| **KLM Technology Group** **#03-12 Block Aronia,** **Jalan Sri Perkasa 2** **Taman Tampoi Utama** **81200 Johor Bahru** **Malaysia** | **PROCESS DESIGN OF DRYERS** **(PROJECT STANDARDS AND SPECIFICATIONS)** |
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# TABLE OF CONTENT

## SCOPE

This Project Standards and Specifications is intended to cover minimum requirements for process design of dryers used in oil, gas, and petrochemical process plants.

Although, as a common practice, dryers are seldom designed by the users, but are brought from companies that are specialized in design and fabrication of drying equipment, the scope covered herein, is for the purpose to establish and define general principles on drying concept and mechanism, dryer classification and selection and to provide a complete design information and criteria required for proper selection, design and operation of solid, liquid and gaseous drying equipment (dryers).

## REFERENCES

Throughout this Standard the following dated and undated standards/codes are referred to. These referenced documents shall, to the extent specified herein, form a part of this standard. For dated references, the edition cited applies. The applicability of changes in dated references that occur after the cited date shall be mutually agreed upon by the Company and the Vendor. For undated references, the latest edition of the referenced documents (including any supplements and amendments) applies.

1. **ISO (International Standard Organization)**

   7183, 1986 "Compressed Air Dryers-Specifications and Testing", Section 4, 1st. Ed., 15th March 1986

   1st. Ed., 19815388, 1981 "Standard Air Compressors, Safety Rules and Code of Practice",

## DEFINITIONS AND TERMINOLOGY

**Adiabatic Drying -** The drying process described by a path of content adiabatic cooling temperature on the psychrometric chart.

**Adsorbate -** The molecules that condense on the adsorbent surface e.g., water in the case of drying.

**Adsorbate Loading -** The concentration of adsorbate on adsorbent, usually expressed as kg adsorbate per 100 kg adsorbent.

**Adsorbent -** A solid material which demonstrates adsorption characteristics.

**Adsorption -** The phenomenon whereby molecules in the fluid phase spontaneously concentrate on a solid surface without undergoing any chemical change.

**Adsorption Selectivity -** The preference of a particular adsorbent material for one adsorbate over another based on certain characteristics of the adsorbate such as polarity or molecular mass.

**Capillary Flow -** Is the flow of liquid through the interstices and over the surfaces of a solid, caused by liquid-solid molecular attraction.

**Constant-Rate Period -** Is the drying period during which the rate of liquid removal per unit of drying surface is constant.

**Critical Moisture Content -** Is the moisture content of the material at the end of the constant-rate period. The critical moisture content is not a unique property of the material but is influenced by its physical shape as well as the conditions of the drying process.

**Cycle Time -** The amount of time allocated for one bed in an adsorption system to complete adsorption to a predetermined outlet specification level and to be reactivated.

**Desiccant -** An adsorbent that shows primary selectivity for the removal of water. All adsorbents are not necessarily desiccants.

**Desiccant Fouling -** Material adsorbed from the carrier stream may not be desorbed satisfactorily on regeneration. Some reaction may also occur on the adsorbent leading to products that are not desorbed. These reaction products may inhibit efficient adsorption and obstruct or "foul" capacity of the active surface.

**Design Basis -** A good design basis requires a sound knowledge of the stream to be processed as well as what the desired outlet specification is and how the system will be operated. The design conditions on which an adsorption system is based are not necessarily the actual operating conditions, nor the least or most stringent operating conditions.

**Dew Point -** Temperature, referred to a specific pressure (degree Celsius), at which the water vapor begins to condense.

**Drying-Rate -** The amount of water (kg) removed per square meter of drying area per hour. Or the volume flow rate of condensed gas at Standard Reference Atmosphere Condition of an absolute pressure of 101.325 kPa (1.01 bar) and a temperature of 15°C.

**Equilibrium Loading -** The loading of an adsorbate on the given adsorbent, usually expressed in kilogram of adsorbate per hundred kilogram of adsorbent when equilibrium is achieved at a given pressure, temperature, and concentration of the adsorbate.

**Equilibrium Moisture Content -** The amount of moisture, in the solid that is in thermodynamic equilibrium with its vapor in the gas phase, for given temperature and humidity conditions. The material cannot be dried below its corresponding equilibrium moisture content.

**Falling-Rate Period -** The part of drying time which the drying rate varies in time.

**Free Moisture Content -** Is the liquid content that is removable at a given temperature and humidity. Free moisture may include both bound and unbound moisture, and is equal to the total average moisture content minus the equilibrium moisture content for the prevailing conditions of drying.

