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Drying: Basic Food Preservation Method

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Abstract:
Drying is one of the most common and oldest method used for food preservation. It is used since antiquity. Benefits include increased shelf life and reduction of bulk. Fundamentals of drying include the drying curve and moisture content. Most commonly used dryers are rotary dryers, spray dryers, drum dryers, fluidized dryer, tunnel dryers, hot air dryers etc. selection criteria of dryers depend on the particular application.

1. Introuction[7]

Drying is perhaps the oldest, most common and most diverse of chemical engineering unit operations. Over four hundred types of dryers have been reported in the literature while over one hundred distinct types are commonly available. Energy consumption in drying ranges from a low value of under five percent for the chemical process industries to thirty five percent for the papermaking operations.

Drying occurs by effecting vaporization of the liquid by supplying heat to the wet feedstock. Heat may be supplied by convection (direct dryers), by conduction (contact or indirect dryers),radiation or volumetrically by placing the wet material in a microwave or radio frequency electromagnetic field. Over 85 percent of industrial dryers are of the convective type with hot air or direct combustion gases as the drying medium. Over 99 percent of the applications involve removal of water.

This is one of the most energy-intensive unit operations due to the high latent heat of vaporization and the inherent inefficiency of using hot air as the (most common) drying medium. This manual describes different types of dryers, their industrial applications and energy conservation opportunities. Although here we will focus only on the dryer, it is very important to note that in practice one must consider a drying system which includes pre-drying stages (e.g. mechanical dewatering, evaporation, pre-conditioning of feed by solids back mixing, dilution or pelletization and feeding) as well as the post-drying stages of exhaust gas cleaning, product collection, partial recirculation of exhausts, cooling of product, coating of product, agglomeration, etc. Energy cost reduction measures are also generally visible in pre and post drying operations and supporting equipments like blowers and pumps as well.

2 Fundamentals Of Drying:-[9][10]

2.1. The Drying Curve[8]

For each and every product, there is a representative curve that describes the drying characteristics for that product at specific temperature, velocity and pressure conditions. This curve is referred to as the drying curve for a specific product. Fig below shows a typical drying curve. Variations in the curve will occur principally in rate relative to carrier velocity and temperature.

Drying occurs in three different periods, or phases, which can be clearly defined.

- **The first phase**, or *initial period*, is where sensible heat is transferred to the product and the contained moisture. This is the heating up of the product from the inlet condition to the process condition, which enables the subsequent processes to take place. The rate of evaporation increases dramatically during this period with mostly free moisture being removed. In some instances, pre-processing can reduce or eliminate this phase. For example, if the feed material is coming from a reactor or if the feed is preheated by a source of waste energy, the inlet condition of the material will already be at a raised temperature

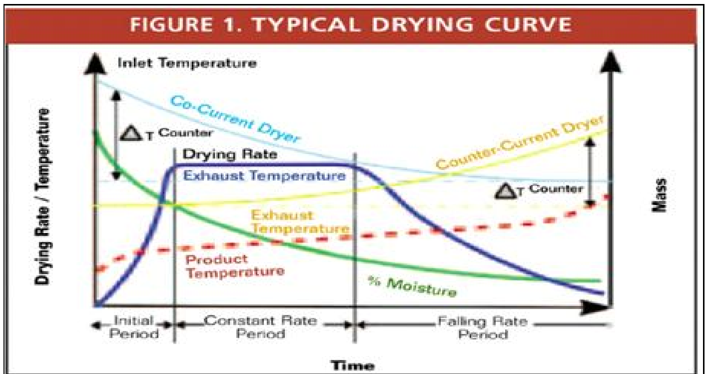

Figure 1. During processing, drying occurs in three different periods, or phases, which can be clearly defined.

Figure 1

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- **The second phase,** or *constant rate period*, is when the free moisture persists on the surfaces and the rate of evaporation alters very little as the moisture content reduces. During this period, drying rates are high, and higher inlet air temperatures than in subsequent drying stages can be used without detrimental effect to the product. There is a gradual and relatively small increase in the product temperature during this period. Interestingly, a common occurrence is that the time scale of the constant rate period may determine and affect the rate of drying in the next phase.
- **The third phase**, or *falling rate period*, is the phase during which migration of moisture from the inner interstices of each particle to the outer surface becomes the limiting factor that reduces the drying rate.

