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A REVIEW OF SPRAY DRYER DESIGN

Kuye A. O[1], D. B. Ayo[6], K. O Okpala[2], T. O. Folami[3], F. O. Chukwuma[1], A. S Ahmed[4], S. N Mumah[5], I. I. Ismail[6], C. Hamilton[6], I. O Ejuya[6], and U. M. Mansur[6]

[1] *Department of Chemical Engineering, University of Port Harcourt, PMB 5323, Port Harcourt.*

[2] *Department of Chemical Engineering, Federal University of Technology, PMB 1526, Owerri.*

[3] *TOF Engineers and Consulting Limited, 56 Femi Ayantuga Cresent, Surulere, Lagos*

[4] *Department of Chemical Engineering, Ahmadu Bello University, Zaria*

[5] *Department of Chemical Engineering, Kaduna Polytechnic, Kaduna*

[6] *Raw Materials Research and Development Council, Abuja*

Abstract: A spray dryer is unit equipment in which a feed that is in the form of solution, slurry, or paste is converted into a dry powder, granules or agglomerates. The main components of a spray dryer include the atomizer, spray chamber and powder separation unit. Separation of the dried powder from the drying air is carried out partly within the drying chamber itself and partly in secondary separation equipment such as gas cyclone. Cyclone separators operate on the 'momentum separation' principle (centrifugal action) and are extensively used in large scale dryers for removal of fines. The design of spray dryer consists of estimating the physical specification of each of the main components within given performance constraints. Design methods for the atomizer and cyclone systems are fairly standardized. The design for the spray chamber is still largely empirical. Knowledge of the manner in which air and spray are contacted and about the flow pattern of both air and the droplets is essential for the sizing of the spray chamber, characterized by its diameter and height. A simple method that is commonly used for general purpose spray dryer is to estimate the chamber volume from the product of the residence time of the drying drops and the overall gas flow rate. The more accurate method involves developing a mathematical model which is solved by computer analysis using experimentally determined data on heat and mass transfer coefficients. An accurate prediction of droplet trajectories will enhance a good estimation of spray chamber size and efficiency. This paper presents a review of the available model equations and sequences used in the design of spray dryers.

Keywords: Spray dryer, Design

INTRODUCTION

Spray dryer is unit equipment in which a feed that is in the form of solution, slurry, or paste is converted into a dry powder, granules or agglomerates. Spray drying process is achieved by atomizing the feed into a hot drying medium usually air which rapidly evaporates the moisture

in the feed. Spray drying has become the most important method for drying various products including fluid foods (See Table 1), clays, detergents, pharmaceutical products and chemicals. The advantage of spray drying over many other drying processes is that both mass and energy are transferred in a very short time without using an exchange surface medium and keeping the product temperature relatively low. Most spray drying processes achieve product temperature below 100oC especially for food applications where products sensitive to temperature are often maintained between 50 and 75oC.

The spray drying process consists of producing a spray of feed material by atomization as homogeneous as possible and mixing it vigorously with a hot air flow. The size and uniformity of the droplets are determined by the atomization. The atomizer generates a larger surface area for transferring the injected energy to the product. The mixing is carried out in a chamber, which has several possible configurations (Fig 1).

Evaporation of moisture from the droplets and formation of dry particles are processed under controlled temperature and airflow conditions. Separation of dry particles is carried out partly within the drying chamber itself and partly in secondary separation equipment. In general it is easy to remove 90% or more of the powder, which is discharged continuously from the drying chamber bottom. The removal of the remainder is carried out using cyclone separations. The exit gas stream, from the cyclones, are more often sent through wet scrubbers to further clean the gas before discharge into the environment.

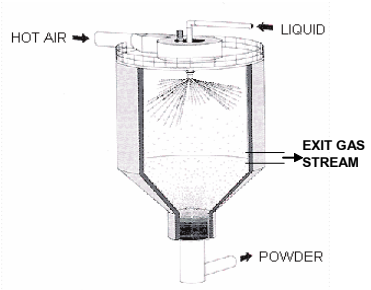

Fig 1: Typical Spray Dryer Chamber Configuration

Table 1: Foods currently processed using spray drying.

