2019-2020 Spring Semester

DRYING

1. INTRODUCTION

In general, drying a solid means the removal of relatively small amounts of water or other liquid from the solid material, to reduce the content of residual liquid to an acceptable low value. Drying is usually the final step in a series of operations, and the product from a dryer is often ready for final packaging. Drying is cat-led out for one or more of the following reasons[1]:

a. To reduce the cost of transport

b. To make a material more suitable for handling

c. To avoid the presence of moisture which may lead to corrosion.

Water or other liquids may be removed from solids mechanically by presses or centrifuges or thermally by vaporization. It is generally cheaper to remove water mechanically than thermally, and thus it is advisable to reduce the moisture content as much as practicable before feeding the material to a heated dryer.

The moisture content of a dried material varies from product to product. Occasionally the product contains no water, and is called bone-dry. More commonly, the product does contain some water. Drying is a relative term and means merely that there is a reduction in moisture content from an initial value to some acceptable final value[2].

2. THEORY

2.1. PHYSICAL DESCRIPTION OF THE DRYING PROCESS

The driving force for mass transfer in a wet solid is the difference between the total moisture content and the equilibrium moisture content.

The drying characteristics of wet solids are best described by plotting the average moisture content of the material against elapsed time measured from the beginning of the drying process. Most wet solids exhibit a drying rate and moisture content versus drying time curves similar to that of Fig 1.1. During the drying of a wet solid in heated air, the air supplies the necessary sensible and latent heat of evaporation to the moisture and also acts as a carrier gas for the removal of the water vapour formed from the vicinity of the evaporating surface.

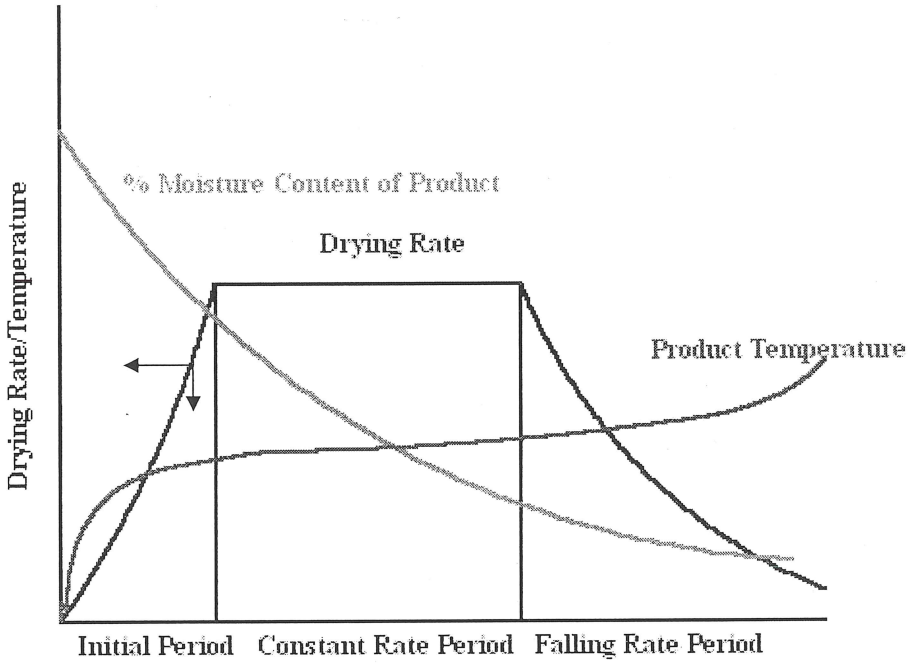

Figure 1.1. Classical drying curve

Consider the situation where an inert solid, wetted with pure water, is being dried in a

current of heated air flowing parallel to the drying surface. Assume that the temperature and humidity of the air above the drying surface remain constant throughout the drying period and that all the necessary, heat is supplied to the material by convection. If the change in moisture content of the material is recorded throughout drying, the data can be presented in the form of curves as shown in Figure 1.1. The different stages observed during drying are as follows:

a. Settling down period

This stage represents a "settling down" period during which the solid surface conditions come into equilibrium with the drying air. It is often a negligible proportion of the overall drying operation but in some cases it may be significant.

b. Constant rate period

This stage is known as the constant rate of drying. During this period the surface of solid remains saturated with liquid water by virtue of the fact that movement of water within the solid to the surface takes place at a rate as great as the rate of evaporation from the surface.