2.2. Moisture Content

Measuring moisture content allows control of the drying process such that drying is carried out until a specific level of moisture content is achieved rather than for a fixed time period.

- **Electrical resistance type meters** operate on the principle of electrical resistance, which varies minutely in accordance with the moisture content of the item measured. Most of these types of instruments are suitable for measuring moisture content in grain, wood, food, textiles, pulp, paper, chemicals, mortar, soil, coffee, jute, tobacco, rice, copra, and concrete. Resistance meters have an average accuracy of + 1% MC over their operating range.
- **Dielectric moisture meters** rely on surface contact with a flat plate electrode that does not penetrate the wood. Similar to resistance meters, the accuracy of dielectric meters in measuring average MC is + 1% moisture content.

Modern portable moisture balances are available with built in infrared heaters, which directly measures the moisture content of the product and gives a profile of moisture content variations with time. For measuring moisture content in paper rolls or stacks of paper, advanced methods include the use of Radio Frequency Capacitance method. The instrument measures the loss, or change, in RF dielectric constant as affected by the presence of moisture.

3. Classification of Dryers[1]

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

types	Criterion
• Batch · Continuous*	**Mode of operation**
· Convection*, conduction, radiation, electromagnetic fields, combination of heat transfer modes · Intermittent or continuous* · Adiabatic or non-adiabatic	Heat input-type
· Stationary · Moving, agitated, dispersed	State of material in dryer
· *Vacuum** · Atmospheric	Operating pressure
· Air* · Superheated steam · Flue gases	Drying medium (convection)
· Below boiling temperature* · Above boiling temperature · Below freezing point	Drying temperature
· Co-current · Counter-current	Relative motion between drying medium and drying

· Mixed flow	solids
· Single* · Multi-stage	Number of stages
· Short (< 1 minute) · Medium (1 60 minutes) · Long (> 60 minutes)	Residence time

Table 1

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

- **Direct dryers –**also known as convective dryers – are by far the most common. About 85 percent of industrial dryers are estimated to be of this type despite their relatively low thermal efficiency caused by the difficulty in recovering the latent heat of vaporization contained in the dryer exhaust in a cost-effective manner. Hot air produced by indirect heating or direct firing is the most common drying medium although for some special applications superheated steam has recently been shown to yield higher efficiency and often higher product quality. In direct dryers, the drying medium contacts the material to be dried directly and supplies the heat required for drying by convection; the evaporated moisture is carried away by the same drying medium. Drying gas temperatures may range from 50º C to 400º C depending on the material.
- **Indirect dryers –** involve supplying of heat to the drying material without direct contact with the heat transfer medium, i.e., heat is transferred from the heat transfer medium (steam, hot gas, thermal fluids, etc.) to the wet solid by conduction. Since no gas flow is presented on the wet solid side it is necessary to either apply vacuum or use gentle gas flow to remove the evaporated moisture so that the dryer chamber is not saturated with vapor. Heat transfer surfaces may range in temperature from -40º C (as in freeze drying) to about 300º C in the case of indirect dryers heated by direct combustion products such as waste sludges. In vacuum operation, there is no danger of fire or explosion. Vacuum operation also eases recovery of solvents by direct condensation thus alleviating serious environmental problem.

Heat may also be supplied by radiation (using electric or natural gas-fired radiators) or volumetrically by placing the wet solid in dielectric fields in the microwave or radio frequency range. Since radiant heat flux can be adjusted locally over a wide range it is possible to obtain high drying rates for surface-wet materials. Convection (gas flow) or vacuum operation is needed to remove the evaporated moisture. Radiant dryers have found important applications in some niche markets, e.g., drying of coated papers or printed sheets. However, the most popular applications involve use of combined convection and radiation. It is often useful to boost the drying capacity of an existing convective dryer for sheets such as paper.

4. Different types of dryers:-[2][3][5]

4.1. Rotary Dryers

The cascading rotary dryer is a continuously operated direct contact dryer consisting of a slowly revolving cylindrical shell that is typically inclined to the horizontal a few degrees to aid the transportation of the wet feedstock which is introduced into the drum at the upper end and the dried product withdrawn at the lower end . To increase the retention time of very fine and light materials in the dryer (e.g., cheese granules), in rare cases, it may be advantageous to incline the cylinder with the product end at a higher elevation.