Bananas	Egg (whole)	Proteins (animals)
Blood	Egg (white)	Proteins (milk)
Cake mixes	Egg (yolk)	Proteins (plants)
Citrus Juice	Fish concentrates	Shortening (bakery)
Coffee	Infant formulas	Starch derivatives
Corn syrup	Milk (whole)	Tea
Cream	Milk (skim)	Tomato puree
Creamers (coffee)	Milk (replacers)	Yeast
Cremes (pharmac.)	Potatoes	Yogurt

Fig 2 shows a schematic representation of a typical spray drying system for milk powder. The dry powder is separated from the moist air in cyclones by centrifugal action. The centrifugal action is caused by the great increase in air speed when the mixture of particles and air enters the cyclone system. The dense powder particles are forced toward the cyclone walls while the lighter, moist air is directed away through the exhaust pipes. The powder settles to the bottom of the cyclone where it is removed through a discharging device

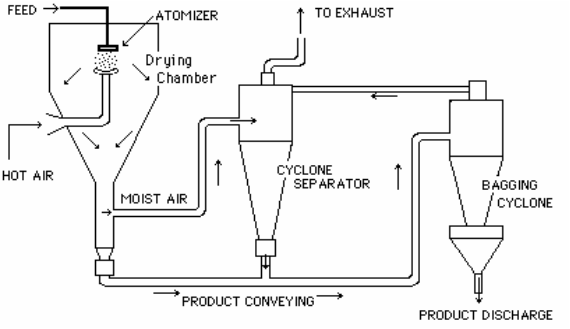

Fig 2: A typical spray drying system for milk powder

THEORY OF SPRAY DRYING PROCESS

A spray drying system may consist of the following unit operations:

- Pre-concentration of liquid feed
- Atomization (creation of droplets)
- Drying of the droplets in stream of hot, dry air
- Separation of powder from moist air
- Cooling
- Packaging of product

Some of these unit operations are described as follows.

Pre-concentration of Liquid Feed

In spray drying operation it is usual practice to pre-concentrate the liquid feed as much as possible for the following reasons:

- Economy of operation (evaporation is less expensive)
- Increased capacity
- Increase of particle size (each droplet contains more solids)
- Increase of particle density (reduction of vacuole size)
- More efficient powder separation (related to increased density)
- Improved dispersibility of product (reduction in surface area)

The powder structure and, therefore, the physical properties of a powder are very dependent upon the total solids concentration of the liquid feed which is being dried. If the droplets are maintained at a constant size, then, the amount of solids will affect both the size and the density of the dry particles. The structure of a spray-dried particle is a hollow sphere, with the solids being a shell which surrounds a central vacuole (Fig 3). As the total solids of the feed increases, the shell becomes thicker and, as a consequence, the particle does not shrink as much during drying. Similarly, as the air-filled vacuole decreases in size, the particle density increases. The increase in particle density has a pronounced influence on the efficiency of powder separation/collection by the cyclones, because these operate on the principle of a difference in the buoyant density difference between air and particles. Drying a liquid of low solids content is the cause of very fine particles which are difficult to collect which results in product losses as well as environmental pollution when they are discharged into the atmosphere.

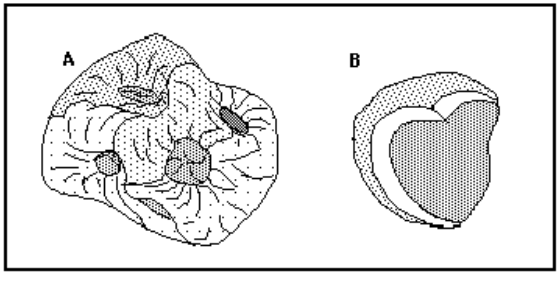

Fig 3: The Structure of Spray-Dried Particle, A: External view and B: Cut-view.