Drying takes place by movement of water vapour from the saturated surface through a stagnant air film into the main stream of the drying air. The rate of drying is dependent on the rate of heat transfer to the drying surface. The rate of heat transfer balances the rate of mass transfer, and so the temperature of the drying surface remains constant. The surface of the solid can be compared to the wick of a wet-bulb thermometer and, under the conditions specified; the constant surface temperature will correspond to the wet-bulb temperature of the drying air. The "driving force" causing vapour movement through the stagnant air film is the water vapour pressure gradient between the drying surface and the main stream of the drying air. The rate of mass transfer can be expressed in the form of an equation as follows:

$$-\left(\frac{dm}{dt}\right)_C = K_g A(P_S - P_a) \qquad \text{Eq. 2.1}$$

where $-(dm/dt)_c$: drying rate, K_g: mass transfer coefficient, A: drying surface area, P_S: water vapour pressure at surface, P_a: Partial pressure of water vapour in air.

Equation 2.1 may also be written in the form:

$$-(\frac{dm}{dt})_C = K'_g A(H_S - H_a) \qquad \text{Eq. 2.2}$$

where K'_g: mass transfer coefficient, H_s: humidity at surface temperature, H_a: humidity at air (lb vapour/lb dry air).

The rate of heat transfer to the drying surface may be expressed thus:

$$(\frac{dQ}{dt})_C = h_C A(T_a - T_S) \qquad \text{Eq. 2.3}$$

where h_c: heat transfer coefficient, T_a: dry-bulb temperature of air, T_S: temperature of drying surface.

Since a state of equilibrium exists between the rate of heat transfer to the body and the rate of mass transfer from it these two rates may be related simply as follows:

$$-(\frac{dm}{dt})_C \lambda = (\frac{dQ}{dt})_C \qquad \text{Eq. 2.4}$$

where λ: latent heat of evaporation at T_S.

Combining Equations 2.3 and 2.4 gives

$$-(\frac{dm}{dt})_C = \frac{h_C A}{\lambda}(T_a - T_S) \qquad \text{Eq. 2.5}$$

If the specific drying rate is expressed in terms of the rate of change of specific moisture content (based on the dry solid). W, Equation 2.5 may be written:

$$-(\frac{dW}{dt})_C = \frac{h_C a}{\lambda}(T_a - T_S) \qquad \text{Eq. 2.6}$$

where a: effective drying surface of unit mass of dry solid.

For a tray of wet material of depth d (ft), evaporating only from its upper surface, assuming no shrinkage during drying:

$$-(\frac{dW}{dt})_C = \frac{h_C}{\rho\lambda d}(T_a - T_S) \qquad \text{Eq. 2.7}$$

where ρ: bulk density of the dry material. The drying time in the constant rate period can be obtained by the integration of the Equation 2.7, thus:

$$t_C = \frac{\rho\lambda d(W_0 - W_C)}{h_C(T_a - T_S)} \qquad \text{Eq. 2.8}$$

where t_C: constant rate drying time, W_0: initial specific moisture content, W_C: specific moisture content at end of constant rate period, known as the critical specific moisture content.

c. Falling rate period

As drying proceeds, a point is reached at which the rate of movement of moisture within the material to the surface is reduced to the extent that the surface begins to dry out. At this point (II) the rate of drying begins to fall and the falling rate period commences. The moisture content of the material at point II is known as the critical specific moisture content (W_C). From point II onwards the surface temperature begins to rise and continues to do so as drying proceeds, approaching the dry-bulb temperature of the air as the material approaches dryness.