The drying medium (hot air, combustion gases, flue gases, etc.) flows axially through the drum either concurrently with the feedstock or counter currently. The latter mode is preferred when the material is not heat-sensitive and needs to be dried to very low moisture content levels. The concurrent mode is preferred for heat-sensitive materials and for higher drying rates in general. In this type of dryer, a wide assortment of granular products of diverse shapes, sizes and size distributions can be processed by proper design of the internal flights and lifters.

Rotary dryers are very flexible, very versatile and are especially suited for high production rate demands. On the negative side, they are typically less efficient, demand high capital costs and significant maintenance costs depending on the material being dried. They are not recommended for fragile materials and for low production rates. Finally, it is useful to note that while most of the continuous rotary dryers are operated under near atmospheric pressure, the term vacuum rotary dryer refers to an entirely different class of dryers.

4.2. Pneumatic/Flash Dryer

The pneumatic or 'flash' dryer is used with products that dry rapidly owing to the easy removal of free moisture or where any required diffusion to the surface occurs readily. Drying takes place in a matter of seconds. Wet material is mixed with a stream of heated air (or other gas), which conveys it through a drying duct where high heat and mass transfer rates rapidly dry the product. Applications include the drying of filter cakes, crystals, granules, pastes, sludges and Slurries; in fact almost any material where a powdered product is required. Salient features are as follows.

- Particulate matter can be dispersed, entrained and pneumatically conveyed in air. If this air is hot, material is dried.
- Pre-forming or mixing with dried material may be needed feed the moist material
- The dried product is separated in a cyclone. This is followed by separation in further cyclones, fabric sleeve filters or wet scrubbers.
- This is suitable for rapidly drying heat sensitive materials. Sticky, greasy material or that which may cause attrition (dust generation) is not suitable.

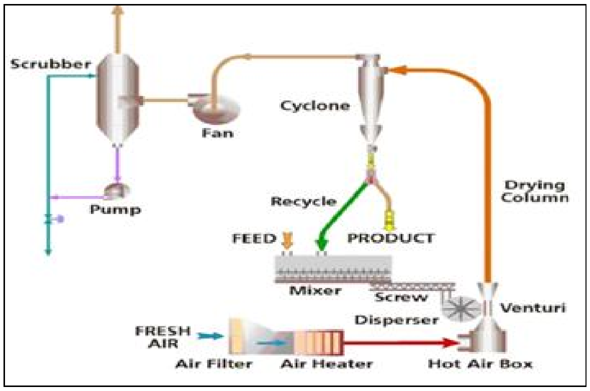

Figure 2: Pneumatic/Flash Dryer

4.3. Spray Dryers

Atomized material in the form of a spray is contacted with hot gas in a suitably designed drying chamber. Proper selection and design of the atomizer is vital to the operation of the spray dryer as it is affected by the type of feed (viscosity), abrasive property of the feed, feed rate, desired particle size and size distribution as well as the design of the chamber geometries and mode of flow, e.g., concurrent, countercurrent or mixed flow .

It must be noted that design of spray dryers depends heavily on pilot scale testing. It is impossible to scale-up quality criteria for spray dryers. Fortunately, in most cases, it is found that the larger scale dryer provides better quality product than the one obtained in smaller scale pilot tests. Aside from drying rate and quality tests, it is also important to check potential of deposits in the drying chamber as this may lead to fire and explosion hazards. Essentially, three major types of atomizers are used in practice. They are: Rotary wheel (or disk) atomizers, Pressure nozzle and Two-fluid nozzle.

The design of the spray drying chamber depends on the needed residence time .The mode of flow, i.e., concurrent, counter-current, mixed flow, depends on the desired characteristics of product as summarized below.

Recommended for	Residence time in chamber
Fine, non-heat sensitive products; surface moisture removal, non-hygroscopic	Short (10-20 s)
Fine-to-coarse sprays (dmean = 180 _m); drying to low final moisture	Medium (20-35 s)
Large powder (200-300 _m); low final moisture, low temperature operation for heat-sensitive products	Long (> 35 s)

Table 2: Residence time requirements for spray drying of various products

Characteristics	Dryer design – flow type
Low product temperature	Concurrent
To produce agglomerated powder	Mixed flow with integrated fluidized beds
For coarse sprays in small chambers; product no heat-sensitive	Mixed flow (fountain type)
Products which withstand high temperatures; coarse particles; high bulk density powders	Counter-current flow

Table 3: Selection of mode of flow in spray drying chamber based on desired powder Characteristics

