CHAPTER III

THEORY

3.1 Drying definitions

Drying generally refers to the removal of water or some other liquid from a solid by thermal vaporization to reduce the content of residual liquid to an acceptably low value. Mechanical methods for separating a liquid from a solid such as decantation, pressing or centrifuge are not generally considered drying. Drying is usually the final step in a series of operations, and the product from a dryer is often ready for final packaging. The solid to be dried may be in many different forms such as flakes, granules, crystals, powders, slabs, or continuous sheets and may have widely differing properties.

Solid drying encompassed two fundamental and simultaneous processes. They are heat transfer to evaporate the liquid and mass transfer as liquid and/or vapor within the solid and as vapor from the surface. The factors governing the rates of these transfer processes determine the overall or apparent drying rate.

Commercial dryers differ fundamentally by the method of heat transfer employed. These industrial-dryer operations may utilize heat transfer by convection, conduction, radiation, or a combination of these. However, in each case, heat must flow to the outer surface and then into the interior of the solid. The single exception is dielectric and microwave drying, in which high-frequency electricity generates heat internally and produces a high temperature within the material and on its surface.

Mass is transferred in drying as liquid and vapor within the solid and as vapor from the exposed surfaces. Movement within the solid results from a concentration gradient which is dependent on the characteristic of the solid. A solid to be dried may be porous or non-porous. It can also be hygroscopic or nonhygroscopic. Many solids fall intermediately between these two extremes, but it is generally convenient to consider the solid to be one or the other.

Because of the wide variety of materials that are dried in commercial equipment and the many types of equipment that are used, there is no single general theory of drying that covers all materials and dryer types. Variation in shape and size of stock, in moisture equilibrium, in the mechanism of flow of moisture though the solid and in the method of providing the heat required for the evaporation prevent a unified treatment. Generally, a study of how a solid dries at steady or quasi-steady state may be based on the internal mechanism of liquid flow or on the effect of external conditions of temperature, humidity, air flow, state of subdivision, etc., on the drying rate of the solids. The former procedure generally requires a fundamental study of the internal condition. The latter procedure, although less fundamental, is more often used because the results have greater immediate application in equipment design and evaluation.

3.2 General drying behavior

When a solid is dried experimentally with a gas of fixed temperature and humidity, one general pattern of behavior always appears. Figures 3.1 and 3.2 illustrates general drying curves for constant drying conditions. The curves are plotted between

moisture content of solid versus drying time and drying rate versus drying time. In figure 3.1, as the time passes, the moisture content typically falls, after a short period the graph becomes linear, then curve toward the horizontal and finally levels off. While in figure 3.2, the drying rate rises, then toward horizontal and finally falls. They represent the general case when a wet solid loses moisture first by evaporation from saturated surface on the solid, followed in turn by evaporation from a saturated surface of gradually decreasing area or increasing depth.
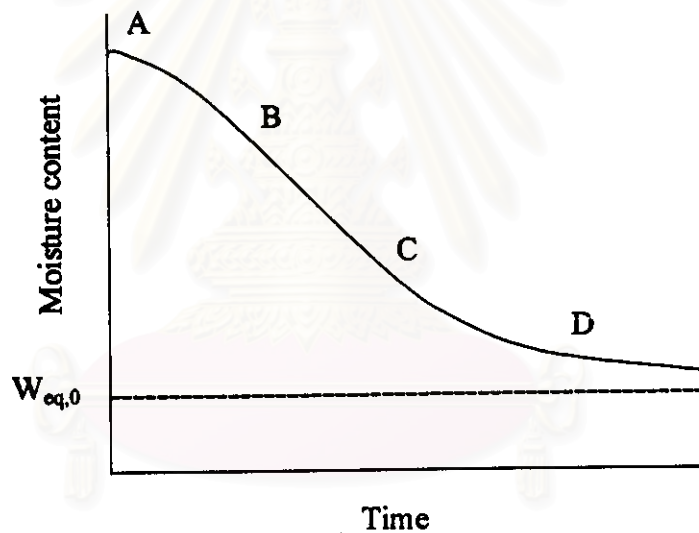