In many cases it appears that the two mechanisms may be applicable to a single drying operation, i.e, capillarity accounting for the moisture movement in the early stages of drying while a diffusional mechanism applies at lower moisture contents.

In a capillary flow mechanism, the rate of drying can often be expressed with reasonable

accuracy by an equation of the type:

$$(\frac{dW}{dt})_f = -K(W - W_e) \qquad \text{Eq. 2.9}$$

where $(-dW/dt)_f$: specific drying rate for falling rate period, W: specific moisture content of the material at time t, W_e: equilibrium specific moisture content of the material at air temperature and humidity.

On the other hand, Equation 2.9 can be written also for the end point of constant-rate period (at the critical point).

$$(\frac{dW}{dt})_C = -K(W_C - W_e) \qquad \text{Eq. 2.10}$$

Combining Equations 2.7, 2.9 and 2.10

$$(\frac{dW}{dt})_f = -\frac{h_C(T_a - T_S)}{\rho\lambda d}\frac{(W - W_e)}{(Wc - We)} \qquad \text{Eq. 2.11}$$

Integration of this expression within the following limits

t=0 W=W_c (initial condition)

$t=t_f$ W=W (final condition)

gives the drying time in the falling rate period thus:

$$t_f = \frac{\rho\lambda d(W_e - W_c)}{h_C(T_a - T_S)} \ln\frac{(W - W_e)}{(W_c - W_e)} \qquad \text{Eq. 2.12}$$

where t_f: drying time for falling rate period.

Liquid Diffusion of Moisture in Drying

When liquid diffusion of moisture controls the rate of drying in the falling rate period, Fick's second law for unsteady-state diffusion can be applied. This type of diffusion is often

characteristic of relatively slow drying in nongranular materials such as soap, gelatin, and glue, and in the later stages of drying of bound water in clay, wood, textiles, leather, paper, foods, starches, and other hydrophilic solids.

A major difficulty in analyzing diffusion drying data is that the initial moisture distribution is not uniform throughout the solid at the start if a drying period at constant rate proceeds this falling-rate period. During diffusion-type drying, the resistance to mass transfer of water vapour from the surface is usually very small, and the diffusion in the solid controls the rate of drying. Then the moisture content at the surface is at the equilibrium value W_e. This means that the free moisture content W at the surface is essentially zero.

For slab-shaped solids, drying from one large face only, where liquid diffusion controls the internal movement of moisture, the following type of expression:

$$\frac{(W-W_e)}{(W_o-W_e)}=\frac{8}{\pi^2}\left\{\exp\left[-Dt(\frac{\pi}{2d})^2)\right]+\frac{1}{9}\exp\left[-9Dt(\frac{\pi}{2d})^2\right]+.....\right. \qquad \text{Eq. 2.13}$$

where W: average specific moisture content at time t of an infinite slab of thickness d, W_0: initial moisture content assumed to be uniform throughout the slab, D: liquid diffusion coefficient.

For large values of t, Equation 2.13 may be reduced to:

$$\frac{(W-W_e)}{(W_o-W_e)}=\frac{8}{\pi^2}\left\{\exp\left[-Dt(\frac{\pi}{2d})^2\right]\right\} \qquad \text{Eq. 2.14}$$

or

$$t=\frac{4d^2}{\pi^2 D}(\ln\frac{W_o-W_e}{W-W_e}+\ln\frac{8}{\pi^2}) \qquad \text{Eq. 2.15}$$

Equation 2.15 holds for values of $(W_o- W_e)/(W - W_e) <0.6$.

By differentiating Eq.15 a rate equation for slab-shaped solids is obtained.

$$(\frac{dW}{dt})_f=-\frac{\pi^2 D}{4d^2}(W-W_e) \qquad \text{Eq. 2.16}$$

The rate Equations 2.7, 2.8, 2.11 and 2.16 can be applied when drying takes place from only one side.

