CHAPTER II

LITERATURE REVIEW AND THEORY

1. Introduction

This chapter provides a brief review of pertinent works with respect to the experimental investigations and empirical mathematical modeling of thin layer chili drying using continuous fluidized bed technique.

2. Prior works in drying

Drying is generally used to remove moisture or liquid from wet solids by bringing this moisture into a gaseous state. In most drying operations, water is the liquid evaporated and air is the normally employed purge gas. Drying can be regarded as one of the most important and most frequently applied unit operation in all sectors producing solid products. In many practical applications, drying is a process which requires high energy input because of the high latent heat of water evaporation and relatively low energy efficiency of industrial dryers. It reported that industrial dryers consume on average about 12% of the total energy used in manufacturing processes. In manufacturing processes where drying is required, the cost of drying can approach to 60-70% of total cost(R.E. Bahu, 1991). Thus, one of the most important challenges of the drying industry is to reduce the cost of energy sources for good quality dried products(Kaleemullah, 2002).

Drying equipment may be classified in several ways. The most common classification is based on the mode of heat input. The heat needed for drying is supplied to the material by one of the following methods(V.vanecek, M.Markvart, R.Drbohlav, 1996; CG.J Baker, 1997; C.W. Hall, 1980; I. Turner, 1997; J.S.M. Botteril, 1975; R.E. Bahu, 1991; S.Syahrul, 2002; I.Dincer, 1998) radiation drying, convection drying (using a drying medium, i.e., air) and contact drying(by conduction from surface that is in direct contact with the material to be dried).

Drying is removal of moisture to save moisture content and dehydration refers to removal of moisture in liquid form. Generally, drying is defined as the removal of moisture by the application of heat and drying is practiced to main the quality of fruits during storage by preventing the growth of bacteria, fungi and the development of insects and mites. The safe moisture content of fruits by heated air, by natural means or artificially and vapor pressure or concentration gradient thus created causes the movement of moisture from inside the surface.

The moisture is evaporated and transport by the air. Drying rate depends on drying air temperature, moisture content of the products, relationship between the moisture content of the products and relative humidity of the drying air, product type and maturity. There are two methods for expressed moisture content, viz., wet basis and dry basis. Moisture content on a wet basis is expressed as the ratio of mass of water present to the total mass of material. Moisture content on dry basis is expressed as the ratio of mass of water present to the bone dried material. The equilibrium moisture content(M_{eq}) of any material is defined as the moisture content of the material after it has been exposed to a particular environment for an infinitely long period of time. The M_{eq} is dependent upon the relative humidity and temperature condition of environment as well as on the species, variety and maturity of fruits or food products. The relationship between the moisture content of any material and its equilibrium relative humidity and temperature can be expressed by mathematical equation.

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Drying is defined as a process of moisture removal due to simultaneous heat and mass transfer. Heat transfer from the surrounding environment evaporates the surface moisture. The moisture can be either transported to the surface of the product or then evaporated, or evaporated internally at a liquid vapor interface and then transported as vapor to the surface. The transfer of energy depends on the air temperature, air humidity, airflow rate, and exposed area of material and pressure. The physical nature of the material, including temperature, composition, and in particular moisture content, govern the rate of moisture transfer. The dehydration equipment generally utilizes conduction, convection, or radiation to transfer energy from a heat source to the material. The heat is transferred directly form a hot gas or indirectly through a metal surface(Soponronnarit, 1997). The 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. Physical changes that may occur include shrinkage, puffing, crystallization and glass transition. 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 dryer), by conduction (contact or indirect dryer), radiation or volumetrically by placing the wet material in a microwave or radio frequency electromagnetic field. Transport of moisture within the solid may occur by any one or more of the following mechanisms of mass transfer.

The drying process cannot be discussed without a thorough understanding of the basic heat and mass transfer concepts. The typical drying cycle consists of three stages: heat the food to the drying temperature, evaporation of the moisture from the solid surface occurring at a rate proportional to the moisture content, and once the critical moisture point is reached, the falling rate associated with drying is set in motion.