Figure 3.1 Typical drying curve for constant drying conditions, moisture content as a
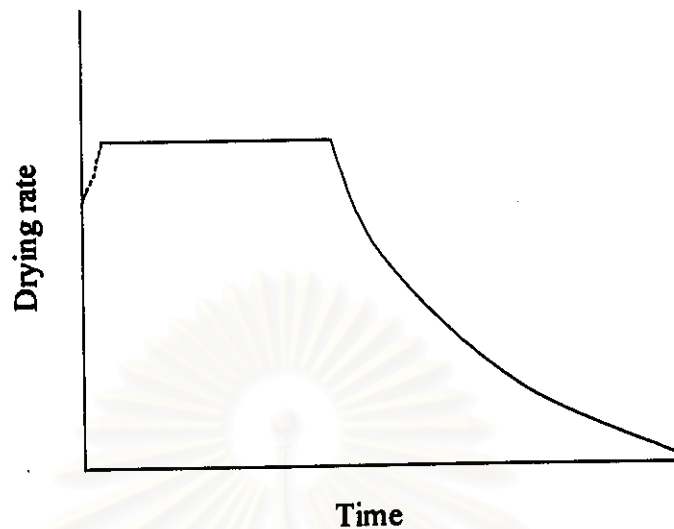function of time

Figure 3.2   Typical drying rate curve for constant drying conditions, drying rate as a

function of time

3.2.1 Constant drying rate period

From figures 3.1 and 3.2, the section AB represents a warming-up period of the

solids. In this period, most of the heat which transfers from hot gas to solid is used to

raise the temperature of wet solid. The solid temperature rises rather quickly from its

initial value to the vaporization temperature.

Section BC represents the constant drying rate period. It is characterized by a

rate of drying independent of moisture content. During this period, the solid is so wet

that a continuous film of water exists over the entire drying surface. If the solid is

nonporous, the water removed in this period is mainly superficial water on the solid

surface. In a porous solid, there is internal moisture movement to evaporate at solid

surface but the movement is rapid enough to maintain a saturated condition at the

exposed surface. The mechanism of moisture movement and consequently the rate of this movement vary markedly with the structure of the solid itself. With solids having relatively large, open void spaces, the movement is likely to be controlled by surface tension and gravity forces within the solid. With solid of fibrous or amorphous structures, liquid movement is by diffusion through the solid (McCabe, 1993).

Therefore, the rate of drying is controlled by the rate of heat transferred to the evaporating surface. The rate of mass transfer balances the rate of heat transfer so the temperature of the solid surface remains constant. If heat is transfer only by convection and there is no other effects, the surface temperature approaches the wet-bulb temperature. However, when heat is transferred by radiation, conduction, or a combination of these and convection, the solid temperature at the saturated surface is between the wet-bulb temperature and the boiling point of water. This mechanism of moisture removal is equivalent to evaporation from a body of water so it is essentially independent of the nature of the solids. The magnitude of the constant drying rate depends upon three factors:

1) The heat or mass transfer coefficient

2) The area exposed to the drying medium

3) The difference in temperature or humidity between the gas stream and the wet surface of the solid

All these factors are the external variables. The internal mechanism of liquid flow does not affect the constant drying rate (Perry, 1984).

The drying time in this period may be a few seconds or many hours and sometimes may be absent if the initial moisture content of the solid is less than a certain minimum (McCabe, 1993).