2.2. DRYERS

Drying equipment can be classified according to following design and operating features:

1. Batch or continuous,
2. Physical state of feed: liquid, slurry, wet solid,
3. Method of conveyance of solid: belt, rotary, fluidized,
4. Heating system: conduction, convection, radiation.

Except for a few specialized applications, hot air is used as the heating and mass transfer medium in industrial dryers. The air may be directly heated by the products of combustion of the fuel used (oil, gas or coal) or indirectly heated, usually by banks of steam-heated finned tubes. The heated air is usually propelled through the dryer by electrically driven fans.

Table 2.1. Basic features of the various types of solid dryers used in the process industries.

Mode of operation	Generic type	Feed condition 1	Feed condition 2	Feed condition 3	Specific Dryer types	Jacketed	Suitable for heat-sensitive materials	Suitable for vacuum service	Retention or cycle time	Heat transfer method #	Capacity	Typical evaporation capacity	
Batch	Stationary	←	←	→	1. Shelf 2. Cabinet 3. Compartment	Yes	Yes	Yes	6-48 h	Radiant and conduction	Limited	0·15–1·0	kg/hm² heat transfer area
			←	→	Truck	No	Yes	No	6-48 h	Convection	Limited	0·15–1·0	
		←	→		1. Kettle 2. Pan	Yes	No	Yes	3-12 h	Conduction	Limited	1·5–15	
			←	→	Rotary shell	Yes	Yes	Yes	4-48 h	Conduction	Limited	0·5–12	
			←	→	Rotary internal	Yes	Yes	Yes	4-48 h	Conduction	Limited	0·5–12	
			←	→	Double cone	Yes	Yes	Yes	3-12 h	Conduction	Limited	0·5–12	
Continuous	Drum	←	→		1. Single drum 2. Double drum 3. Twin drum	No	Yes	Yes	Very short	Conduction	Medium	5–50	
	Rotary		←	→	Rotary, direct heat	No	No	No	Long	Convection	High	3–110	kg/hm³ dryer volume
			←	→	Rotary, indirect heat	No	No	No	Long	Conduction	Medium	15–200	
			←	→	Rotary, steam tube	No	Depends on material	No	Long	Conduction	High	15–200	
			←	→	Rotary, direct-indirect heat	No	No	No	Long	Conduction Convection	High	50–150	
			←	→	Louver	No	Depends on material	No	Long	Convection	High	5–240	
	Conveyor		←	→	Tunnel: belt, screen	No	Yes	No	Long	Convection	Medium	1·5–35	
			←	→	Rotary shelf	Yes	Depends on material	No	Medium	Conduction Convection	Medium	0·5–10	kg/hm²
			←	→	Trough	Yes	Depends on material	Yes	Varies	Conduction	Medium	0·5–15	
			←	→	Vibrating	Yes	Depends on material	No	Medium	Convection Conduction	Medium	0·5–100	
			←	→	Turbo	No	Depends on material	No	Medium	Convection	Medium	1–10	
	Suspended particle	←	→		Spray	No	Yes	No	Short	Convection	High	1·5–50	kg/hm³
			←	→	Flash	No	Yes	No	Short	Convection	High	—	
			←	→	Fluid bed	No	Yes	No	Short	Convection	Medium	—	

←→ = applicable to feed conditions noted

Key to feed conditions:
1. Solutions, colloidal suspensions and emulsions, pumpable solids suspensions, pastes and sludges.
2. Free-flowing powders, granular, crystalline or fibrous solids that can withstand mechanical handling.
3. Solids incapable of withstanding mechanical handling.

Batch dryers are normally used for small-scale production and where the drying cycle is likely to be long. Continuous dryers require less labour, less floor space and produce a more

uniform quality product.

When the feed is solids, it is important to present the material to the dryer in a form that will produce a bed of solids with an open, porous, structure. For pastes and slurries, some form of pretreatment equipment will normally be needed, such as extrusion or granulation.