The limit on the extent of pre-concentration of the feed is dictated by the viscosity of the liquid, which must not be so high, that the product cannot be pumped or atomized. For milk powder manufacture, it is common to pre-concentrate the milk (9% total solids in skim milk; 13% total solids in whole milk) to 45% in an evaporator.

45% is also typical for clays. For many protein isolates, such a high concentration cannot be used, because most protein solutions are very viscous. In this case, spray drying must be done with a concentrate of about 25% total solids concentration.

Atomization

The formation of a spray is the characteristic of spray drying, as the name suggests. The selection and operation of the atomizer is of supreme importance in achieving economic production of top quality product. The atomization stage must create a spray for optimum evaporation conditions, leading to formation of the desired product.

Atomization is a high technology area where a variety of atomizers based on different principles and mechanisms are developed and used in spray dryers. Although details of the drop forming process vary widely among the different types of atomizers, the following events are common to all of these processes:

1. The applied force, whether due to pressure or rotation, separate protuberances, filaments, or sheets of liquid from the bulk liquid.
2. These protuberances, filaments, or sheets are broken up (owing to their inherent instability and to interact with a mass of gas or liquid) into small particles.
3. These particles assume spherical shape if they are small enough. Or, if large enough to be unstable, they break into smaller masses, which then become spherical.

Atomization governs the size and uniformity of the droplets, and the initial droplet size distribution of the spray generated by the atomizer forms the basis of the chamber design. Karel (1975) has described this operation as the most important feature of a spray dryer. The three principal types of atomizers used today are rotary atomizers, pressure nozzles and pneumatic nozzles. Rotary atomizers are generally employed for high capacities owing to their flexibility and ease of maintenance. Pressure nozzles are preferred for highly viscous feeds and where multiple atomizers are desired. Pneumatic nozzles are used only for small capacities due to the high cost of compressed air and their low efficiency.

Rotary (Centrifugal) Atomizers

Rotary atomizers, also known as centrifugal atomizers utilize centrifugal force to overcome the cohesive surface tension and viscous forces and break the liquid into droplets. Feed is introduced centrally into a wheel or disk rotating at high speed (2000-20,000 rpm). The feed flows outwards over the surface, accelerating to the periphery. Feed, on leaving the periphery, readily disintegrates into a spray of droplets. Rotary atomizers form a low pressure system. A wide variety of spray characteristics can be obtained for a given product through combinations of feed rate, atomizer speed and atomizer design. Designs of atomizer wheels have vanes, spacers or bushings. Designs of disk include vane-less plates, cups and inverted bowls. Figs 4 and 5 present two designs of rotary atomizers.

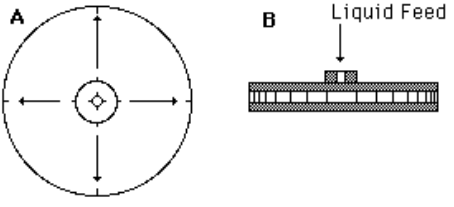

Fig 4: Rotary Atomizer with Spacers, A: Top view, B: Side view

Fig 5: Disk Type Rotary Atomizer

Rotary atomizers are reliable, easy to operate and can handle fluctuating feed rates. They have fewer tendencies to become clogged. For this reason, they are preferred for spray drying of non-homogeneous foods. Further advantages include their ability to handle high feed rates without atomizer duplication, and to handle abrasive feeds.

Droplet Sizes Produced from Rotary Atomizer

The mean droplet size, defined as surface mean diameter, is the diameter of a droplet with the same surface-volume ratio as the whole spray cloud. It increases with increased liquid flow rate, viscosity and surface tension and diminishes with increased rotary speed, disk diameter, wetted periphery and liquid density. The relations depend on the operation conditions.

Disk operating at low feed rates of 13.6kg/h, and forming a wide drop spectrum at the periphery can be made to produce homogeneous sprays if the drops are separated in sizes by gravity. At high and more practical feed rates, and especially with high peripheral speeds, turbulent air streams entrained around the disk inhibit a clean separation.