3.2.2 Falling drying rate period

As drying proceeds, moisture content decreases and reaches point C where the constant drying rate ends and the drying rate begins to fall. Point C is called the critical moisture content and the curved portion CD is termed the falling drying rate period. The critical point marks the instant when the liquid water on the surface is insufficient to maintain a continuous film covering the entire drying area. In nonporous solids, the critical point occurs at about the time when the superficial moisture is evaporated. In porous solid, the critical point is reached when the rate of moisture flow to the surface no longer equals the rate of evaporation called for by the surface evaporative process (McCabe, 1993). Therefore, the drying rate is now governed by the rate of internal moisture movement and the influence of external conditions diminishes. The structure of the solid determines the mechanism for which internal liquid flow may occur. These mechanisms can include (1) diffusion in continuous, homogeneous solids, (2) capillary flow in granular and porous solids, (3) flow caused by shrinkage and pressure gradients, (4) flow caused by gravity, and (5) flow caused by a vaporization-condensation sequence. In general, one mechanism predominates at any given time in a solid during drying, but it is not uncommon to find different mechanisms predominating at different times during the drying cycle. The study of internal moisture gradients establishes the

particular mechanism which takes control during the drying of a solid. The experimental determination of reliable moisture gradients is extremely difficult.

However, these mechanisms are very slow compared to the convection transfer from the saturated surface. Thus, solid temperature increases because of imbalance between heat and mass transfer rate. Consequently, the moisture content gradually approaches equilibrium moisture content which is the lowest moisture content obtainable with this solid under the drying conditions used.

3.2.3 Liquid diffusion

Diffusion is characteristic of slow-drying material. The resistance to mass transfer of water vapor from the exposed solid surface to the surrounding air is usually negligible, and diffusion in the solid controls the overall drying rate. The moisture content at the surface, therefore, is at or very near the equilibrium value (McCabe, 1993). The velocity of the air has little or no effect, and the humidity of the air influences the process primarily through its effect on the equilibrium moisture content

Diffusion controlled mass transfer is assumed when the vapor or liquid flow conforms to Fick's second law of diffusion. This is stated in the unsteady-state diffusion equation using mass transfer notation as

$$\frac{\partial C}{\partial t} = D_{AB} \frac{\partial^2 C}{\partial X^2} \qquad (3.1)$$
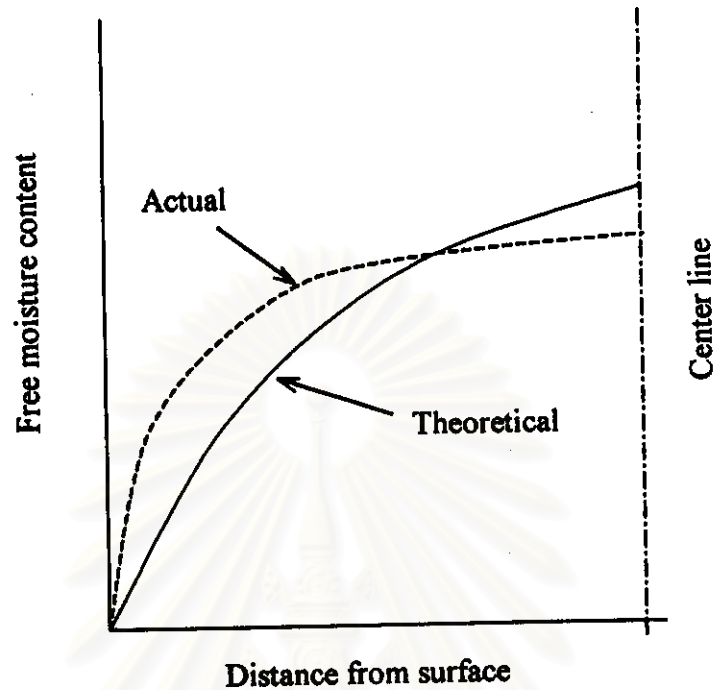
Figure 3.3 Moisture distribution in solid for liquid diffusion