2.1 Moisture content

The moisture content of solid denotes the quantity of water per unit mass of either wet or dry solid. It is usually on a percentage basis. The moisture on a wet basis (%, M_{wb}) is defined as:

$$M_{wb} = \frac{m_w}{m_w + m_d} x100 \tag{2.1}$$

The moisture content dry basis (% M_{db}) is defined as:

$$M_{db} = \frac{m_w}{m_d} x100 \tag{2.2}$$

where m_w is mass of water in product (kg) and m_d is mass of bone dry material (kg).

The moisture content in a product is an indicator of its quality and key to safe storage. Farmers and commercial operators use the wet basis moisture content. At the same time, engineers and scientist employ moisture content on a dry basis because it is easier to use in drying calculation. Conversion from a dry basis (%M_{db}) to a wet basis (%M_{wb}) moisture content, and vice versa, is done as follows:

$$M_{wb} = \frac{100M_{db}}{100 + M_{db}} \tag{2.3}$$

$$M_{db} = \frac{100M_{wb}}{100 - M_{wb}} \tag{2.4}$$

2.2 Drying characteristics

The drying behavior of a product can be characterized by measuring the moisture content loss as a function of time. Menon and Mujumdar(1987) have defined a generalized drying curve that includes an induction period, a constant drying rate period and falling drying rate period. After the induction period, where the food is heated to the drying temperature, the product undergoes a constant drying rate when a film of water is freely available at the drying surface for evaporation into the drying medium. During this period the rate of heat transfer to the solid and the rate of mass transfer to the air will be in equilibrium. The surface maintains a constant temperature equal to the wet-bulb temperature of drying air in the hot air during this process. The factors, which control the rate of drying during this period, are air temperature, air velocity, total pressure and partial pressure of vapor.

The falling rate-drying period is the indicative of an increased resistance to both heat and mass transfer. This period occur when the free water at surface no longer exists and water to be evaporated comes from within the structure and must be transported to the surface. In this period the surface temperature increases above the wet-bulb temperature and the rate of drying is influenced mainly by the factors, which control the movement of water within the solid and external factors become less important. The drying rate decreases and the moisture content of material slowly reaches the equilibrium moisture content corresponding to the actual relative humidity of the air.

2.3 Thermodynamic properties of drying air

Moist air, which is a mixture of dry air and water vapor, almost always is used both to supply the heat for evaporation and to carry away the evaporated moisture from solid. Dry air consists of a number of gases, mainly oxygen and nitrogen plus minor components such as argon, carbon dioxide, and neon. Moist air contains a varying amount of water vapor. Although the mass fraction of water vapor in the air used for drying is always less than one tenth, the presence of water vapor molecules has a profound effect on the drying process. Thus, thermodynamic properties of humid air are required for the design calculations of such dryers. The definitions discussed bellow are given in Soponrounnarit(1997) and Brooker et al.,(1992).

Three humidity terms are used in the solid drying literature to describe the amount of water vapor held in the drying air: vapor pressure, relative humidity, and humidity ratio. The temperatures of moist air may be referred to as dry-bulb and wet-bulb temperatures. Two additional moist air properties frequently used in solid drying calculations are enthalpy and specific volume. These seven moist-air thermodynamic properties are defined in the following paragraphs.

2.3.2 Vapor pressure

The water vapor pressure (P_v) is the partial pressure exerted by the water vapor molecules of a solid or liquid in moist air. When air is fully saturated with water vapor, its vapor pressure is called the saturated vapor pressure (P_v)

2.3.2 Relative humidity

The relative humidity (RH) is the ratio of the mole fraction (or vapor pressure) or water vapor in the air to the mole fraction (or vapor pressure) of the water vapor in saturated air at the same temperature and atmospheric pressure. The relative humidity is expressed as a decimal or percentage.

2.3.3 Humidity ratio

The humidity ratio (w) is the mass of the water vapor contained in the moist air per unit mass of dry air. Other terms used for humidity ratio are absolute humidity, moisture content and specific humidity.

2.3.4 Dry-bulb temperature

The dry-bulb temperature (T_{db}) is the temperature of moist air indicated by an ordinary thermometer.