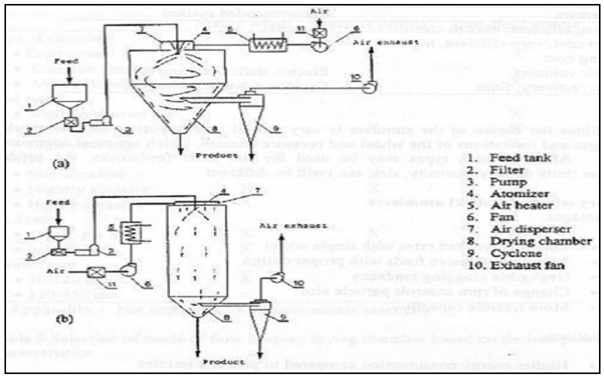

Figure 3: A process schematic of a spray dryer plant

Since the choice of the atomizer is very crucial it is important to note the key advantages and limitations of the wheel and pressure nozzles, which are most common in practice. Although both types may be used for the same feedstocks, the product properties (bulk density, porosity, size, etc.) will be different.

<u>4.3.1. Rotary wheels (or disk) atomizers</u>

- Advantages: Handle large feed rates with single wheel, nuited for abrasive feeds with proper design, negligible clogging tendency, Change of rpm controls particle size and more flexible capacity
- Limitations: Higher energy consumption compared to pressure nozzles, more expensive and broad radical spray requires large drying chamber (cylindrical-conical type)

<u>4.3.2. Pressure nozzles</u>

- Advantages: Simple, compact, cheap, no moving parts,and low energy consumption
- Limitations: Low capacity (flow rates), high tendency to clog and erosion can change spray characteristics

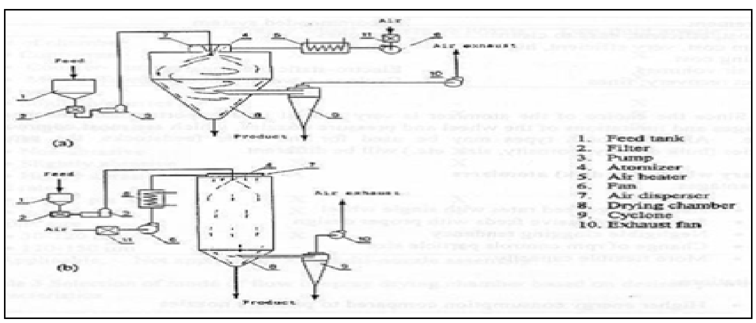

Figure 4

Figure below shows the layout of a spray dryer system, which is self-inertizing and used to handle materials with high risk of fire and explosion. Here, excess air entering the system passes through the burner flame and used as combustion air thus was inactivating it.