Figure 3.3 illustrates the moisture distribution in a solid as the dotted line, in which the local moisture content is plotted against distance from the surface. The accuracy of the diffusion theory for drying suffers from the fact that the diffusivity usually is not constant but varies with local moisture content. It is especially sensitive to shrinkage. The value of diffusivity is less at small moisture content than at large and may be very small near the drying surface. Thus, the moisture distribution called for by the diffusion theory with constant diffusivity is like that shown by the solid line in figure 3.3 (McCabe, 1993). In addition to the moisture content, diffusivity increases with temperature, hence the rate of drying increases with the temperature of the solid (Perry, 1984). Thus, the integrated diffusion equations assuming constant diffusivity

only approximate the actual behavior. However, in practice, an average value of diffusivity, established experimentally on the material to be dried, is used.

3.2.4 Equilibrium moisture content

The air entering a dryer is seldom completely dry but contains some moisture and has definite relative humidity. For air of definite humidity, the moisture content of the solid leaving the dryer cannot be less than the equilibrium moisture content corresponding to the humidity of the entering air. That portion of the water in the solid that cannot be removed by the inlet air, because of the humidity of the latter, is called the equilibrium moisture content.

Equilibrium moisture content of a solid is particularly important in drying because it represents the limiting moisture content for given conditions of humidity and temperature. If the material is dried to a moisture content less than it normally possesses in equilibrium with atmospheric air, it will return to equilibrium value on storage unless special precautions are taken.

Generally, equilibrium moisture content varies with the temperature and humidity of the surrounding air. Raw cotton of equilibrium relationship is shown in figure 3.4. However, at the low temperatures, e.g. 15 to 50 °C, a plot of equilibrium moisture content versus percent relative humidity is essentially independent of temperature. At zero humidity the theoretical equilibrium moisture content of all materials is zero (Foust, 1980).
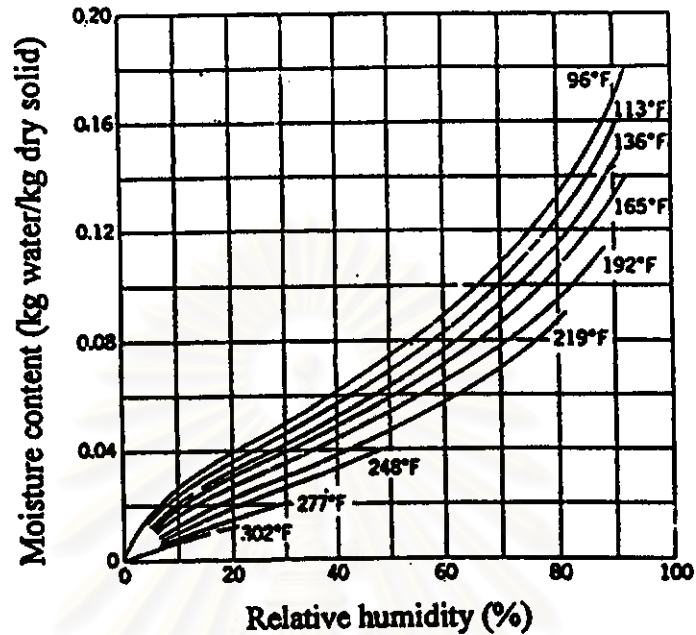
Figure 3.4 Equilibrium moisture content of raw cotton

Figure 3.5 illustrates more examples of equilibrium moisture content that vary

with relative humidity. If an equilibrium curve like one of those in figure 3.5 is

continued to its intersection with the axis for 100 percent humidity, the moisture content

so defined is the minimum moisture this material can carry and still exert a vapor

pressure at least as great as that exerted by liquid water at the same temperature. If such

a material contains more water than that indicated by this intersection, it can still exert

only the vapor pressure of water at the solid temperature. This makes possible a

distinction between two types of water held by a given material. The water

corresponding to concentrations lower than that indicated by the intersection of the

curves in figure 3.5 with the line for 100 percent humidity is called bound water,