2.3.5 Wet-bulb temperature

A distinction should made between the psychometric and thermodynamic wet-bulb temperature. The psychometric wet-bulb temperature (T_{wb} T_{wb}) is the temperature of moist air indicated by a thermometer whose bulb is covered with a wet wick. The airflow passing over the wick should have a velocity of at least 4.6 m/s(Soponronnarit, 1997).

The thermodynamic wet-bulb temperature(T_{wb}) is the temperature reached by moist air and water if the evaporating water adiabatically saturates the air. The psychometric and thermodynamic wet-bulb temperatures of moist air are nearly equal.

2.3.6 Enthalpy

The enthalpy(h) of a dry air-water mixture is the heat content of the moist air per unit mass of dry air above a certain reference temperature. Since only differences in enthalpy are of practical engineering interest, the choice of the reference temperature is non-consequential. For liquid water the reference temperature usually chosen is 0°C.2

2.3.7 Specific volume

The specific volume(v) of moist air is defined as the volume per unit mass of dry air. The specific density of the moist air is equal to the reciprocal of its specific volume.

2.4 Psychometric chart and drying process

A psychometric chart is a special chart that contains values of the most common thermodynamic properties of moist air: dry-bulb temperature, wet-bulb temperature, dew point temperature, ,humidity ratio, relative humidity, specific volume and enthalpy. Several processes relative to solid conditioning can be represented conveniently on the psychometric chart. Sensible heating and drying processes is presented in this section. Other processes are presented in Brooker et al., (1992).

2.4.1 Sensible heating and cooling

During sensible heating and cooling of the air at constant humidity ratio, heat is added to or withdraws from the drying air in a heat exchanger as in an indirect heater (for solid drying) or in an evaporator (for solid chilling)

The processes of sensible heating and cooling are represented on the psychometric chart by straight lines parallel to the abscissa (Figure 2.1); both result in changes in dry-bulb and wet-bulb temperatures, enthalpy, specific volume, and relative humidity of the moist air. Assuming that no drying take place, the humidity (moisture content) of the air remains the same because no water is added or removed.

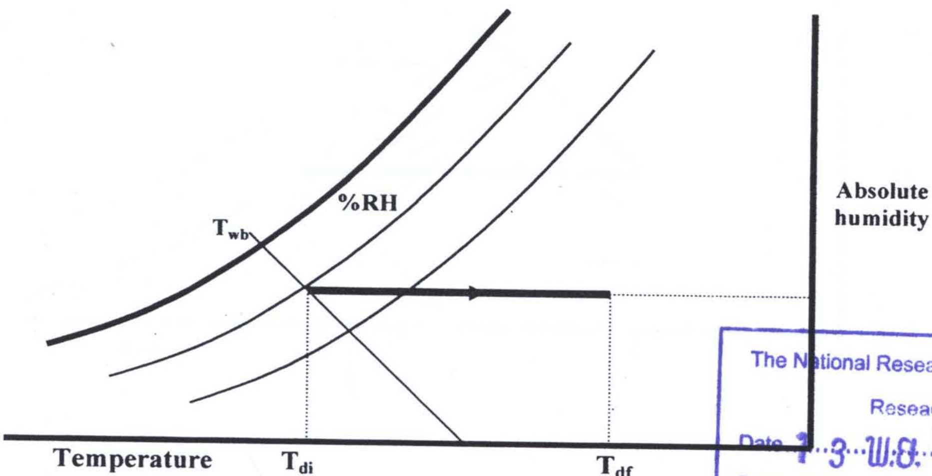

Figure 1.1 Representation on the psychometric chart of the sensible heating and cooling process of moist air(Brooker et al., 1992)

2.4.2 Drying processes

The drying of a mass of solid in a dryer can be considered an adiabatic process. The drying air, without transfer of heat supplies the heat required for evaporation of the solid moisture by conduction or radiation to or from the surroundings. As the air pass through the wet solid mass, a large part of the sensible heat of the air is transformed into latent heat as a result of the increasing amount of water held in the air as vapor. During the adiabatic process there will be an increase in the humidity ratio and relative humidity, the vapor pressure, and the dew point temperature. The enthalpy and wet-bulb temperature remain practically constant during the adiabatic drying process. The process of solid drying is illustrated in Figure 2.2