Because of difficulties involved in sampling dense clouds of heterogeneous liquid drops, formulae relating their sizes to the operating variables are only approximate and vary from one worker to another (Fraser, 1957). One formula, which correlates data over a wide range of variables, can be written for the surface mean diameter (SMD) as:

$$SMD=7.4x10^{3}(1/N)^{0.6}(1/\rho)^{0.5}(\eta m/D)^{0.2}(\gamma/x)^{0.1} \quad (1)$$

This equation is valid for the following operating range:

D (disk diameter) = 0.05 – 0.20m
N (rotary speed) = 90 – 1885 radian per sec.
m (mass flow rate) = 0.004 – 0.510 kg/s
γ (Surface tension) = 74 – 100 mN/m
ρ (liquid density) = 999.55 – 1409.62 kg/m^3 and
η (viscosity of the slurry) = 0.11 – 9.9 Nsec/m^3(cp)
n = number of vanes,
x = wetted periphery, m (πD for flat disks and bowls, and n$*$h for vaned disks).
h = height of vanes, m

The maximum droplet size for a very wide range of flow rates is approximately three times the mean droplet size as given by Equation (1). The equation shows that for a given liquid, the most important factors influencing the droplet size are the rotor speed and disk diameter. The length of wetted perimeter has a relatively small effect.

In another formula mean droplet size for a spinning disk atomizer may be estimated from the Marshall equation (Charm, 1968)

$$DA = 0.4\left[\frac{M}{\rho_L N_r^2}\right]^{0.6}\left(\frac{\mu}{M}\right)^{0.2}\left(\frac{\sigma \rho_L L W}{M^2}\right)^{0.1} \quad (2)$$

where M = mass velocity 1b/min ft of wetted periphery
L_W = wetted periphery, ft
μ = viscosity
N = speed of disc, rpm
σ = surface tension
ρ_L = density of the liquid
r = radius of disc.

In still another formula the mean droplet size is defined as:

$$d_m^d = \frac{\sum N_i d_i}{N} \quad (3)$$

And, volume diameter for a vane disk type rotary atomizer as:

$$d_m^v = \frac{9.118 \times 10^4 \, G^{024}}{(Nd)^{0.83}(n)h^{0.12}} \quad (4)$$

Where d_m^v = mean volume diameter, G = liquid mass flow rate (kg s^{-1}); N = rotation speed (rpm), d = wheel diameter (m); n = no. of vanes; h = height of vanes.

Pressure Nozzles

The feed concentrate is fed to the nozzle under pressure. Pressure energy is converted to kinetic energy, and feed issues from the nozzle orifice as a high speed film that readily disintegrates into a spray as the film is unstable. The feed is made to rotate within the nozzle, resulting in cone-chapped spray patterns emerging from the nozzle orifice. Sprays from pressure nozzles are generally less homogeneous and coarser that sprays from vaned wheels. At low feed rates, spray characteristics are comparable. However, duplication of nozzles is required to atomize high feed rates successfully. Nozzles are generally used to form coarse particle powders (mean size 120-300μm). Fig 6 shows a typical pressure nozzle atomizer.

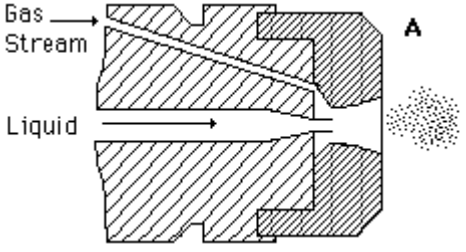

Fig 6: High Pressure Nozzle Atomizer

Pressure nozzle may be of the single fluid direct type in which fluid is forced though a simple office to produce a spray or of the swirl chamber type in which fluid is introduced, at pressure, tangentially into a chamber to increase turbulence and instability in the fluid before it exits from the nozzle or of the centrifugal pressure type where the turbulence and instability are enhanced with grooved inserts. Orifice diameter in pressure nozzle ranges between 0.02-0.2 in diameter while discharge rates vary between 0.01 and 200 gallons/min. Recommended operating pressures do not exceed 300 psi although for milk, up to 1000 – 7000 psi are used (Perry et al, 1963).