because it exerts a vapor pressure less than that of free liquid water at the same

temperature. Water corresponding to concentrations greater than that indicated by the intersections is called unbound water. Substances containing bound water are often call hygroscopic substances. Bound water may exist in several conditions. Liquid water in fine capillaries; moisture in cell or film walls may suffer a vapor-pressure lowering because of solids dissolved in it; water in natural organic substances is in physical and chemical combination, the nature and strength of which vary with the nature and moisture content of the solid. Unbound water, on the other hand, exerts its full vapor pressure and is largely held in the void of the solid. Large wet nonporous particles, such as coarse sand, contains only unbound water.

Equilibrium moisture content of a hygroscopic material may be determined in a number of ways, the only requirement being a source of constant temperature and constant humidity air. Determination may be made under static or dynamic conditions, although the latter case is preferred.

Equilibrium moisture content depends greatly on the nature of the solid. For nonporous, i.e., nonhygroscopic, materials, the equilibrium moisture content is essentially zero at all temperature and humidities. For organic materials such as wood, paper, and soap, equilibrium moisture contents vary regularly over wide ranges as temperature and humidity change. In the special case of the dehydration of hydrated inorganic salts such as copper sulfate, sodium sulfate, or barium chloride, temperature and humidity control is very important in obtaining the desired degree of moisture removal, and the proper conditions must be determined from data on the water of hydration or crystallization as a function of air temperature and humidity.
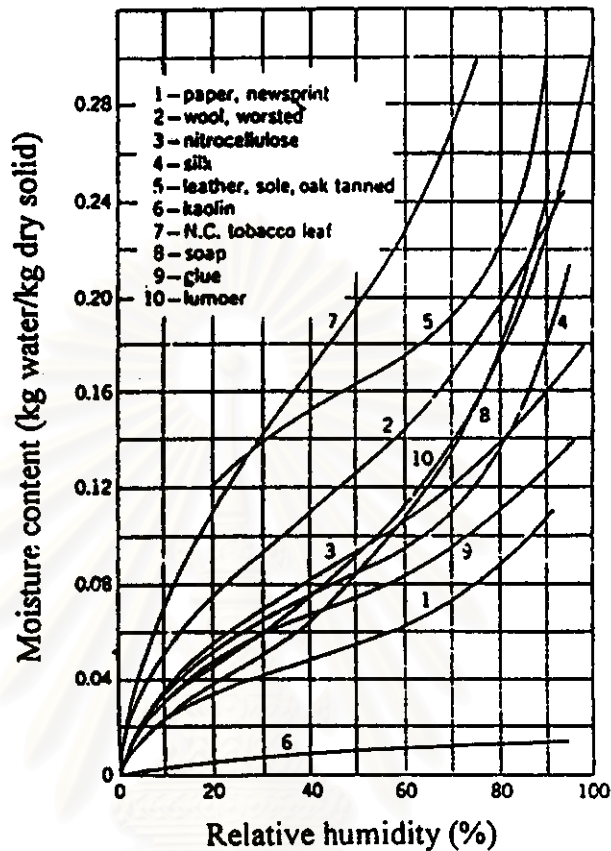
Figure 3.5 Equilibrium moisture content of some solids at 25 °C