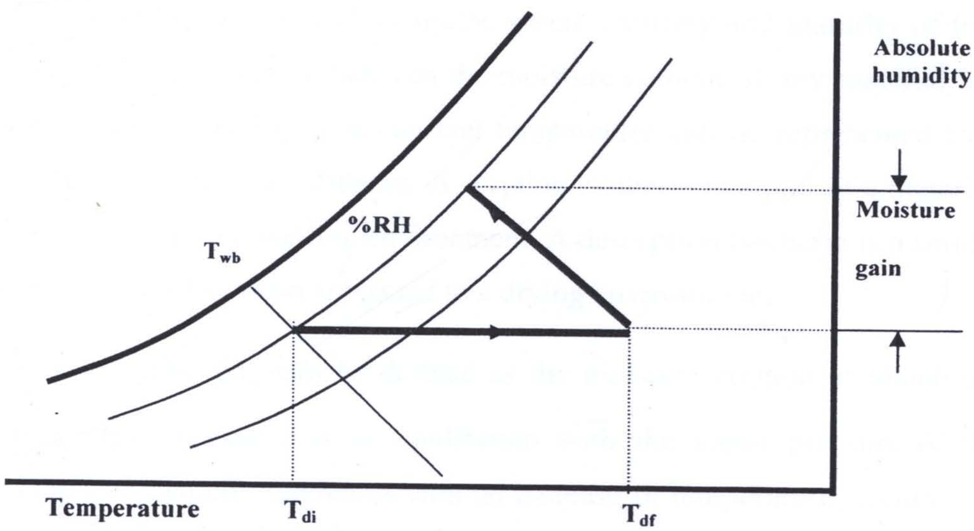

Figure 1.2 Representation on the psychometric chart of the solid drying adiabatically(Brooker et al., 1992)

Assuming the dry-bulb temperature, T_{di} , and wet-bulb temperature, T_{wi} , of the ambient air are known, then the initial state can be determined (point A in Fig. 2.2). The corresponding relative humidity can be read directly from the diagram, as also the absolute humidity. The horizontal line from A shows the process when the air is heated without adding or losing moisture to B. This is the sensible heating processes. It can also be seen that the relative humidity of the air decreases. From state B, the hot air is driven past the product. No heat gain or loss occurs in the system during this process, called an adiabatic process or drying process. This is shown along the part BC. The drying processes take place because the hot air become cooler and receive moisture from the product. The part BC carried out at constant enthalpy that should be identical with a process at constant wet-bulb temperature.

2.4.3 Equilibrium moisture content

The equilibrium moisture content(M_{eq}) is the limiting moisture to which a given material can dry under specific conditions of air temperature and relative humidity. This value depends on the relative humidity and temperature conditions of the environment as well as on the species, variety and maturity of fruit or food products. The relationship between the moisture content of any material and its equilibrium relative humidity at a constant temperature can be represented by a curve and this curve is called an isotherm. A sorption isotherm is a plot of a material, which has been subjected to a wetting environment. A desorption isotherm is a similar plot for a material which has been subjected to a drying environment.

The M_{eq} can be defined as the moisture content at which the internal product vapor pressure is in equilibrium with the vapor pressure of the environment. The M_{eq} usually decreases with an increase in temperature, solid (food material) properties such as species, variety and maturity and depend on whether the amount of humidity is shifted from high to low (desorption) or from low to high (absorption). The following direction of the mass transfer between the surface of the material and the surrounding air are possible:

2.4.3.1 From the air to the solid when the partial vapor pressure of air is greater than internal product vapor pressure.

2.4.3.2 From the solid to the air when the partial vapor pressure of air is smaller than internal product vapor pressure.

2.4.3.3 Rate of water absorption by the solid equals the rates of water desorption from the solid when the partial vapor pressure of air is equal to internal product vapor pressure.