Power expended in pressure nozzles is given as.

$$P = 5.82 \times 10\, Q.\, \Delta P \quad (5)$$

where P = power consumed at the nozzle horse power
ΔP = pressure drop across nozzles, psi
Q = volume flow of liquid through the nozzle, gal/min

Average dropped diameter for single fluid pressure nozzles is given as (Perry et al, 1973).

$$DA = \frac{500}{\sqrt[3]{\Delta P}}, \mu m \quad (6)$$

Where ΔP = pressure drop across the nozzle, 1bs/in^2, with maximum particle size $D_{max} = 3D_A$, μm. for grooved core nozzle, the Turner-Monlton equation gives the droplet diameter as:

$$D_A = 16.56\,(D_o)^{1.52} W^{-0.44}\, \sigma^{0.713} \mu^{0.155} \quad (7)$$

Where D_0 = orifice diameter, mm between 0.7 to 1.55mm
W = mass flow rate according to Charm (1968) or volume flow rate between 1 and 30 USA gallons per second according to Masters (1976).
σ = surface tension, dynes/cm (range 26 – 37 dynes/cm)
μ = viscosity, cP (range 0.9 – 2.03 cP).

Masters (1976) reports D_A as a surface mean diameter while Charm (1968) reports it as a median diameter. The Tate and Marshall equation for surface mean diameter of drops from a swirl nozzle is (Masters, 1976).

$$DA = 286\,(D_0 + 0.17)\exp\left[\frac{13}{UV} - 0.0094\, UT\right] \quad (8)$$

Where $U_V = \frac{Q}{\Pi(r_0^2 + rc^2)}$; $40 < UV < 150$ ft/s

$$U_T = \frac{Q}{A_{sw}} \quad ;7 < U_T < 50 \text{ft/s}$$

D_0 = orifice diameter, inches
R_0 = orifice radius, inches
A_{SW} = area of flow into swirl chamber

The average geometric standard deviation, S, is given for each nozzle as:

$$S = 0.173 + 126 \log D_0 \quad (9)$$

Pneumatic Nozzles

Pneumatic atomization is a process of producing sprays by the disruptive action of a high-velocity gas upon a liquid jet. Because two fluid streams are involved it is sometimes called two-fluid atomization. Pneumatic nozzles are particularly well suited to produce fine spray, that is, less than 50μm in mass median diameter. Other atomizers are generally not capable of producing sprays of this drop-size range except under extreme operating conditions. However, the fine size production from pneumatic atomizers is accomplished only with relatively modest capacities, several gallons per hour at most. Nevertheless, this type of atomization has an advantage in that liquid and air streams can be controlled independently. Some viscous fluids and thick suspensions can be atomized by pneumatic nozzles better than pressure nozzles.

When air is used to break up the liquid jet into a spray of fine drops thereby expanding isothermally from an initial pressure P_1 to a lower pressure P_2 the energy, E required is

$$E = mRT \ln P_1/P_2 \quad (10)$$

where m = kg air/kg liquid.

Knowledge of the droplet size distribution in sprays from pneumatic nozzles permits predictions of the performance of equipment using such sprays. The drop size distribution from pneumatic nozzles has been shown to follow Nukijama and Tanasawa equation (Equation 11), (Masters, 1975)

$$D = \frac{1410}{V_A}\left[\frac{\sigma}{\rho_1}\right]^{0.5} + 191\left[\frac{\mu_2}{(\sigma\rho_1)^{0.5}}\right]^{0.45}\left[\frac{Q_L}{Q_A} X 10^3\right]^{1.5} \quad (11)$$

where Q_A, Q_L = volumetric flow of air and liquid respectively, ft^3/min

This equation is applicable in the range of $7 < D < 97$ μm; $19 < Q < 73$ dyne/cm; $43 < p < 75$ 1b/ft^3; $0.3 < \mu < 30$ cP; and to mass ratio of air to liquid between 1 and 10, liquid rate between 0.02 and 1.0 1b/min. the liquid nozzle diameter to which this equation applies, under these conditions, should be between 0.008 and 0.08 in, air nozzle diameter 0.04 and 0.02 inches while the area of the air annulus should be between 0.0012 and 0.030 in^2. The same equation has also been reported as (Dittman and Cook, 1977).