**Moisture Content -** The ratio of water and water vapor by mass to the total volume (gram per cubic meter).

**Partial Pressure -** Absolute pressure exerted by any component in a mixture (millibar).

**Relative Humidity (Relative Vapor Pressure) -** Ratio of the partial pressure of water vapor (millibar) to its saturation pressure (millibar) at the same temperature.

**Saturation Pressure -** Total pressure at which moist air at a certain temperature can coexist in equilibrium with a plane surface of pure condensed phase (water or ice) at the same temperature (millibar).

**Vapor Concentration (Absolute Humidity) -** The ratio of water vapor by mass to the total volume (gram per cubic meter).

## SYMBOLS AND ABBREVIATIONS

| SYMBOL/ABBREVIATION | DESCRIPTION |
|---|---|
| ABS | Acrylonitrile-Butadine-Styrene. |
| FMC | Final Moisture Content. |
| HDPE | High Density Poly-Ethylene. |
| IMC | Initial Moisture Content. |
| P | Partial pressure of vapor in the gas environment, in (kPa). |
| PP | Poly Propylene. |
| PVC | Poly Vinyl Chloride. |

## UNITS

This Standard is based on International System of Units (SI) except where otherwise specified.

## WET SOLID DRYERS

### General

In drying process the goal of many operations is not only to separate a volatile liquid, but also to produce a dry solid of specific size, shape, porosity, texture, color or flavor. So, well understanding of liquid and vapor mass transfer mechanism prior to design work is strongly recommended.

In drying of wet solids, the following main factors, which essentially are used in process design calculation of dryers should be defined in accordance with mass and heat transfer principles, process conditions and drying behavior:
- Drying characteristics.
- Constant-rate period.
- Falling-rate period.
- Moisture content.
- Diffusion concept.

### Drying Characteristics

1. The drying characteristics of wet solids is best described by plotting the average moisture content of material against elapsed time measured from the beginning of the drying process. Fig. 1 represents a typical drying-time curve.

The experimental estimation of this curve must be made before one can begin the design calculations. The influence of the internal and external variables of drying on the drying-time curve should be determined in order that an optimal design can be developed.

2. The drying-rate curve, Fig. 2, is drived from the drying-time curve by plotting slopes of the latter curve against the corresponding moisture content. The distinctive shape of this plot, shown in Fig. 2, illustrates the constant-rate period, terminating at the critical moisture content, followed by the falling-rate period. The variables that influence the constant-rate period are the so-called external factors consisting of gas mass velocity, thermodynamic state of the gas, transport properties of the gas, and the state of aggregation of the solid phase changes in gas temperature, humidity, and flow rate will have a pro-found effect on the drying rate during this period. The controlling factors in the falling-rate period are the transport properties of the solids and the primary design variable is temperature.

3. The characteristic drying behavior in these two period are markedly different and must be considered in the design. In the context of economics, it shall be costlier to remove water in the falling-rate period than it is removed in the constant-rate period, accordingly it is recommended to extend the length of the constant-rate period with respect to falling-rate as much practicable.
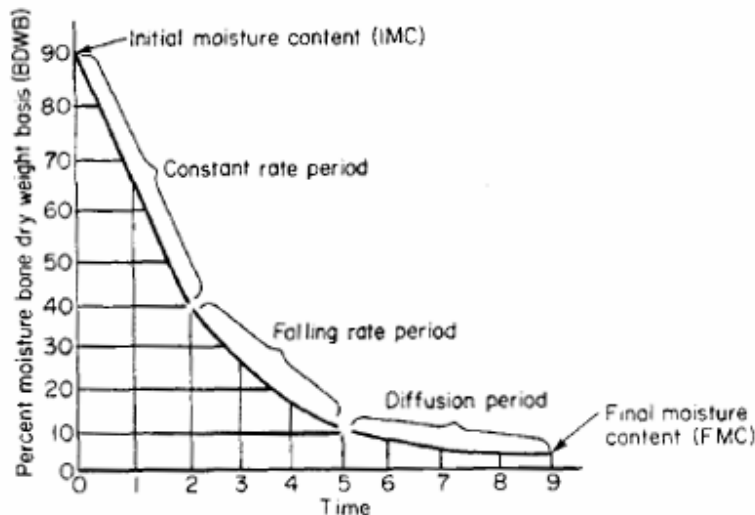