The value of equilibrium moisture content, for many materials, depends on the direction in which equilibrium is approached as shown in Figure 3.6. A different value is reached when a wet material loses moisture by desorption, as in drying, from that obtained when a dry material gains it by adsorption. For drying calculations the desorption values are preferred. In the general case, the equilibrium moisture content reached by losing moisture is higher than that reached by adsorbing it (Mujumdar, 1995).
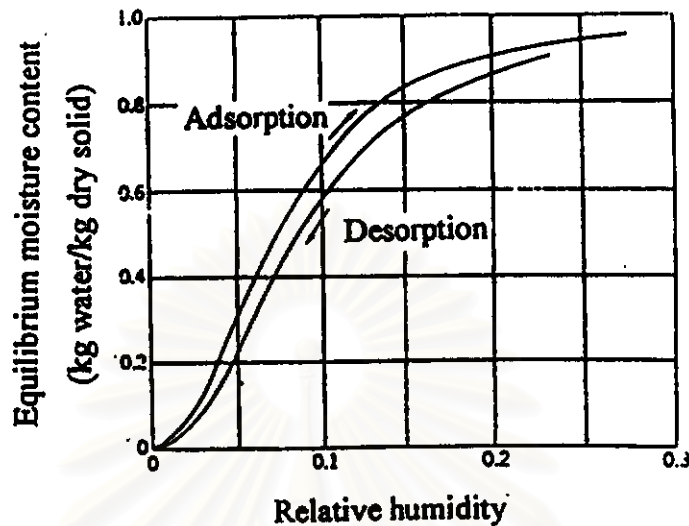
Figure 3.6 Equilibrium moisture content of sulfite pulp showing hysteresis

3.2.5 Critical moisture content

The moisture content exiting at the end of the constant drying rate peroid is called the critical moisture content. At this point, the internal movement of liquid to the solid surface become insufficient to replace the liquid being evaporated. Therefore, the critical moisture content depends upon the ease of moisture movement through the solid (McCabe, 1993). Since the critical moisture content is the average moisture through the material, its value depends on the rate of drying, the thickness of the material, and the factors influencing moisture movement and resulting gradients within the solid. As a result, the critical moisture content increases with increased drying rate and with increased thickness of the mass of material being dried. Furthermore, the critical moisture content depends on the drying history.

The complicated and uneven structure of porous solids makes predicting the critical moisture content very difficult. At present, the engineer must depend upon experimental measurements made under simulated production condition in order to determine the critical moisture content (Foust, 1980).

3.3 Pneumatic conveying dryer

In a pneumatic conveying or flash dryer, fine, powdered, wet feed material is introduced into the dryer together with the hot drying air or gas that conveys the drying material to the dry product collection system. A dryer of this type is shown in figure 3.6. Drying takes place during transportation in the vertical tube in which warm air is flowing with a velocity greater than the free falling speed of the largest particles in the wet solid. The rate of heat transfer from the gas to the suspended solid particle is high, and drying is rapid, so that no more than 3 or 4 seconds is required to evaporate substantially all the moisture from the solid. The temperature of the gas is high often about 650 °C at the inlet – but the time of contact is so short that the temperature of the solid rarely rises more than 50 °C during drying. Pneumatic conveying drying may therefore be applied to sensitive materials that in other dryers would have to be dried indirectly by a much cooler heating medium.

A pneumatic conveying dryer is simple, occupying little space and having few moving parts. Such a simple system consists of a long tube or duct carrying a gas at high velocity, a fan to propel the gas, a suitable feeder for addition and dispersion of particulate solids in the gas stream, and a cyclone collector or other separation equipment for final recovery of solids from the gas. A modification of this system could
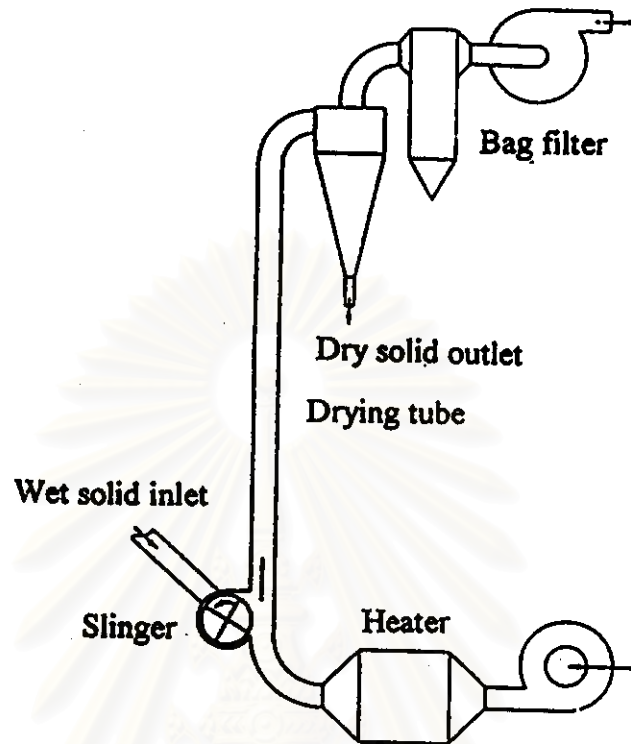
Figure 3.7 Diagram of typical pneumatic conveying dryer