$$DA = \frac{1920}{V_A}\left[\frac{\sigma}{\rho_1}\right]^{1/2} + 597\left(\frac{\mu}{(\sigma\rho_L)^{1/2}}\right)^{0.45}(1000q)^{1.5} \quad (12)$$

Where q = relative flow rate, liquid to gas

Yet another version of the Nukiyama and Tanasawa equation was given by (Perry et al 1963) as;

$$D = \frac{585}{V_A}\left[\frac{\sigma}{\rho_1}\right]^{1/2} + 597\left(\frac{\mu}{(\sigma\rho_L)^{1/2}}\right)^{0.45}\left(1000\frac{Q_L}{Q_A}\right)^{1.5} \quad (13)$$

Drying of Spray Droplets

Relatively high temperatures are needed for spray drying operations. However, heat damage to products is generally only slight, because of an

evaporative cooling effect during the critical drying period and because the subsequent time of exposure to high temperatures of the dry material may be very short. The typical surface temperature of a particle during the constant drying zone is 45-50 C. For this reason, it is possible to spray dry some bacterial suspensions without destruction of the organisms. Drying of spray or moisture evaporation involves simultaneous heat and mass transfer. Heat is transferred by convection from the hot gas (air) to the droplet surface and by conduction into the droplet. The vaporized liquid passes first by diffusion through pores in the crust formed on the drop and finally by convection into the stream (Van Meel, 1958 and Keey 1968). The drying follows two stages; the first (constant rate) and second (falling rate) periods of drying.

In the constant rate period, the majority of moisture in the droplet is removed and the rate of evaporation is virtually constant because a moisture migration from the droplet interior is sufficient to maintain surface saturation. The droplet temperature is represented by the wet bulb temperature.

The falling rate period consist of one or two falling rate periods. In this period, the moisture level within the droplet has decreased to a point (critical moisture content) whereby surface saturation cannot be maintained by moisture migration. The evaporation rate thus decreases until drying is complete. Evaporation at this stage is predominantly through diffusions and capillary mechanism. The drying rate is also affected by the change in solid concentration of droplets. To calculate the drying time for droplets the constant rate and falling rate periods must be considered separately.

2.3.1 Constant rate period

The rate of mass transfer during the constant rate period is given by the following expression. This will be dependent on the amount of heat present in the product i.e. it can be related to the rate of heat transfer.

$$\frac{dw}{dt} = \frac{\mathrm{dQ}}{\mathrm{dt}} \Big/ \lambda = -\frac{\mathrm{hA}\left(\mathrm{T_a T_w}\right)}{\lambda} \tag{17}$$

T_a = dry bulb temperature; T_w = wet bulb temperature; T_s = droplet surface temperature. Heat transfer coefficient for a spherical particle at $Re < 20$

$$h = \frac{2\mathrm{k_a}}{D}$$

K_a = thermal conductivity of air, D = droplet diameter. Droplet diameter will change during the constant rate period

Surface area of a sphere = $\pi D^2 = m\pi r^2$.

$$\frac{dw}{dt} = \frac{\text{-}2\mathrm{k_a}}{\mathrm{D}} \frac{\pi \mathrm{D}_2}{\lambda} \left(T_a - T_w\right) \tag{18}$$

$$\int_0^{t_r} dt = \int_{W_o}^{\mathrm{W_c}} -\frac{\lambda}{2\mathrm{ka}\pi\mathrm{D}\left(\mathrm{T_a} - \mathrm{T_w}\right)^{dw}} \tag{19}$$

$$tc = \frac{-\lambda}{2\mathrm{k_a}\pi\left(\mathrm{T_a} - \mathrm{T_w}\right)} \int_{W_o}^{W_c} \frac{1}{\mathrm{D}} \mathrm{dw} \tag{20}$$

Equation (20) is solved to obtain

$$t_c = \frac{\lambda \rho \mathrm{w}\left(\mathrm{D_0^2} - \mathrm{D_c^2}\right)}{8k_a\left(T_a - T_w\right)} \tag{21}$$

2.3.2 Falling Rate Period

The rate of heat transfer during the falling rate period is given by the following expression:-

$$q = \frac{\mathrm{dQ}}{\mathrm{dt}} = \mathrm{h_a\ A}\left(\mathrm{T_a} - \mathrm{T_s}\right) \tag{22}$$

Where: T_s is the surface temperature of the particle.