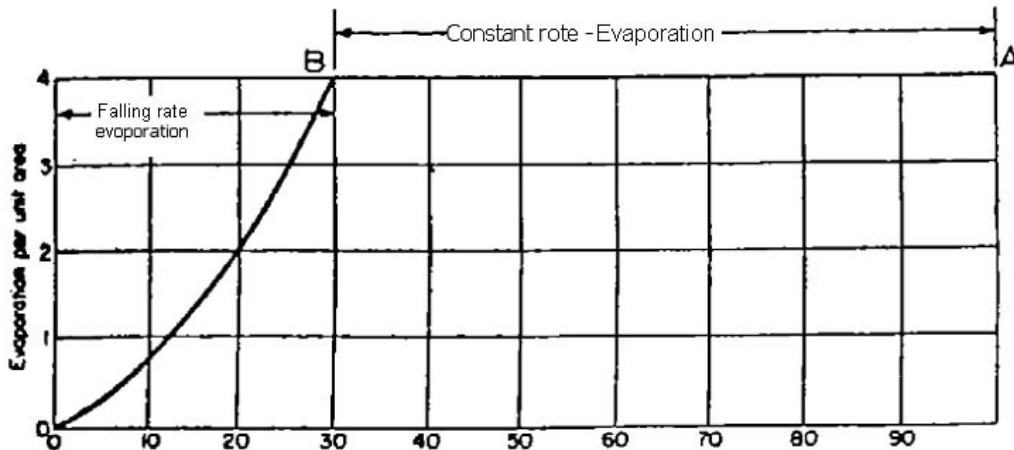**Fig. 1 Typical Classic Drying-Time Curve**

**Fig. 2 Moisture Content, Percent Bone Dry Mass Basis Drying-Rate Curve**

**Constant-Rate Period**

1. In Fig. 2, the horizontal segment AB which pertains to the first major drying period is called the constant-rate period. During this period, the solid is so wet that a continuous film of water exists over the entire drying surface, and this water acts as if the solid were not there. If the solid is nonporous, the water removed in this period is mainly superficial water on the solid's surface.

   The evaporation from a porous material is subject to the same mechanism as that from a wet-bulb thermometer.

2. The drying rate in constant-rate period can precisely be calculated from Equation 1 which is a steady-state relationship between heat and mass transfer.

$$-\frac{dW}{d\theta} = \frac{h_t.A}{L's}(t - t's) = K'a.A(p's - p) \qquad \text{Eq. (1)}$$

Where:

$dw/d\theta$     is drying rate, in (kg/s);
$h_t$     is the sum of all convection, conduction, and radiation components of heat transfer, in[kW/(m².K)];
A     is surface area for vaporization and heat transfer, in, (m²);
L's     is latent heat of vaporization at t's, in (kJ/kg);
K'a     is mass transfer coefficient, in [kg/(s.m².kPa)];
t     is average source temperature for all components of heat transfer,in kelvin (K);

t's       is liquid surface temperature, in kelvin (K);
P's      is liquid vapor pressure at t's, in (kPa);
P is partial pressure of vapor in the gas environment, in (kPa).

**Critical Moisture Content**

The critical moisture content is the average material moisture content at which the drying rate begins to decline. A prototype drying test should be conducted to determine the critical moisture content. In Fig. 2, the point B represents the constant-rate termination and marks the instant when the liquid water on the surface is insufficient to maintain a continuous film covering the entire drying area. The critical point (B) occurs when the superficial moisture is evaporated. In porous solids the point B of Fig. 2 is reached when the rate of evaporation become the same as obtained by the wet-bulb evaporative process.

**Equilibrium Moisture Content**

The equilibrium condition is independent of drying rate or drying method, but is a material property. Only hydroscopic materials have equilibrium moisture content under specific conditions of temperature and humidity. In prediction/ estimation of equilibrium moisture content, the Henry's Law (Eq. 2) may be followed:

$$P = H'(x) \hspace{4cm} \text{Eq. (2)}$$

Where:

P     is partial pressure of vapor in the atmosphere, in(kPa);
H'    is Henry's constant;
x     is Dry basis, moisture content, in (kg/kg). Henry's constant is a function of the pure liquid's vapor pressure.

$$H = i(p_w) \hspace{4cm} \text{Eq. (3)}$$

Where:

i     is a constant that is independent of temperature;
$p_w$   is the pure liquid's vapor pressure at any temperature, in (kPa) therefore;
p     is $i(p_w)(x)$, and since percent relative humidity = 100 $(p/p_w)$.

$$100 \ (p/p_w) = 100 \ I \ (x) \hspace{4cm} \text{Eq. (4)}$$

### Falling-Rate Period

1. Estimation of the drying for the falling-rate period primarily depends on experimental data. However, the drying rate during this period is considered to be a complex function of transport, physical, and thermodynamic properties of the solid phase, as well as of the same properties of the gas phase.