Several theoretical, semi-theoretical and empirical models have been proposed to describe the isotherm of agricultural products. In the literature there are several relationships describing experimental sorption isotherms for different temperature by means of approximation. The important M_{eq} models compiled of Oswin's model is shown in equation:

$$M_{eq} = A[RH/(1-RH)]^{B} \tag{2.5}$$

Where: M_{eq} = the equilibruim moisture content

RH = the relative humidity

A, B = constant which are the function of absorption temperature.

Lewis(1921) developed a simplified drying model based on the Newton's law of cooling that assumes the rate of change on moisture content is proportional to difference between the grain moisture and its equilibrium moisture content. The mathematical expression of Lewis's equation is:

$$MR = \frac{M_t - M_e}{M_o - M_e} = \exp(-k_1 t) \tag{2.6}$$

Where : MR = moisture ratio

M_t = moisture content at time t,(% d.b.),

M_e = equilibrium moisture content (% d.b.),

M_o = initial moisture content (% d.b.),

k_1 = drying constant determined from experimental data(min^{-1}) and

t = time (min)

Henderson and Pabis(1961) modified the Lewis equation (Eq.2.6) by adding another constant as:

$$MR = a\exp(-bt) \qquad (2.7)$$

Where: a = empirical drying constant, and

b = empirical drying constant (min^{-1})

Aghabaslo et al.,'s(2008) model is given by the following equation:

$$MR = \exp(-\frac{k_1 t}{1+k_2 t}) \qquad (2.8)$$

Where: k_1, k_2 = empirical drying constant

This model was new model for demonstrate changes of moisture content of carrot using thin-layer drying.

A two-term model that uses the first two terms of the general series solution of Fick's diffusion equation can characterize drying of different types of food grains without restrictions of geometric considerations:

$$MR = A\exp(-Bt) + C\exp(-Dt) \qquad (2.9)$$

Where: A, B = empirical drying constant, and

C, D = empirical drying constant (min^{-1})

3. Drying kinetics

The moisture migration within a kernel is described by mass diffusion. The assumption is stated that water moves in the radial and axial direction and chili is an isotropic solid. In this work, the partial differential equation of moisture diffusion for a single chili kernel, assuming a finite cylindrical shape, is written as follows:

$$\frac{\partial M}{\partial t} = D\left[\frac{\partial^2 M}{\partial r^2} + \left(\frac{1}{r}\right)\frac{\partial M}{\partial r} + \frac{\partial^2 M}{\partial Z^2}\right] \qquad (2.10)$$

The initial and boundary conditions for chili drying are given by:

$$t = 0, \quad 0 \le r \le r_0 \qquad M = M_{in}$$

$$-l \le z \le +l \qquad M = M_{in}$$

$$t > 0 \quad r = r_0 \qquad M = M_{eq}$$

$$z = \pm l \qquad M = M_{eq}$$

$$t > 0, \quad r = 0 \qquad \frac{\partial M}{\partial r} = 0$$

Where: D = effective moisture diffusion; m^2/min

D	=	effective moisture diffusion; m^2/min
l	=	half length
M	=	moisture content at any time t, decimal (dry-basis)
M_{in}	=	initial moisture content, decimal (dry-basis)
M_{eq}	=	equilibrium moisture content, decimal (dry-basis)
r	=	co-ordinate along the radius of cylinder, m
r_0	=	radius of cylinder, m
t	=	time, min
z	=	length of cylinder, m

The analytical solution for the local moisture content of a single kernel is expressed by the following equation:

$$MR(r,l,t)=\frac{M(r,l,t)-M_{eq}}{M_{in}-M_{eq}}=\frac{4}{\pi}\sum_{m=1}^{\infty}\frac{2}{\lambda_m^2 J_1(\lambda_m)}J_0\left(\lambda_m\frac{r}{r_0}\right)\exp\left(\frac{\lambda_m^2 Dt}{r_0^2}\right)\times$$
$$\sum_{n=0}^{\infty}\frac{(-1)^n}{2n+1}\cos\frac{(2n+1)\pi z}{2l}\exp\left(-\frac{\pi^2(2n+1)^2 Dt}{4l}\right) \quad (2.11)$$