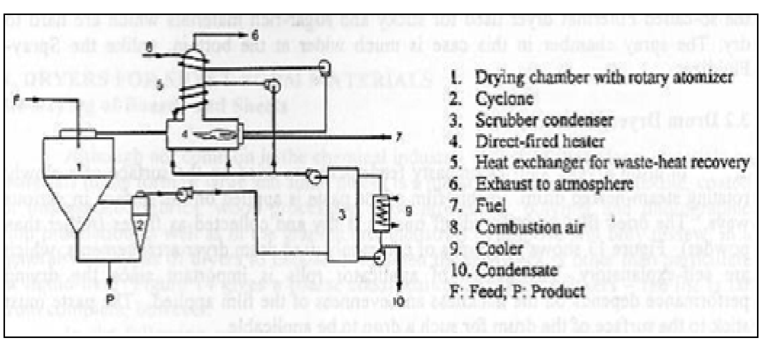

Figure 5: Self-inertizing spray dryer system

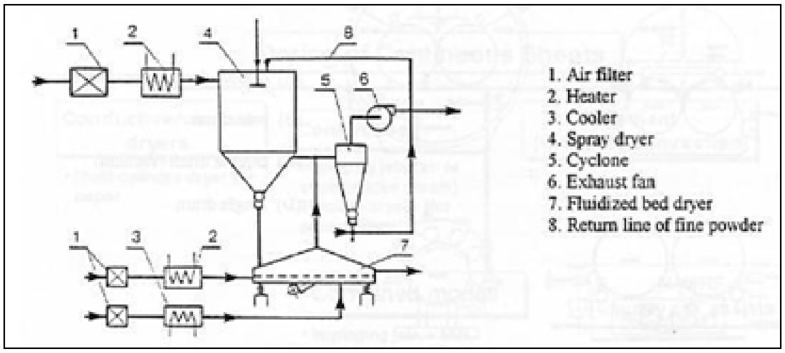

Figure 6

4.4. Drum Dryers

In drum dryers, slurries or pasty feedstocks are dried on the surface of a slowly rotating steam-heated drum. A thin film of the paste is applied on the surface in various ways. The dried film is doctored off once it is dry and collected as flakes (rather than powder). Figure 13 shows four types of commonly used drum dryer arrangements, which are self-explanatory. The design of applicator rolls is important since the drying performance depends on the thickness and evenness of the film applied. The paste must stick to the surface of the drum for such a drop to be applicable.

Four key variables influence the drum dryer performance. They are: (a) steam pressure or heating medium temperature, (b) Speed of rotation, (c) Thickness of film and (d) Feed properties, e.g., solids concentration, rheology and temperature. Because it allows good control of the drying temperature, drum dryers may be used to produce a precise hydrate of a chemical compound rather than a mixture of hydrates.

Vacuum operation of both single- and double-drum dryers are done commercially to enhance drying rates for heat-sensitive materials, such as pharmaceutical antibiotics. They are also used when a porous structure of product is desired. When recovery of solvents is an issue, once again, vacuum operation is recommended. When recovering high boiling point solvents such as ethylene glycol, lowering the pressure depresses the boiling point. For a detailed description and discussion of the various types of drum dryers, the reader is referred to Moore (1995).

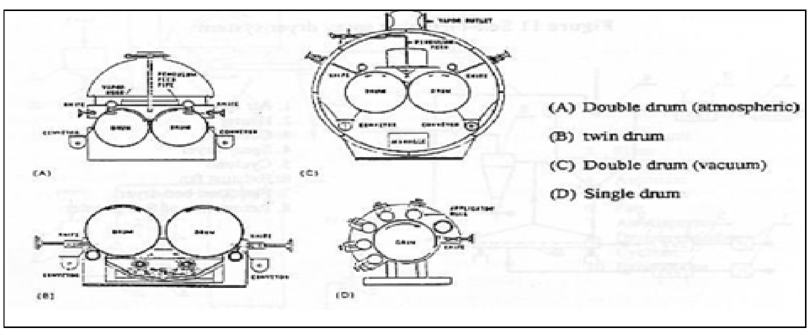

Figure 7: Four types of drum dryers in common use

4.5. Fluidised Bed Dryers

Fluid bed dryers are found throughout all industries, from heavy mining through food, fine chemicals and pharmaceuticals. They provide an effective method of drying relatively free flowing particles with a reasonably narrow particle size distribution. In general, fluid bed dryers operate on a through-the-bed flow pattern with the gas passing through the product perpendicular to the direction of travel. The dry product is discharged from the same section.

- With a certain velocity of gas at the base of a bed of particles, the bed expands and particles move within bed.
- Batch/continuous flow of materials is possible.
- The hot gas stream is introduced at the base of the bed through a dispersion/distribution plate and high rate of heat transfer is achieved with almost instant evaporation.