   Since the mechanisms of internal liquid and vapor flow during falling-rate drying are complex, the falling-rate can rarely be described with mathematical precision. However, for evaluation of falling-rate drying, an integration of Equation 5 can be employed provided several assumptions are made:

   - diffusivity is independent of liquid concentration;
   - initial liquid distribution is uniform;
   - material size, shape, and density are constant;
   - the material's equilibrium moisture contents is constant.

$$\frac{dc}{d\theta} = D_{AB} \frac{d^2c}{d^2z} \qquad \text{Eq. (5)}$$

   The Equation 5 is the unsteady-state diffusion equation in mass transfer notation and,

   Where:

   $c$       is concentration of one component in a two-component phase of A and B;
   $\theta$ (theta)   is diffusion time;
   $z$       is distance in the direction of diffusion;
   $D_{AB}$     is binary diffusivity of the phase A-B.
   This equation applies to diffusion in solids, stationary liquids, and stagnant gases.

2. The shape of the falling-rate curve sometimes may be approximated by a straight line, with Equation 6, as:

$$-\frac{dW}{d\theta} = K(W - W_e) \qquad \text{Eq. (6)}$$

   Where:

   $W_e$       is the equilibrium moisture content;
   $K$       is a function of the constant-rate drying period.

## Determining of Drying Time

1. Three following methods are generally used in order of preference for determining of drying time:

   - Conduct tests in a laboratory dryer simulating conditions in the commercial machine, or obtain performance data directly from the commercial machine.

   - If the specific materials is not available, obtain drying data on similar material by either of the above methods. This is subject to the investigator's experience and judgment.

   - Estimate drying time from theoretical Equation 1 or any such appropriate theorical formulas

2. When designing commercial equipment, tests are to be conducted in a laboratory dryer that simulates commercial operating conditions. Sample materials used in the laboratory tests should be identical to the material founds in the commercial operation. Result from several tested samples should be compared for consistency. Otherwise, the test results may not reflect the drying characteristics of the commercial material accurately.

   When laboratory testing is impractical, commercial drying can be based on the equipment manufacturer's experience as an important source of data.

   Since estimating drying time from theoretical equations are only approximate values, care should be taken in using of this method.

3. When selecting a commercial dryer, the estimated drying time determines what size machine is needed for a given capacity. If the drying time has been derived from laboratory test, the following should be considered:

   - In a laboratory dryer, considerable drying may be the result of radiation and heat conduction. In a commercial dryer, these factors are usually negligible.

   - In a commercial dryer, humidity conditions may be higher than in a laboratory dryer. In drying operations with controlled humidity, this factor can be eliminated by duplicating the commercial humidity condition in the laboratory dryer.

   - Operating conditions are not as uniform in a commercial dryer as in a laboratory dryer.

   - Because of the small sample used the test material may not be representative of the commercial material. Thus, the designer must use experience and judgment to correct the test drying time to suit commercial conditions.