include a dispersion unit, which is required to break up the dried product into an acceptable particle size. The solid feeder may be of any type; screw feeders, venturi sections, high-speed grinders, and dispersion mills are employed. For pneumatic conveyors, selection of the correct feeder to obtain thorough initial dispersion of solids in the gas is of major importance. For example, by employing an air-swept hammer mill in a drying operation, 65 to 95 percent of the total heat may be transferred within the mill itself if all the drying gas is passed through it. Fans may be of the induced-draft or the forced-draft type. The former is usually preferred because the system can then be operated under a slight negative pressure. Dust and hot gas will not be blown out through leaks in the equipment. Cyclone separators are preferred for low investment. If

maximum recovery of dust or noxious fumes is required, the cyclone may be followed by a wet scrubber or bag collector.

Pneumatic conveying dryer can be used to dry most chemicals, food products, polymers, several by-products, and minerals. Granular materials that are relatively free flowing in the wet state can be dispersed merely by dropping them into the heated air stream. Sludges, filter-press cakes, and similar nongranular or lump-tendency materials, however, must be disintegrated by a disintegrator. The maximum particle size that can be dried is 1-2 mm. Because larger particles are not entrained by air and require a longer drying time than that achieved with pneumatic conveying dryer (Van't Land, 1991). Otherwise, pneumatic conveyors are suitable for materials which are granular and free-flowing when dispersed in the gas stream, so they do not stick on the conveyor walls. Sticky materials such as filter cakes may be dispersed and partially dried by an air-swept disintegrator in many cases. In some case, material that have a tendency to form lumps in the wet state must be mixed with the dry product coming from the recycle line to permit suitable disintegration.

An effective way to control the drying operation is via the fuel or steam flow on the basis of the air-outlet temperature. The dryer must be able to cope with varying feed flows because there is usually no buffer between the liquid/solid separating system and the dryer; hold-up of wet solids cannot be easily controlled. It is a good practice not to vary the air flow because this affects the transport function.

3.3.1 Advantages and disadvantages of pneumatic conveying dryer

The advantages of the pneumatic conveying dryer are:

(a)   The short contact time and co-current flow often permit satisfactory drying of heat-sensitive materials.

(b)   For the same reason, high air inlet temperature and low air rates can often be used, resulting in high thermal efficiency.

(c)   The dryer transports the solid so that its use may avoid the need for separate conveying equipment.

(d)   The dryer requires little floor space and may be installed outdoors. The final dust collector should, however, be housed in a warm enclosure to prevent dewing and dust deposition in the flues and choking of bag filters if installed.

(e)   The dryer is readily controlled as the low solids hold-up gives a quick response to changing conditions.

(f)   There are few moving parts so that the maintenance requirements are low.

(g)   The capital cost is usually low compared with other types of dryer.

The disadvantages include:

(a)   Efficient dust collection is essential; difficulties with this may make the dryer unsuitable for some materials.

(b)   Because of dust emission, the dryer is unsuitable for toxic materials; the use of superheated steam as the drying medium may overcome this difficulty in a few cases.

(c) Operating difficulties will result if the feed contains many large agglomerates which are difficult to disperse.