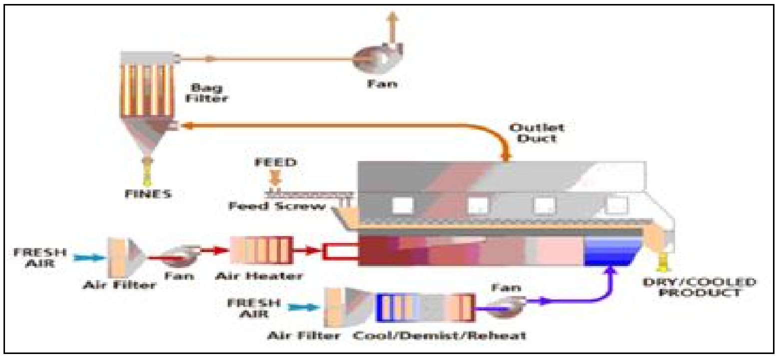

Figure 8: Fluidised bed dryer

4.6. Tunnel Dryers

In this simple dryer concept, cabinets, trucks or trolleys containing the material to be dried are transported at an appropriate speed through a long insulated chamber (or tunnel) while hot drying gas is made to flow in concurrent, countercurrent, cross-flow or mixed flow fashion . In the concurrent mode, the hottest and driest air meets the wetted material and hence results in high initial drying rates but with relatively low product temperature (wet-bulb temperature if surface moisture is present). Higher gas temperatures can be used in concurrent arrangements while in counter-current dryers the inlet drying gas must be at a lower temperature if the product is heat-sensitive. If the material to be dried is not heat-sensitive and low residual moisture content is a requirement, one may employ higher gas temperatures in the countercurrent arrangement as well. Combination flow or cross-flow arrangements are used less commonly. The latter offer high drying rates but the tunnels must be designed to fit the trolleys snugly so the drying gas flows through the material much like a through-circulation packed bed dryer. Total drying times that can be handled range from 30 minutes to 6 hours.

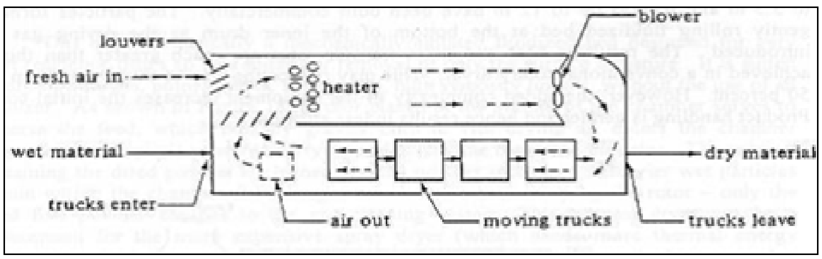

Figure 9; A tunnel dryer

4.7. Band Dryers

For relatively free-flowing granules and extrudates that may undergo mechanical damage if they are dispersed, band dryers are a good option. It is essentially a conveyor dryer wherein the band is a perforated band over which the bed of drying solids rests.

Drying air at rather low velocities flows upwards through the band to accomplish drying. Clearly, this type of dryer is not a good choice for very wet or very fine solids. Gas cleaning requirements are minimal as low gas velocities are used. Also, power requirements for air handling are low due to the low pressure drops needed. In commercial designs of very large band dryers, it is important to ensure uniform distribution of the product on the band and also uniform distribution of the air flow within the chamber of the dryer to ensure uniform product moisture content.

4.8. Hot Air Dryer- Stente

Fabric drying is usually carried out on either drying cylinders (intermediate drying) or on stenters (final drying). Drying cylinders are basically a series of steam-heated drums over which the fabric passes. It has the drawback of pulling the fabric and effectively reducing its width. For this reason it tends to be used for intermediate drying.

The stenter is a gas fired oven, with the fabric passing through on a chain drive, held in place by either clips or pins. Air is circulated above and below the fabric, before being exhausted to atmosphere. As well as for drying processes, the stenter is used for pulling fabric to width, chemical finishing and heat setting and curing. It is a very versatile piece of equipment.

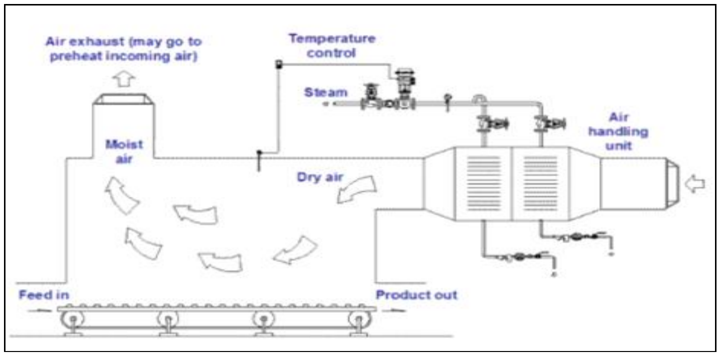

Figure 10: Schematic of a stenter

Modern stenters are designed with improved air circulation, which helps to improve drying performance, and with integrated heat recovery and environmental abatement systems. Infrared drying is used for both curing and drying. It is used as either a stand-alone piece of equipment or as a pre-dryer to increase drying rates and hence fabric speed through a stenter.
In the carpet industry there are a number of different types of drying/curing machine used. Wool wash dryers at the end of scouring machines for drying the loose stock wool; wool drying ranges for drying wool hanks prior to weaving; and wide 4 and 5-metre latexing or backing machines used to apply and dry/cure the latex backing on to carpets. Low level VOC emissions are produced by this process.