## Psychrometry

Before drying can begin, a wet material must be heated to such a temperature that the vapor pressure of the liquid content exceeds the partial pressure of the corresponding vapor in the surrounding atmosphere. The effect of atmospheric vapor content of a dryer on the drying rate and material temperature is conveniently studied by construction of a psychrometric chart. (See typical Fig. 3)
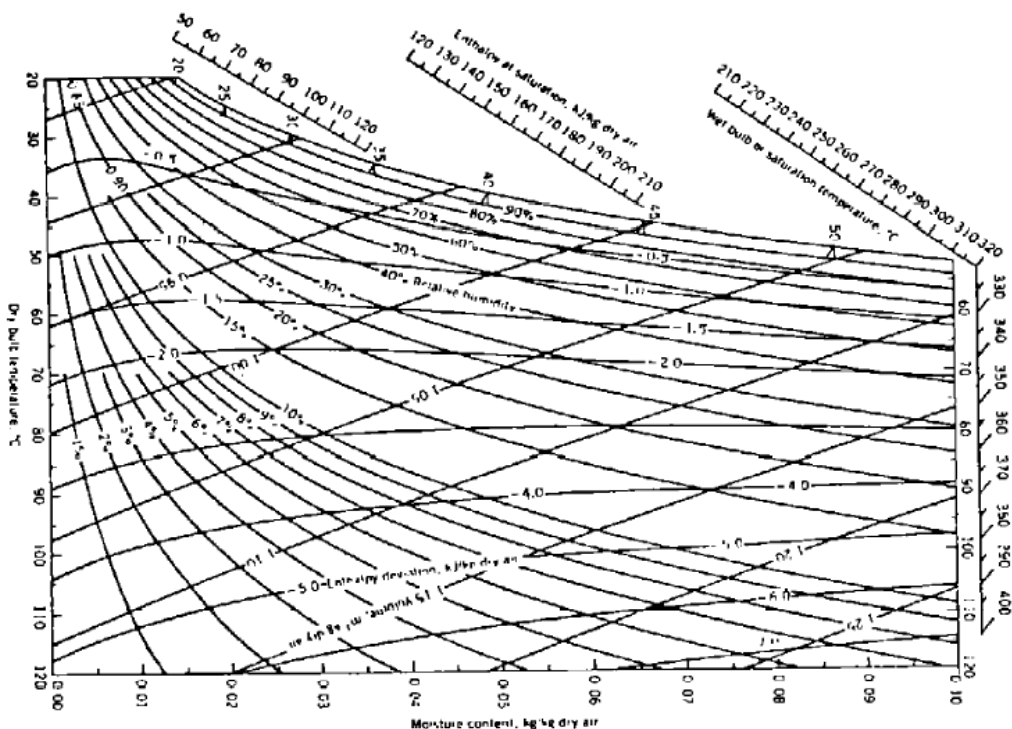


**Fig. 3 Psychrometric Chart [Air-Water Vapor at 101.325 kPa (=1 atm.)]**

## Classification of Industrial Drying

Industrial dryers may be classified according to the following categories:

1.  Method of operation

    This category refers to the nature of the production schedule. For large-scale production the appropriate dryer is of the continuous type with continuous flow of the material into and out of the dryer. Conversely, for small production

requirements, batch-type operation is generally desired. A typical classification of dryers based on the method of operation is given in Table 1.

2. Physical properties of material

The physical state of the feed is probably the most important factor in the selection of the dryer type. The wet feed may vary from a liquid solution, a slurry, a paste, or filter cake to free-flowing powders, granulations, and fibrous and non-fibrous solids. The design of the dryer is greatly influenced by the properties of the feed; thus dryers handling similar feeds have many design characteristics in common.

Table 2, represents a typical classification of dryers based on physical properties of material.

Note:

A comprehensive classification of commercial dryers based on properties of materials handled, is given in Perry's Chemical Engineering Handbook.

3. Conveyance

In many cases, the physical state of the feed dictates the method of conveyance of the material through the dryer; however, when the feed is capable of being preformed, the handling characteristics of the feed may be modified so that the method of conveyance can be selected with greater flexibility. Generally, the mode of conveyance correlates with the physical properties of the feed.

4. Method of energy supply

Where the energy is supplied to the material by convective heat transfer from a hot gas flowing past the material, the dryer is classified as a convection type. Conduction-type dryers are those in which the heat is transferred to the material by the direct contact of the latter with a hot metal surface.

5. Cost

Cost effect of dryer selection influence the classification of industrial drying. When capacity is large enough, continuous dryers are less expensive than batch units. Those operating at atmospheric pressure cost about 1/3 as much as those at vacuum. Once through air dryers are one-half as expensive as reciprocating gas equipment. Dielectric and freeze dryers are the most expensive and are justifiable only for sensitive and specialty products. In large scale drying, rotary, fluidized bed and pneumatic conveying dryers cost about the same.

6. Special process features

Special characteristics of the drying material together with particular features of the product is carefully considered in classifying of dryer and selection of dryer type. Hazardous, heat sensitive, quality sensitive products and cost effects can clearly dictate process consideration in classifications. A typical classification of dryers based on process special features is given in Table 3.