Where: MR = moisture ratio, decimal

λ_m = root of the Bessel function of the n^{th} kind of zero order

Integrating Equation 2.11 over the volume of cylinder and dividing by its total volume, the average moisture content can thus be formulated as:

$$\overline{MR}=\left(\frac{8}{\pi^2}\right)\sum_{m=1}^{\infty}\frac{4}{\lambda_m^2}\exp\left(\frac{\lambda_m^2 Dt}{r_0^2}\right)\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-\frac{\pi^2(2n+1)^2 Dt}{4l}\right) \quad (2.12)$$

Where D is the effective moisture diffusion coefficient accounting for the heterogeneous solid and it may be described by the Arrhenius type equation as follows:

$$D=D'\exp\left(\frac{-E_a}{RT_{abs}}\right) \quad (2.13)$$

Where D' is an Arrhenius factor and E_a is an activation energy. D' may depend on the drying air temperature and the moisture content or has a constant value(Mulet, et al. 1989; Rovedo, et al. 1998; Hebber and Rastogi, 2001). This uncertainty may result from the inherent characteristics of particular material.

4. Chili or red pepper drying

One of works in chili drying belongs to Doymaz and Pala(2002). This work presents a theoretical and experimental study of drying kinetics of red peppers under different pretreatment and air drying conditions. Moreover, presents results delineating the effect of drying process on red peppers pretreated with various ethyloleate solutions and subsequently dried in a hot-air dryer, drying curves of sliced peppers were obtained using Page and exponential equations—Page model can be describe drying characteristics better than exponential model.

Akpinar et al.,(2003) present the thin layer drying behavior of red pepper slices is experimentally investigated in convective dryer and the mathematical modeling by using thin layer drying models in literature is performed. This research showed eleven different thin layer mathematical drying models were compared according to their coefficient of correlation to estimate drying curves and the effects of drying air temperature on the model constants and coefficients were predicted by regression models. The constants and coefficients of this model could be explained by the effect of drying air temperature.

Kalemullah and Kailappan(2005) studied about drying kinetics of red chili rotary dryer, they present the moisture ratio of chili reduced exponentially as the drying time increased. In this curves, an increase of drying rate, given by the curve slope, with an increase in temperature was observed. This is in agreement with the reports quoted by Mazza and Maguer(1980) for onions, Madamba et al.,(1996) for garlic; and Lopez et al.,(2000) for lectuce and cauliglower leaves. The drying rate was more for chili dried at higher temperature than the chili dried at lower temperatures for the same average moisture content of the chili. Suitable models are identified to predict the moisture ratio of chili at different drying air temperatures of a rotary dryer.

Simal et al.,(2005) presented Page model which can be described the drying curves better than Peleg model and determine an activation energy using Page equation. The drying results within the range of 50 to 75 °C, would be optimum conditions to achieve a final product with the best color characteristics(highest ASTA and chroma values) and also, with the highest antioxidant capacity. And the air temperature drying seems to be an important factor which should be taken into consideration to ensure the quality of final dried product.

5. Thin-layer drying of grain and crops

Thin-layer : A layer of material exposed fully to an airstream during drying. The depth(thickness) of the layer should be uniform and should not exceed three layers of particles. Particles in the thin layer should be exposed fully to airstream. The airstream approaching the sample should be as uniform as possible in the temperature and humidity at a given cross section parallel to the thin layer so that the air contacts sample particles uniformly. Care should the exercised the prevent displacement of particles in the thin-layer holder during a test. This situation may arise in vertical thin-layer in which airstream flows horizontally through the product, or in horizontal thin-layer in which airstream flows upward through the product.

6. Prior works in fluidized bed drying

One of works in fluidized bed drying belongs to Abid et al.,(1990). They performed an experimental and theoretical analysis of the mechanism of heat and mass transfer during of corn in a fluidized bed containing inert particles. They used the principle of irreversible thermodynamics in their model. They accounted for the transfer of water by diffusion under the influence of a concentration gradient of the moisture, and by thermodiffusion under the influence of a temperature gradient. They found the external conditions such as the humidity and velocity of the gas have only small effect on the rate of drying. By a sensivity analysis for the coefficient of thermal gradient, they verified that the transfer of water by thermodiffusion was negligible compared to one by ordinary diffusion.