4.9. Infrared Dryers

Infrared (IR) dryers may be gas-fired ceramic radiators or electrically heated panels. The IR wavelength range is from 0.1 mm to 100 mm, which generates heat in the exposed physical body. The wavelength ranges 0.75 - 3.0 mm; 3.0 - 25 mm and 25 – 100 mm are referred to as near IR, middle IR and far IR ranges, respectively. Industrial radiators are of two types: (1) Light radiators (near IR), e.g., quartz glass with peak radiation intensity at 1.2 mm and (2) Dark radiators, e.g., ceramic (3.1 mm) or metal radiators (2.7 - 4.3 mm).
While convection can yield heat fluxes of the order of 1-2 kW m-2, radiation can yield much higher levels of heat flux, i.e., 4-12 kW m-2 (light radiators) or 4-25 kW m-2 (dark radiators). In many drying operations, the evaporation rates feasible are not high enough to require IR radiators, however. There are some niche applications for IR dryers in some certain industries, e.g., drying of coated paper, booster drying of paper in paper machines. They offer the advantages of compactness, simplicity, ease of local control and low equipment costs. Also, in combination with convection, IR dryers offer the potential for significant energy savings and enhancement in drying rates with better product quality.
On the negative side, the high heat flux may scorch product and enhance fire and explosion hazards. Clearly, IR must be used in conjunction with convection or vacuum. Good control is essential for the safe operation, i.e., IR power source must be cut off if there is upset in the process which may lead to overheating of the product.

4.10. Tray Dryers

By far the most common dryer for small tonnage products, a batch tray dryer consists of a stack of trays or several stacks of trays placed in a large insulated chamber in which hot air is circulated with appropriately designed fans and guide vanes.
Often, a part of the exhausted air is re-circulated with a fan located within or outside the drying chamber. These dryers require large amount of labor to load and unload the product. Typically, the drying times are long (10-60 hours). The key to successful operation is the uniform air flow distribution over the trays as the slowest drying tray decides the residence time required and hence dryer capacity. Warpage of trays can also cause poor distribution of drying air and hence poor dryer performance.

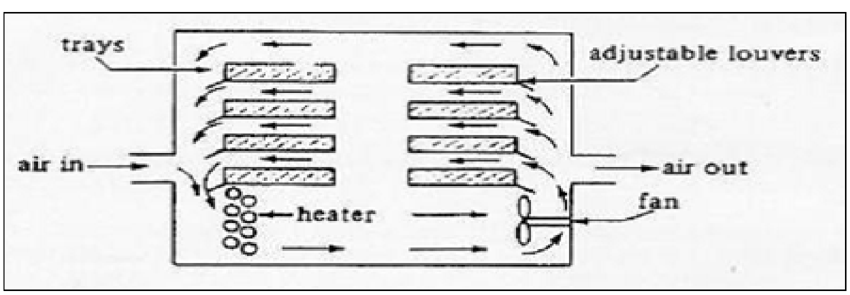

Figure 11

4.11. Freeze Dryers

Highly heat-sensitive solids, such as some certain biotechnological materials, pharmaceuticals and foods with high flavor content, may be freeze dried at a cost that is at least one order-of-magnitude higher than that of spray drying – itself not an inexpensive drying operation. Here, drying occurs below the triple point of the liquid by sublimation of the frozen moisture into vapor, which is then removed from the drying chamber by mechanical vacuum pumps or steam jet ejectors. Generally, freeze drying yields the

highest quality product of any dehydration techniques. A porous, non-shrunken structure of the product allows rapid rehydration. Flavor retention is also high due to the low temperature operation (-40o C). Living cells, e.g., bacteria, yeast's and viruses can be freeze dried and the viability on reconstitution can still be high. Mammalian cells, however, cannot be preserved by freeze drying. Because of its inherently high cost nature, freeze drying is not common in the chemical industry.
Dried products are unloaded through a vacuum lock at the other end of the drying chamber. Low pressure steam is used to heat the plates on which the trays sit. Liapis and Bruttini (1995) have provided a detailed analysis of the drying characteristics, costs and details on various freeze dried products.

4.12. Vacuum Dryers

For drying of granular solids or slurries, vacuum dryers of various mechanical designs are available commercially. They are more expensive than atmospheric pressure dryers but are suited for heat-sensitive materials or when solvent recovery is required or if there are risks of fire and/or explosion. Single-cone and double-cone mixers can be adapted to drying by heating the vessel jackets and applying vacuum to remove moisture.