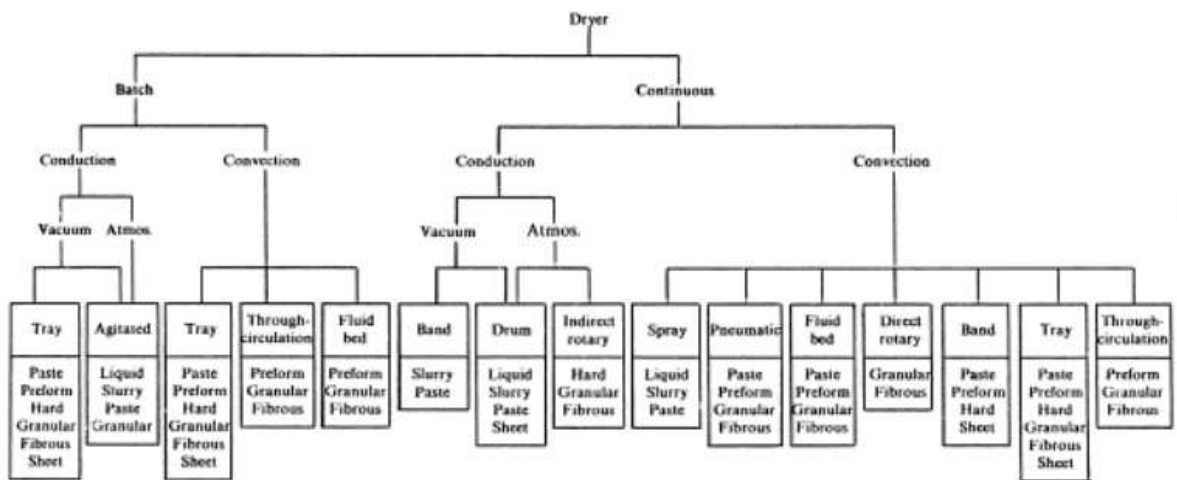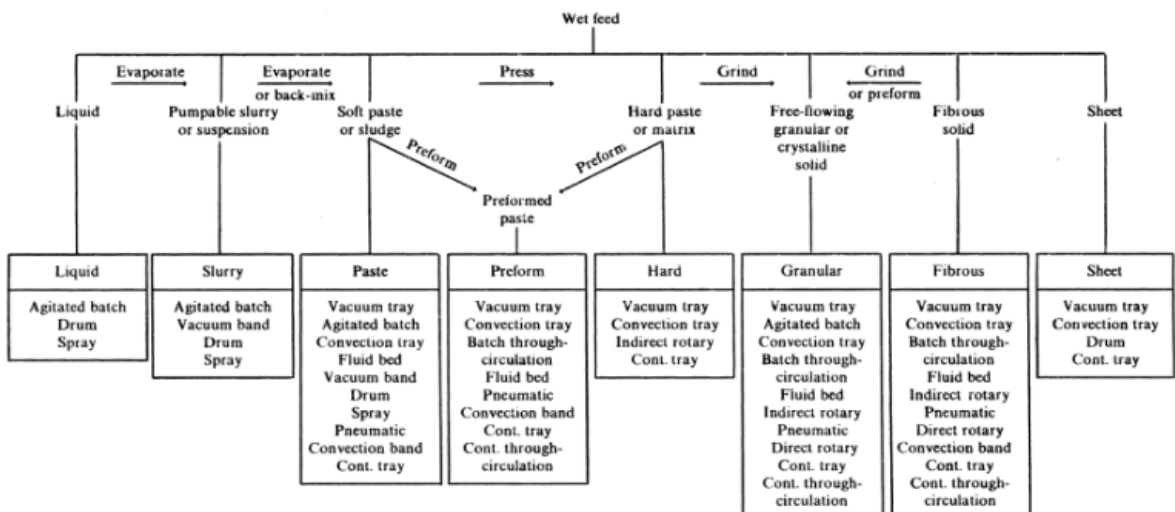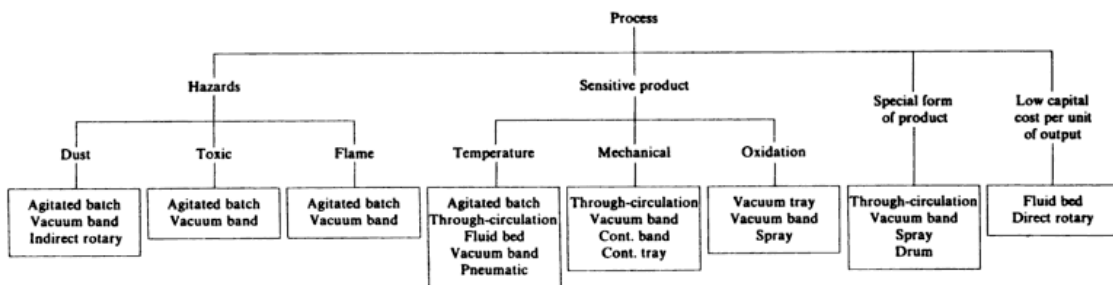**Table 1 - Classification of Dryers Based On Method of Operation**



**Table 2 – Classification of Dryers Based on Physical Form of Feed**

**Table 3 – Classification of Dryers by Suitability for Special Features**



7. Specification forms

A listing of key information to be specified for a typical design is given in Table 4.