Stakic and Milojic(1992) developed a numerical simulation of heat and mass transfer in fluidized bed drying by using a control volume method to discretize the differential equations. They used the classic two-phase theory of fluidization for the hydrodynamics of fluidized bed, and a known equation from the drying kinetic for mass transfer of particles. They reported a successful match between the results of mathematical model with the experimental data available in the literature and with their own experiment results for which unrefined sugar was used. Thomas and Varma(1992) proposed a pseudo-steady state receding core model for drying kinetics of granular cellular materials-green pepper, black pepper and mustard. They indicated that intraparticle diffusion controls the drying process and the falling rate might be nonlinear depending upon the nature of material. The predicted the performance of the continuous fluidized bed drying from the kinetic data obtained, using a batch luidized bed dryer and assuming ideal mixing of solids. Hemati et al.,(1992) studied the drying of maize in flotation fluidized bed, where the corn kernels were immersed in a hot fluidized bed of sand particles. They used an intermittent scheme to increase the efficiency of the bed and reported that under isothermal conditions it leads to 50% reduction of energy consumption.

Srinivasa Kannan et al.,(1994) presented a model for drying of solids in batch fluidized bed considering the heat and mass transfer among the bubble, interstitial gas, and solid phases. They used an analytic solution of diffusion equation to predict the moisture distribution inside the particle with the assumption of uniform temperature for solids in equilibrium with the interstitial gas(equilibrium model). They studied the effect of different experimental conditions, such as the temperature and flow rate of the air, the initial moisture content of solids, and solids hold up on the drying of material such as millet, ragi, and poppy seeds. They reported a good agreement between their model and the experimental data and concluded that heat transfer is the controlling mechanism during the constant rate period, while intraparticle diffusion of moisture controlled period. However, they used a simplified model for mass and energy equation of interstitial gas and bubble phases. They also used the equilibrium assumption between gas and solid particles and evaluated the effective diffusivity of the solid particles by matching the experimental data with the model. They compared the performance of batch and different types of continuous fluidized bed dryers. They reported the spiral fluidized bed dryer has an advantage over the single-stage continuous dryer and that of multistage dryers over the batch fluidized bed dryer.

Zahed et al.,(1995) presented a model for a fluidized bed dryer with allowance for the diffusional moisture transport in the particles and for interstitial gas-to-particle mass transfer within the dense phase, as well as interphase exchange resistance between gas bubbles and the dense phase. They predicted the bed temperature and moisture content of the solids under various batch drying conditions. They did not conducted experiments to verify their numerical results and also could not compare their results with experimental results in the literature since they reported a few experimental data published on fluidized bed drying and those that had been published did not allow adequate information for comparison. However, like Srinivasa Kanan(1994), they neglected the unsteady term in the mass and energy equations for interstitial gas and bubble phases and also assumed a thermal equilibrium model and constant bubble size.

Soponronarit et al.,(1997) investigated the drying characteristics of corn in a small batch fluidized bed dryer. They recycled a fraction of the air to increase the thermal efficiency of the bed. They tried many empirical thin layer drying equations to correlate with their experimental results and found that the Wang and Singh(1978) equation could describe the results with sufficient accuracy.

Grabowski et al.,(1997) experimentally examined the drying of yeast in a laboratory scale fluidized bed and spouted bed needed about 25% higher flow rate than the fluidized bed. However, they found that, base on fluidization and spouting behavior, drying kinetics, and viability determination, drying in a spouted bed or combination of spouted bed and fluidized bed was better than only fluidized bed.

J. Burgschweiger and E. Tsotsas(2002) studied using a lab-scale device, continuous fluidized bed drying has been investigated experimentally under steady-state and dynamic conditions. The mixing behaviour and residence time distribution of particles in the dryer have been shown to be that of a continuous stirred tank reactor. Particle mass flow rate and inlet moisture content, gas mass flow rate, air heater capacity and gas inlet temperature have been varied systematically. The average moisture content of outlet solids has been determined by means of microwave absorption.

