are closely intertwined the interest in making drying more efficient will continue to rise, however. Combustion of fossil fuels used for drying inevitably leads to generation of greenhouse gases – a topic of considerable contemporary interest. Also, use of heat pumps in drying systems is expected to show an increase. Also, the need to make dryers safe, environmentally friendly with smaller carbon footprints while giving high quality product requires investment of R&D resources.

The number of participants, number of countries represented as well as the number of papers presented have all shown steady rise over time with occasional dips related mainly to the geographical location of the specific IDS. Each meeting has had a good distribution of attendees from industry and academia although, for more effective technology transfer, we ought to seek greater industrial participation. IDS series is grateful to the companies that have supported IDS either directly or indirectly through the Major Awards program. Such sponsorship gives the right signal to those participants from industry who need to justify their participation in a meeting such as the IDS.

Some countries have traditionally been more active in drying R&D relative to others, e.g., France, Poland and Canada. The drying activities in the USA have traditionally been at a level one would expect on the basis of papers presented at IDSs and published in Drying Technology – An International Journal. In general there is a rise in interest in drying R&D in Latin America, Asia and Australia while it appears to be steady in other continents. In fact, IDS has spawned other major meetings of a regional nature, e.g., the Inter-American Drying Conference (IADC) held in Itu, Brazil in July 1997 followed by a series of regional drying conferences in Inter-American region, IADC'2001 (Veracruz, Mexico), IADC'2005(Montreal, Canada), IADC 2009 (Montreal) and the Asian-Australian Drying Conference (ADC'99) held in October 1999 in Bali, Indonesia followed by a series of regional drying conferences in Asia-Pacific region, ADC'2001 (Penang, Malaysia), ADC'2003 (Bangkok, Thailand), ADC'2005 (Kolkata, India), ADC'2007 (Hong Kong) as well as Nordic Drying conferences which have been held in Trondheim, Norway (2001), Copenhagen, Denmark (2003) and Karlstad, Sweden (2005). As this chapter went to the

publisher for printing in Sep 2008, ADC 2009 (Bangkok, Thailand) and IADC 2009 (Montreal, Canada) have already been held successfully. ADC2011 in Tianjin, China will show case the rising economic muscle of Asian Tiger economies once again. Separate drying conferences are held biennially in P.R. China reflecting the high level of interest and activity in drying in that country. On the other hand, a large nation like India appears to have little academic and industrial activity in drying R&D. Further, participation from the middle eastern countries as well as from the great continent of Africa has traditionally been at a low level as well.

As far as industrial sectors are concerned, food and agriculture remain the most dominant sectors in view of the critical importance of drying to their industry – typically over 50 percent of the IDS content is devoted to this area. Regrettably there is a decline in R&D activity in the paper drying area after several attempts to commercialize several new drying concepts for the modern paper machine failed in the seventies and eighties. Drying of wood is a major problem of great interest to the forest products industry. However, IDS has had to contend with biennial meetings which deal exclusively with wood drying which have in recent years been held at about the same time but in different parts of the world. In future, as in the early years of IDS, I hope that we will see greater participation in IDSs by the forest products industry. Drying of coatings is another area of immense industrial interest that is inadequately represented at IDS meetings once again due to specialized meetings in the topical area. The same is true for drying of ceramics, advanced materials and freeze drying of pharmaceutical products and bio-products of extreme heat-sensitivity.

The format of IDS conferences has remained largely unchanged since its inception. It consists of several keynote lectures, several parallel sessions in lecture format and poster sessions to accommodate the increasing number of technical contributions. I believe that each IDS has had the critical mass required for a fruitful interaction and yet has been small enough to allow development of personal contacts which could later flourish into valuable joint R&D projects.

Several hundred dryer configurations and operating modes have been discussed in various papers presented at IDSs over the past years (Mujumdar, 1995). It appears that only a few of these have reached commercialization. I believe that a greater interaction is needed between those who generate and validate new dryer concepts and those who actually commercialize them, e.g., vendors. Except for the few internationally recognized dryer equipment manufacturers the participation by vending companies has been at a low level. I hope that in years to come this will change and we will see a greater impact of drying R&D on industrial drying equipment. Much of the development of industrial dryers today seems to follow an evolutionary process involving incremental changes. It is my fervent hope that there will be a more rapid and dramatic improvement in the design and performance of industrial drying systems by enhanced technology transfer via IDS meetings. Innovation resulting from creativity is central to any R&D. The time required to bring a novel visionary idea into the field is long especially for drying techniques, which have long “shelf life.” Nevertheless, the quest for relevance in drying R&D must continue. I believe that IDS will continue to provide the necessary impetus for such activity.