**Selection of Dryer**

1. General

The choice of the best type of dryer to use for a particular application is generally dictated by the following factors:

a. the nature of the product, both physical and chemical;
b. the value of the product;
c. the scale of production;
d. the available heating media;
e. the product quality consideration;
f. space requirements;
g. the nature of the vapor, (toxicity, flammability);
h. the nature of the solid, (flammability, dust explosion hazard, toxicity).

For application of factors specified above, in selection of process, a systematic procedure involving the following steps is recommended:

a. Formulating of drying case as completely as possible:

In this step, the specific requirements and variables should explicit be identified; thus, the important information derived can be summarized as:

i) the product and its purity;
ii) initial and final moisture content;
iii) range of variation of initial and final moisture content;
iv) production rate and basis.

b. Collecting all available data related to the case:

In this step, the previous experience related to drying of particular product of interest or of a similar material should be investigated.

c. Physical and chemical properties to be established:

The physical and chemical properties of feed and product including physical state of feed (filter cake, granulations, crystals, extrusions, briquettes, slurry, paste, powder, etc.) including size, shape, and flow characteristics; chemical state of the feed (pH, water of crystallization, chemical structure, degree of toxicity of vapor or solid, corrosive properties, inflammability of vapor or solid, explosive limits of vapor); and physical properties of dry product (dusting characteristics, friability, flow characteristics, and bulk density). Finally, available drying data in the form of prior laboratory results, pilot-plant performance data, or full-scale plant data on the drying of similar materials should be obtained.

d. Defining of critical factors, constraints and limitations associated with particular product and with available resources:

- Any particular hazards related to the handling of the product (wet or dry) should be specifically and quantitatively identified.

- Any characteristics of the product that present potential problems should be recognized.

- Degree of uniformity of drying will work as an important consideration in the selection process.

e. Making a preliminary identification of the appropriate drying systems

In this Step, an identification of several dryer types that would appear to be appropriate should be made. This can be accomplished by simply comparing the properties and critical factors identified above with the characteristic features of the industrial dryers classified previously in this Standard.

f. Selection of optimal drying system and determining it's cost effectiveness:

This step, is followed on the basis of forging, and the optimal dryer type is identified and the appropriate design calculations or experimental programs can be conducted. Thus, the ultimate choice is usually that which is dictated by minimum total cost. However, it should be noted that a detailed economic analysis might lead to a selection based on maximum profit rather than minimum cost.

2. When selecting a dryer, there are several questions that need to be answered for all types of dryers. Rotary dryers will be used to illustrate problems because they dry more material than any other dryer. A few of the problems are as follows:

a.  What type of dryers can handle the feed? If the feed is liquid, dryers such as spray, drum, or one of the many special dryers that can be adapted to liquids may be used.

   If the feed is quite sticky, it may be necessary to recycle much of the product in order to use a certain type of dryer. The best solution to the feed problem is to try the material in a pilot unit. The pilot unit for a spray dryer needs to be near the size of the production unit as scale-up is quite difficult in this case.

b.  Is the dryer reliable? Is the dryer likely to cause shut-downs of the plant, and what performance history does this unit have in other installations? How long is the average life of this type of dryer?

c.  How energy-efficient is this type of dryer? For example, a steam tube dryer may have an efficiency of 85% while a plain tube type of rotary dryer may have an efficiency of only 50%. However, production of the steam entails additional costs so the plain tube may be more efficient in overall production.

   The higher the temperature of inlet gas stream, the higher the efficiency of the dryer in general. A fluid-bed dryer has a high back-mix of gas so it is possible to use a fairly high entering gas temperature.

   Any dryer can use recycled stack gas to lower the inlet gas temperature and thus obtain a high efficiency for dryer. However, if there is any organic material in the stack gas, it may be cracked to form a very fine carbonaceous particulate which is almost impossible to remove from the stack. Recycle also increases the dew point of the incoming gas which lowers the drying potential of the dryer. This lowering of the potential is quite important when drying heat-sensitive material.

d.  What type of fuel can be used for heating? Direct heating is usually the most efficient unit, and natural gas and LPG are the best fuels. However, both gases are getting more expensive and in many cases will not be available. The next best fuel is light fuel oil which can be burned readily with a "clean" stack.