The main factors to be considered when selecting a dryer are:

1. Feed condition: solid, liquid, paste, powder, crystals.
2. Feed concentration: the initial liquid content.
3. Product specification: dryness required, physical form
4. Throughput required.
5. Heat sensivity of the product.
6. Nature of the vapour: toxicity, flammability
7. Nature of the solid: flammability (dust explosion hazard), toxicity

Basic Dryer Types

Most industrial dryers can be categorized in terms of six basic dryer types; rotary, tray, continuous through-circulation spray, flash and fluid bed.

a. Rotary dryer

This basic dryer is most suitable for free-flowing granular solids. Typical products dried in a rotary dryer include ammonium sulfate, nitrate, and phosphate fertilizer salts, sand, fluorspar and vinyl resins. It's advantages include low capital cost, fairly close temperature control, drying and calcining in the some unit, high thermal efficiency, low labor requirement and moderate drying times. Some disadvantages are difficulty of sealing high structural load, tendency to create dust non uniform residence time.

b.Vacuum-rotary dryer

Vacuum-rotary dryers are batch dryers at least in currently available commercial forms. The more common type of vacuum-rotary dryer consists of a stationary cylindrical shell mounted horizontally in which a set of agitator blades mounted on a revolving central shaft stirs the solids being treated. Heat is supplied by circulation of hot water or steam through a jacket surrounding the shell and in larger units, through the hollow central shaft. The agitator is either a single discontinuous spiral or a double continuous spiral. The dryer is charged

through a part at the top and emptied through one or more discharge nozzles at the bottom. Vacuum is applied and maintained by any of the conventional methods i.e., steam jets, vacuum pumps; etc.

Another type of vacuum-rotary dryer consists of a rotating horizontal cylindrical shell, suitably jacketed. Vacuum is applied to this unit through hollow trunnions with suitable packing glands Rotary glands must be used also for admitting and removing the heating medium from the jacket. The inside of the shell may have lifting bars, welded longitudinally, to assist agitation of solids.

c. Tray dryer

Typical materials dried in the tray dryer include alter cake, dyestuffs, pharmaceuticals and almost any material in small quantities. Tray dryers are specifically appropriate for drying batches of a large number of products. Advantages of this dryer are capability of handling fragile products, no loss of product during drying, low space

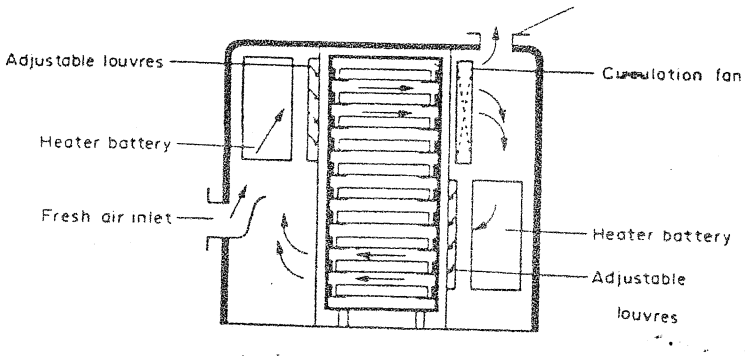

Figure 2.1. Tray dryer

requirement, ease of cleaning. Some disadvantages include high labor requirements and long drying time.

d. Through-circulation continuous dryer

This type of dryer is suitable for catalyst pellets; chemicals such as pigments, carbonates, synthetic and natural fibers such as nylon, rayon and food products including nuts, fruits and vegetables. Advantages of the system are good control of product quality, zone control of temperature, humidity and air flow, high thermal efficiency. Disadvantages include high capital cost, poor control of fines and frequent maintenance.

e. Spray dryer

Spray dryers are adapted to handle liquids, slurries, or, in general, any product that is pumpable. The material to be dried is atomized by a nozzle or disk-type atomizer and dispersed as a fine spray into a vertical cylindrical chamber with a conical bottom through which hot gas flows. The droplets quickly vaporize, leaving a dry solid residue which is discharged from the main chamber. Particles entrained in the exiting gas stream are removed in a cyclone separator or bag collector. The major advantages of spray-dryers are short drying times, adaptability to heat-sensitive products and control of particle size and density which is desirable from the standpoint of product flow properties and rapid dehydration. Disadvantages are low solid content critical maintenance of atomizing equipment, and tendency to product built up on interior walls.