Unfortunately T_s varies from T_w at the end of the falling rate period. Use

$$T_s = \frac{\mathrm{T_a} + \mathrm{T_w}}{2}$$

Then

$$\frac{dQ}{dt} = h_a A\left(T_a - \left(T_a/2 + T_w/2\right)\right) = \frac{h_a A}{2}\left(T_a - T_w\right)$$

We thus need to convert this expression relating heat transfer to time to one relating mass transfer to time. This is achieved by using the latent heat multiplied by the mass of the particle. Mass is equal to the density of the dry particle multiplied by the volume of the particle

$$w = \rho d\, V$$

$$\frac{dw}{dt} = \frac{dQ}{dt}\frac{1}{\lambda w} = \frac{dQ}{dt}\frac{1}{\lambda \rho dV}$$

$$\frac{dw}{dt} = \frac{dQ}{dt}\frac{1}{\lambda \rho dV} = \frac{-h_a A\left(T_a - T_w\right)}{2\lambda \rho d V}$$

Now area and volume can be expressed in terms of the diameter of the particles, thus

$$\frac{A}{V} = \frac{\pi D^2}{\pi D^3/6} = \frac{6}{D}$$

and $$h_a = \frac{2k_a}{D}$$

Assume in falling rate period that D is constant = D_c

$$\frac{dw}{dt} = \frac{ak_a}{D_c}\frac{6}{D_c}\frac{\left(T_a - T_w\right)}{2\lambda \rho d}$$

thus $$\frac{dw}{dt} = \frac{6k_a\left(T_a - T_w\right)}{2\lambda \rho D_c^2}$$

$$\int_o^t dt = \frac{-\lambda \rho d D_c^2}{6k_a\left(T_a - T_w\right)}\int_w^{W_f} dw$$

$$t_f = \frac{\lambda \rho d D_c^2}{6k_a\left(T_a - T_w\right)}\left(w_f - w_c\right) \qquad (23)$$

DESIGN OF THE PHYSICAL SYSTEMS

There are three major components that are usually considered in the design of spray dryer. These are the atomizer, the spray chamber and the cyclone separator. The other parts which include the air heater for providing the hot air, the evaporator for pre-concentration of the liquid feed, the dust collection and control equipment, blowers, etc. are normally considered as proprietary equipment and can be specified and selected from existing range. The design of the atomizer and the spray chamber are considered here.

Design of the Spray Chamber

The design of spray dryer chamber consists of estimating the physical specification of the sizes within given performance constraints and is still largely empirical. Knowledge of the manner in which air and spray are contacted and about the flow pattern of both air and the droplets is essential for the sizing of the spray chamber, characterized by its diameter and height. There are two methods commonly adopted. The first method the chamber volume is estimated from the product of the residence time of the drying drops and the overall gas flow rate (Nnolim, 1997). Model equations are then applied to estimate the residence time of single drops evaporating in a large mass of air. This method is only approximate in that many drops, some in clusters are involved and not a single drop. The method is relatively simple and is usually adequate for general purpose spray dryer. The second method involves developing a mathematical model which is solved using experimentally determined data on heat and mass transfer coefficients. An accurate prediction of droplet trajectories will enhance a good estimation of spray chamber size and efficiency. This is facilitated by computer analysis.

Spray-air contact is determined by the position of the atomizer relative to the drying air inlet. There are three principal arrangements; the co-current flow; the counter current flow; and the

mixed flow. In co-current flow, both air and feed enter the spray tower from the same end. In counter-current flow the air and feed enter from opposite ends, and the mixed flow is a mixture of the first two. The product to be dried determines how best to contact the spray with the drying medium.