M. IZadifar and D. Mowla(2003) developed mathematical model to simulate the drying of moist paddy in a Cross-Flow Continuous Fluidized Bed Dryer(CFCFBD). The proposed model is solved by writing a computer program, which takes the operating conditions as input and gives the hydrodynamic properties as well as the variation of moisture content of paddy through the dryer as output.

I. Hideo et al.,(2006) studied the effect of heat and mass transfer on the efficiency of fluidized bed drying have been studied to optimize the input and output conditions. The analysis was carried out using two different materials, wheat and corn. Energy and exergy models based on the first and second law thermodynamic are developed. Furthermore, some unified non-dimensional experimental correlations for predicting the efficiency of fluidized bed drying process have been proposed. The effects of hydrodynamics and thermodynamics conditions such as the inlet air temperature, the initial moisture cont and well known Fourier and Reynolds numbers on energy efficiency and exergy efficiency were analyzed using the developed model. A good agreement was achieved between the model predictions, non-dimensional correlations and the available experimental results.

7. Theory of fluidized bed technique

Fluidization of gas or solid is a process that happens under two conditions; for example, the status of solid under the fluidization. The behavior of the solid will be similar to the process when it flows through layers of particles. Gas will slowly flow through the bed layer of the particle. As the velocity of gas increases, the pressure decreases. On the opposite, the layers of the particle will increase according to the velocity of gas until the pressure goes down to the same level as the weight of the particle in the bed layer. At this point, every particle will be lifted according to the flow of the gas against the weight of the particle. The layer of the particle will begin to create fluidized-bed and it seems that the layers of the particle will become more like liquid from just a mix of particle. We call the speed of gas at this point, *minimum fluidization velocity*. When the velocity of gas increases more than the U_{mf} value, the gas that creates fluidized-bed will go through the layer of the bubble layer of particle. The size of the bubbles will be occurred according to the bubbles spreading device. However, these bubbles will merge very quickly and the layer of the particle will rise. The reason to this is the strong mixing of the particle that creates fluidized-bed. At this point, we will call it the particle border moving out of the bed layer, turning into gas removing all the solid substance from the bed. *Fluidized-bed* can be explained as the enough velocity from the flow of the liquid through the solid, making it rise higher. The velocity at this point is called *Incipient fluidizing velocity*.

8. Heat and Mass transfer in fluidized bed drying process

Drying process is very important in heat and mass transferring. Heat is very crucial in the evaporation of water into the particle of the materials. The humidity will be released from the materials being dried. Heat will be transferred from the environment to the surface of the particle and from the surface to the inner part of the particle. Humid will be released in the opposite direction between liquid and air. The surface of the particle will create an evaporation to the environment. The excessive amount of moisture content of particles may affect the behavior of particles during the fluidization process. The general correlation for minimum fluidization velocity, U_{mf} is given by Kunii and Livenspiel(1991):

$$U_{mf} = \frac{\varepsilon^3_{mf}}{180(1-\varepsilon_{mf})} \frac{(\rho_p - \rho_g)(\phi d_p)^2 g}{\mu} \tag{2.14}$$

Where Re is the Reynolds number and Ar is the Archimedes number defined as:

$$Re_{mf} = \frac{d_p U_{mf} \rho_g}{\mu_g} \tag{2.15}$$

$$Ar = \frac{d_p^3 \rho_g (\rho_p - \rho_g) g}{\mu_g^2} \tag{2.16}$$

Where:
ϕ = sphericity of particle
ε_{mf} = bed voiding at minimum fluidization
ρ_g = gas density, kg/m^3
ρ_p = dry particle density, kg/m^3

μ_g = viscosity of hot air, $kg(m.s)^{-1}$

U_{mf} = Minimum fluidization velocity

Further, most fluidized bed dryers are nearly adiabatic contactors, e.g., they are well-insulated and the heat and mass transfer between the drying particles and the hot gas is by convection only. This implies that the product surface temperature (when surface moisture is being removed) will attain the wet-bulb temperature corresponding to the inlet gas temperature and humidity while the state of the exit gas follows the adiabatic saturation line. When the internal moisture is being removed the product temperature is above its wet-bulb temperature and, in the limit attains the fluidizing gas temperature at long drying times.