f. Flash dryer

In some respects, flash drying is similar to spray drying in that in each process the wet product is dispersed as fine particles into flowing hot stream. The high velocity of gas stream transports the solid particles through the drying chamber to a cyclone separator or a bag collector where the dried particles are removed. The advantages of the flash dryers are extremely short drying times and a low product discharge temperature. In the flash dryer the atomizing device is eliminated, but often a high-speed mill must be substituted to disperse the wet solids. There are limitations on the particle size that can be handled since only surface water will be removed in the short holding time. Other disadvantages include erosion of internal surface and the danger in the drying of flammable materials at high temperature.

g. Fluidized bed dryer

If the fluidizing agent is a hot gas and the particles are wet, the conditions are such that rapid drying will occur. Since each particle is surrounded by the hot gas and the relative velocity between particles and gas is high increased rates of heat transfer are achieved and consequently drying times are very short. Fluidized bed dryers are suitable for granular and crystalline materials within the particle size 1 to 3mm. They are designed for continuous and batch operation. Some advantages of fluidized-bed dryers are rapid and uniform heat transfer, relatively short drying times and small floor-space requirements. Disadvantages

include high power cost, non uniform residence time.

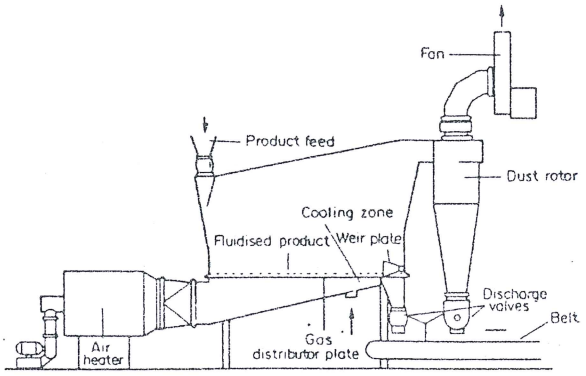

Figure 2.2. Fluidized bed dryer

h. Conveyor dryers

In this type, the solid are fed on the endless, perforated, conveyor belt, through which hot air is forced. The belt is housed in a long rectangular cabinet, which is divided up into zones, so that the flow pattern and temperature of the drying air can be controlled. The relative movement of the solids and drying air through the dryer can be parallel or, more usually, countercurrent.

This type of dryer is clearly only suitable for materials that form a bed with an open structure. High drying rates can be achieved, with good product-quality control. The disadvantages of this type of dryer are high initial cost and, due to the mechanical belt, high maintenance cost.