   This material is expensive, and in some cases may be in short supply. The third best fuel is heavy fuel oil which is usually available, but this oil requires special burners and may not give a sufficiently clean stack. Coal is dusty and hard to handle.

   The stack gas usually is too contaminated for use in most installations.

e.  Does the dryer have a dust problem? Steam tube units use very low air flow and have minor dust problems, while a plain tube uses high air rates and may have serious dust problems. In some cases the stack dust removal devices may cost more than the dryer.

f.  How heat sensitive is the material to be dried? Most materials have a maximum temperature that can be used without the product deteriorating. This temperature is a function of the time of exposure as the thermal deterioration usually is a rate phenomena. Wet material can stand much higher temperatures in the gas due to the evaporation cooling.

   As an example: A rotary dryer working with alfalfa can use 760°C entering gas in a cocurrent unit. A countercurrent unit at this temperature would burn the alfalfa. As the temperature of the entering gas determines the efficiency of the dryer, concurrent dryers, on the average, are more efficient than countercurrent dryers.

g.  What quality of product will be obtained from the dryer? Freeze drying usually will give an excellent product, but the cost is prohibitive in most cases. A dryer needs to balance quality against cost of production of a satisfactory product.

h.  What space limitations are placed on the installation? There are certain height limitations in some buildings, and floor space may be limited or costly.

i.  Maintenance costs are often a major consideration. If moving parts either wear out or break down due to material "balling-up" or sticking, the plant may be shut down for repair, and repairs cost money. If this is problem, a record should be kept of the performance of the unit. It may be possible to get this information from a plant which is using this particular unit on a similar product.

j.  What is the labor cost? A tray dryer has high labor costs, but it is the best dryer in many cases where only small amounts of material need to be handled.

k.  Is a pilot unit available which can be used to get data to design the needed production facility? Nearly all new products need pilot plant data for a satisfactory design of a dryer.

   In the case of spray drying an industrial size unit needs to be used. Drum and rotary units and most other dryers can be scaled-up with sufficient success from laboratory sized units.

l.  What is the capital investment for the dryer and all the accessories?

m.  What is the power requirement for the dryer? A deep fluid-bed dryer needs hot gas at a higher pressure than most other dryers: 0.47 m³/s of gas requires approximately 0.75 kW per 102 mm of water pressure.

n.  What quantity of product is desired? For larger production a spray or rotary dryer should be considered. Rotary and spray dryers handle most

large production demands, but in small production plants other dryers are often more economical.

o. Can the dryer perform over a wide range of production rates and still give a satisfactory product in an efficient manner?

p. Is a sanitary dryer needed? A sanitary dryer is one that has no grooves or corners that can trap product, and hence can be easily cleaned. If no corrosion can be allowed, most of the units should be made of stainless steel.

Once the above points have been examined, it is possible to select a few types of dryers that appear to be the best for the particular operation. Sufficient information and data should be obtained on these dryers to determine the size needed. Firm quotations should be obtained from the manufacturers. The most economical dryer now can be selected on the basis of quality of product and capital and operating costs.

**Polymer Dryers**

1. Polymer dryers may be classified and selected according to the mode of heat transfer, i.e., direct-heat and indirect heat dryers. Dryers combining both heat-transfer modes are often used for polymer drying.

2. Radiant-heat dryers are not commonly used, because most polymers are heat sensitive to some degrees and material temperature is difficult to control under radiant sources.

3. Within broad ranges, polymer dryers may be classified on the basis of material residence time as:

   a. Short resident time: Spray dryers, pneumatic conveyors, drum dryers, and thin-film belt dryers, when the material residence time is less than one minute.

   b. Medium residence time: Continuous-fluid-bed dryers, vibrating-fluid-bed dryers, steam-tube dryers, and direct-heat rotary dryers; when the residence time is up to one hour.

   c. Long residence time: Batch fluid-bed dryers, batch or continuous-tray dryers, rotating-shelf dryers, hopper dryers, vacuum rotary and rotating dryers; when the residence times vary from one to several hours.

4. Short residence-time dryers are usually employed only for solutions and fine particle slurries during constant rate drying. The longer residence-time dryers are used for materials containing bound moisture and for operations involving