(d) In general, individual particles do not receive exactly the same treatment, especially in a dryer with recirculation, and this may be a disadvantage in some case.

3.3.2 Factors affecting the drying rate

The drying rate of a particle in such a system depends on many factors, which can be summarized as follows.

(a) Particle diameter

(b) Type of moisture transfer mechanism, whether it is diffusion or capillary mechanism controlling

(c) Length of diffusion path for moisture transfer within the particle, if it is diffusion mechanism controlled

(d) Length and size of particles, if it is capillary mechanism controlled

(e) Size uniformity

(f) Physical properties of the wet and dry solid particles

(g) Product mass flow rate

(h) Hot air mass flow rate

(i) Diameter of the dryer section

(j) Critical moisture content of the material

(k) The characteristic drying rate curve

In most dryers, the particle sizes are not uniform but have a reasonably wide distribution. This effect is enhanced when agglomerates are taken into consideration. As a result, the dryer contains both fine particles and coarse particles. The fine particles, having relatively small resistance to drying because of the capillary flow controlling mechanism, can be overdried, whereas the coarser ones, in which the moisture migration by diffusion is predominant, are underdried. To overcome this undesirable result, most of the flash dryers available in the industry have recycle design arrangements. With the help of such modifications, the coarser particles are allowed to remain longer in the dryer and thus more uniform product moisture distribution can be obtained.

3.3.3 Heat and mass transfer in pneumatic conveying dryer

The application of pneumatic conveying dryers to heat-sensitive material is limited by several factors. The main controlling factor for drying should be related to the external convective heat transfer taking place on the wet surface of the particle, not to internal heat transfer. For larger particles this may lead to some errors because in this case the internal heat and mass transfer within the particle structure may be controlling even in the very short resident time. If the convective heat flux between the gas and particles is too high, the rate of moisture removed from the particle surface would be higher than the rate of internal moisture migration to the surface from the interior structure of the particle because of the resistances encountered against diffusion and capillary flow phenomena. Dry spots appear on the surface of the particles, which changes the solubility of water in the skin layer at the surface. Other changes as a result

of thermal degradation could also alter the internal heat and mass transfer mechanism. For this range of conditions the observed rate of drying may be smaller than for conditions in which a lower entrance gas temperature is applied.

The heat transferred during the pneumatic drying process may be considered the result of the following four stages:

1. Drying in the disintegrator if dry recycle steam is used

2. Drying during high air-particle slip velocity, which occurs after the feed point and after each elbow

3. Drying during a nearly steady particle velocity after the acceleration point

4. Drying in the cyclone

Since convective heat transfer is always influenced by flow phenomena, the fluid dynamics of dispersed two-phase must be considered. The important considerations are (1) velocity of the particles and their swarms, (2) the rate of rise of these swarms, (3) the agglomerations taking place, and (4) the loading rate with respect to the phase in which it is introduced. It can be observed that the heat transfer coefficient increases sharply after the feed entrance point, and it may reach 10-100 times the value for stationary beds because dispersed two-phase systems differ from a single-phase flow because they contain solid particles that have a difference in density from the suspension phase. The relative velocity of these particles characterizes the fluid behavior. This difference in the mechanism necessarily influences the heat transfer.

The experimental studies of many authors have demonstrated various relations of heat transfer coefficients for the pneumatic conveying dryer. However, the majority of authors examined use

$$Nu = 2 + 0.6 Re^{1/2} Pr^{1/3} \qquad (3.2)$$

by assuming that the coefficient of heat transfer stays essentially constant throughout the pneumatic conveying dryer. The mass transfer coefficient could be estimated by the analogy Sh = Nu. Then the equation for mass transfer coefficient is

$$Sh = 2 + 0.6 Re^{1/2} Sc^{1/3} \qquad (3.3)$$

which also assumes that the mass transfer coefficient is constant throughout the dryer (Mujumdar, 1995).