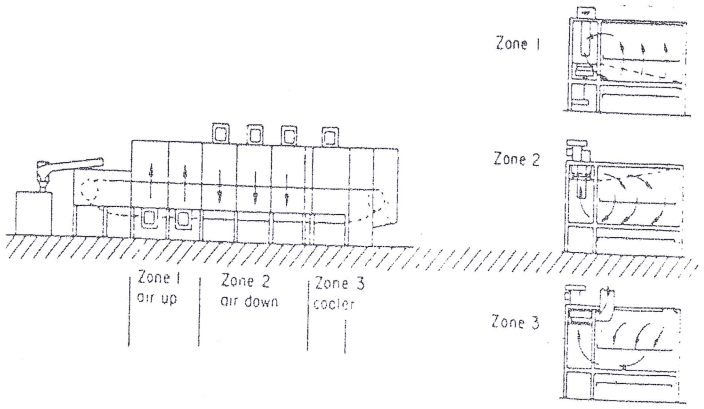

Figure 2.3. Conveyor dryer

3. EXPERIMENTAL SET UP

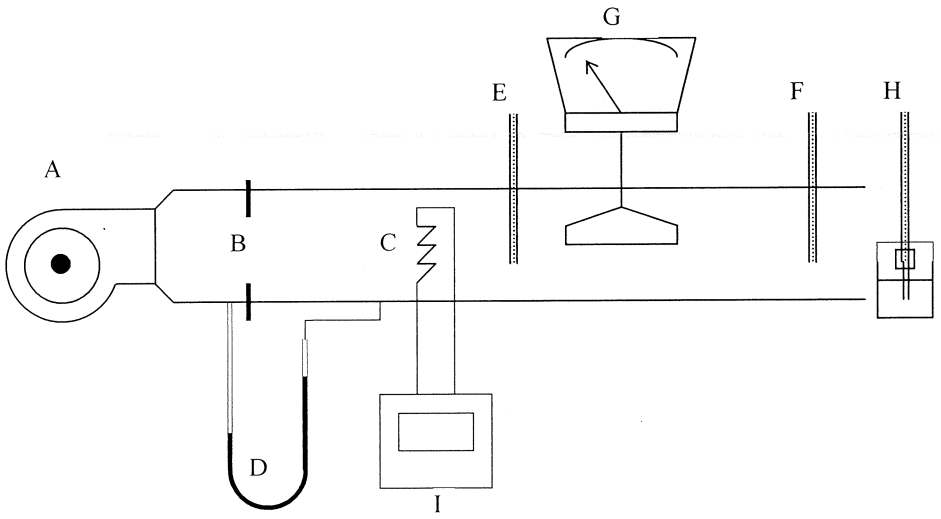

Figure 3.1. Experimental set-up

A: fan
B: orificemeter
C: electric heater
D: manometer
E and F: thermometer
G: balance
H: wet-bulb thermometer
I: kw-hour counter
J: water container

4. EXPERIMENTAL PROCEDURE

a. Start up fan and switch on the electric resistance and wait at least 15 minutes until the dryer reaches the steady state.
b. Measure pressure drop in orificemeter.
c. Put the wet material into the balance pan and turn on it, and record the initial value of kw-hour counter.
d. Measure and record the weight of wet material with the interval of 5 minutes, and continue the measuring at least 3 hours.
e. Read and record dry and wet bulb temperatures from related thermometers at different

times.

f. Determine the energy supplied to the system by using kw-hour counter values.

g. After this operation, dry your material in an oven for a long time to determine the final dry weight.

5. CALCULATIONS

1. Calculate the volumetric flow rate of air by using of orificemeter data.

2. Write energy balance equation for the drying tunnel and calculate the heat loss from the system to surroundings by using related data.

3. Plot the following graphs according to m-t data;

   W vs. t

   -(dW/dt) vs. t

   -(dW/dt) vs. W

4. Find $(dW/dt)_0$ from W vs. t graph in constant rate period and calculate the heat transfer coefficient h_c.

5. Calculate the mass transfer coefficient K'_g from Eq. 2 by using values of H_s and H_a obtained from the humidity chart.

SYMBOLS

A	: Drying surface area
a	: Specific drying surface area
D	: Liquid diffusion coefficient
d	: Depth of wet material
H_a	: Humidity in air
H_S	: Humidity at surface temperature
h_c	: Heat transfer coefficient
K_g	: Mass transfer coefficient based on the vapor pressure difference
K'_g	: Mass transfer coefficient based on the humidity difference
m	: Mass of material
P_a	: Partial pressure of water vapour in air
P_S	: Water vapour pressure at surface temperature
Q	: Quantity of heat transferred
T_a	: Dry-bulb temperature of air
T_S	: Drying surface temperature
t	: Time
t_C	: Drying time in constant rate period
t_f	: Drying time in falling rate period
W	: Specific moisture content of wet solid based on dry solid
W_c	: Critical specific moisture content of wet solid based on dry solid
We	: Equilibrium specific moisture content based on dry solid
W_o	: Initial specific moisture content
λ	: Latent heat of vaporization at surface temperature
ρ	: Bulk density of the dry material

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