It was in 1985 that I suggested to Dr. Carl W. Hall, then Editor of Drying Technology – An International Journal and Deputy Director for Engineering at the National Science Foundation, Washington D.C., that since IDS had matured and developed its own momentum and recognition around the world, it was time to honor those who have made outstanding contributions to the field. Much to my delight Dr. Hall accepted the idea and went ahead to seek successfully sponsors for four major awards that were initiated at IDS'86 held on the august campus of MIT, Cambridge, MA. This program has now evolved into a major event with the support of large multi-national companies. I believe that this program in its own right has helped promote drying as a viable research area worthy of serious investigation. It has also helped bring "new blood" into drying R&D – an extremely important and desirable by-product of the success of IDS. ADC series have already started a Major Awards program from its very inception.

India has awakened recently and initiated significant drying R&D activity particularly at Institute of Chemical Technology, Mumbai. A number of workshops have been held very successfully focusing on drying but also incorporating filtration and crystallization to meet the needs of the growing chemical industry of India. Indeed, IDS2008 was held very successfully in Hyderabad in October 2008. In the coming years I expect China, Iran, Brazil and several western European countries to drive drying R&D in the next decade. Currently the contribution from North America, Japan, UK etc to the global archival literature in drying is miniscule by any standard. However, the total output on global scale is up due to more intensive activity in the rapidly emerging economies with strong manufacturing base. As expected, service-dominated economies have lesser need for drying R&D.

9.3. CLOSING REMARKS

An important feature of IDS since its very inception has been the formal publication of the technical papers presented at the meetings so that relevant knowledge is made available globally. Since the meetings are not obviously accessible to all the interested parties around the world an important part of IDS tasks has been to edit and publish the bound proceedings volumes. Indeed, some 4000 papers have been presented at IDS meetings to date and a majority of them are (some are out-of-print now) available to the worldwide community. In recent years, bound preprint volumes of IDS proceedings have been supplied to all attendees (and a limited number to external bodies) while only a small number of selected (typically only 10-20%) papers has been refereed and published in special IDS issues of Drying Technology – An International Journal (Drying Technology has also its devoted special issues to other major drying conferences around the world to keep its readership well informed about the R&D activities worldwide). The selectivity of these issues is necessarily very high. In view of the glowing success of IDS over the years, it is reasonable to expect that future IDS meetings will continue the successful streak and contribute to advances in industrial drying technologies.

The IDS series have been proven to catalyze drying R&D around the globe and it is my fervent hope that it will continue to do so for another decade at least. The rapidly rising interest in drying has led to evolution of complementary drying conferences around the world which demonstrates the significance of the IDS movement itself. I

hope that the next two decades will see rapid development of new drying technologies that have a significant edge over the current ones.

Interested readers are referred to the website at http://serve.me.nus.edu.sg/arun/ for access to a wide range of latest resources on drying including free downloads of relevant e-books especially edited for this purpose.

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Publications of TPR Group (Period: 2005 – Present)

Details:

Topic – Drying

Members covered – Arun S. Mujumdar, Sakamon Devahastin, X.D. Chen, C.L. Law, M.Zhang, W. Zhonghua, B.N. Thorat, M.W. Woo, Sachin V. Jangam, S.M.A. Rahman, P.P. Sutar, N.P. Sutar

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Sachin Vinayak Jangam is a Research Fellow in Minerals, Metals and Materials Technology Centre (M3TC) at National University of Singapore. He completed his Ph D in Chemical Engineering at the Institute of Chemical Technology, Mumbai, India. He has worked on drying of various food products as major part of his Ph D thesis. Sachin Jangam is currently working on developing cost-effective drying techniques for minerals; however, he still has interest in dehydration of food and related products.

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Dr. Mujumdar, the world-renowned "Drying Guru", is Professor of Mechanical Engineering at National University of Singapore. Winner of numerous prestigious awards and honors, Prof. Mujumdar has published over 400 refereed papers and over 100 book chapters in heat-mass transfer and drying. Founder of the International Drying Symposium (IDS) series, he is Editor-in-Chief of the archival journal Drying Technology (Taylor & Francis) since 1988 and is also the Editor of over 60 books including the widely acclaimed Handbook of Industrial Drying (CRC Press) now in third edition.

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