4.13. Microwave (MW) and Radio Frequency (RF) Drying

Unlike conduction, convection or radiation, dielectric heating heats a material containing a polar compound volumetrically, i.e., thermal energy supplied at the surface does not have to be conducted into the interior, as limited by Fourier's law of heat conduction. This type of heating provides advantages of enhanced diffusion of heat and mass, development of internal pressure gradients which enhance drying rates, increased drying rates without increasing surface temperatures and better product quality
When an alternating electromagnetic field is applied to a “lossy” dielectric material, heat is generated due to friction of the excited molecules with asymmetric charges, e.g., water. This is a result of ionic conduction or dipole oscillations (Strumillo and Kudra,1986). The radio frequency range extends from 1-300 MHz while the microwave range is from 300 to 3000 MHz. However, only specific frequency ranges are permitted for industrial heating applications, i.e., ranges 13.56, 27.12 and 40 MHz for RF and 915 (896 in Europe) and 2450 MHz for MW.
The main limitation of MW and RF drying is that the technique is highly capital-intensive. It also consumes high-grade energy, i.e., electricity, and the conversion efficiency to dielectric field is only in the order of 50%. Thus, these techniques are suited only for special applications involving very high value products, extremely long drying time to remove traces of moisture or to obtain products of special characteristics not obtained otherwise.
It is therefore not surprising that MW/RF drying is used only in special niche applications. Further, these techniques are used mainly to boost drying capacity (to remove free water rapidly without generation of large thermal gradients in the material) or to remove the last few percent of water which comes out very slowly. Generally, dielectric heating is combined with convection or vacuum to reduce the energy consumption. Microwave vacuum drying and microwave freeze drying are among the commercial drying technologies that have so far found some applications. Microwave freeze drying is typically carried out at temperatures well below the triple point of water.

5. Selection of Dryers:-[1][4]

In view of the enormous choices of dryer types one could possibly deploy for most products, selection of the best type is a challenging task that should not be taken lightly nor should it be left entirely to dryer vendors who typically specialize in only a few types of dryers. The user must take a proactive role and employ vendors' experience and benchscale or pilot-scale facilities to obtain data, which can be assessed for a comparative evaluation of several options. A wrong dryer for a given application is still a poor dryer, regardless of how well it is designed. Note that minor changes in composition or physical properties of a given product can influence its drying characteristics, handling properties, etc., leading to a different product and in some cases severe blockages in the dryer itself.
Tests should be carried out with the “real” feed material and not a “simulated” one where feasible. Although here we will focus only on the selection of the dryer, it is very important to note that in practice one must select and specify a drying system which includes predrying stages (e.g., mechanical dewatering, evaporation, pre-conditioning of feed by solids backmixing, dilution or pelletization and feeding) as well as the post-drying stages of exhaust gas cleaning, product collection, partial recirculation of exhausts, cooling of product, coating of product, agglomeration, etc. The optimal cost-effective choice of dryer will depend, in some cases significantly, on these stages. For example, a hard pasty feedstock can be diluted to pumpable slurry, atomized and dried in a spray dryer to produce a powder, or it may be pelletized and dried in a fluid bed or in a through circulation dryer, or dried as is in a rotary or fluid bed unit. Also, in some cases, it may be necessary to examine the entire flow sheet to see if the drying problem can be simplified or even eliminated. Typically, non-thermal dewatering is an order-of-magnitude less expensive than evaporation which, in turn, is many-fold energy efficient than thermal drying. Demands on product quality may not always permit one to select the least expensive option based solely on heat and mass transfer considerations, however. Often, product quality requirements have over-riding influence on the selection process.
As a minimum, the following quantitative information is necessary to arrive at a suitable dryer:

- Dryer throughput; mode of feedstock production (batch/continuous)
- Physical, chemical and biochemical properties of the wet feed as well as
- desired product specifications; expected variability in feed characteristics
- Upstream and downstream processing operations
- Moisture content of the feed and product
- Drying kinetics; moist solid sorption isotherms

- Quality parameters (physical, chemical, biochemical)
- Safety aspects, e.g., fire hazard and explosion hazards, toxicity
- Value of the product
- Need for automatic control
- Toxicological properties of the product
- Turndown ratio, flexibility in capacity requirements
- Type and cost of fuel, cost of electricity
- Environmental regulations
- Space in plant

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