Spray Droplets Flow Pattern

The spray droplets flow pattern can be determined by calculating the droplet trajectory from the atomizer to the chamber wall using stepwise methods. Most of the studies on the flow patterns of droplets seem to have come out with the conclusion that the droplets' movement can be identified by two zones, 'the jet or nozzle zone' and the 'free entrainment zone'. The droplet movement in the nozzle zone depends largely on the characteristics of the atomizer employed to obtain the spray (Stein, 1972 and Frazer, 1957). For a rotary atomizer in a small spray drier, the droplet trajectory is governed initially by the air swirl around the wheel caused by the rotation and finally by the drying air. For large industrial driers, the influence of wheel rotation is negligible. In the free entrainment zone, there is a considerable amount of spray-droplet mixing and the trajectory mostly depends on the drying air.

Air Flow Pattern

In the nozzle zone the droplets decelerate from their high initial velocity to the point where they begin to be entrained by the swirling drying gas and are mostly affected by the atomizing nozzle type. It is also characterized by the large amount of drying gas, which is entrained into it from the surroundings. For disk type rotary atomizer, Gluckert (1962) presented the following equations from an experimental study

$$V_c/V_o=1.2[b'/(r-Rd)]^{½}(r/Rd) \qquad (24)$$

$$b' = W_1/[\sqrt{2}.(2\pi Rd)^2 N\rho a_2] \qquad (25)$$

Where b' is the width of an imaginary annular jet of gas (of same composition as that leaving the spray dryer) having the same velocity and momentum as the initial liquid jet.

Diameter of Chamber

Droplet trajectory approach

Three forces act on a particle in its trajectory. These are Buoyancy; Gravity and Drag force - Stokes' law. For rotary atomizer (Stokes' law regime) the maximum distance traveled by particle before it reaches low moisture content is given as:

$$S_{max} = \frac{V_{po}}{K} = \frac{V_{po}\, D_p^2 \rho p}{18\mu} \qquad (26)$$

Where: v_{po} is peripheral velocity of disk or nozzle exit.

Therefore, the diameter of the chamber,

$$D_c = 2x\, S_{max} = 2V_{po}\, D_p{}^2 \rho_p /18\mu \qquad (27)$$

Using the angle of spread (especially for co-current gas spray flow) the diameter (related to the maximum horizontal distance from the feeding inlet point) traveled by the particles in the direction of the chamber wall can be calculated. More studies will have to be carried out to predict the path of the droplet trajectory and utilize the representative angle of spread.

Height of Chamber

Preliminary approach:

For co-current spray-air contact height of column is conventionally taken as 4-5 times the diameter if pressure nozzle atomizer is used and 0.5-1 time the diameter is used for rotary atomizer.

Using knowledge of drying time:

Height of chamber, H_c = velocity of particle x drying time

Terminal velocity of particle, v_p is given as

$$V_p = \sqrt{4gDp(\rho p - \rho)/3\rho C_D} \quad (28)$$

where

$$C_D = \left(\frac{24}{Re}\right)\left(1 + 0.14\ Re^{0.7}\right) \text{for } 3 < Re < 1000 \quad (29)$$

Drying time = constant rate period, t_c + falling rate period, t_f, where,

$$t_c = \frac{\lambda\rho_p\left(D_p^2 - D_c^2\right)}{8k_a\left(T_a - T_w\right)}\left(\text{for } D_p \subseteq 100\mu\right) \quad (30)$$

$$t_f = \frac{\mu\rho p D_c^2}{6k_a\left(T_a - T_w\right)}\left(W_f - W_c\right) \quad (31)$$

Design of the Atomizer

The required speed of the atomizer (N) is obtained from Equation (19) below:

$$\left(\frac{G}{\rho_L r}\right)\left(\frac{r}{D_{av}}\right)^{1.67}\left(\frac{\mu}{G}\right)^{0.33}\left(\frac{\sigma\rho_L}{G^2}\right)^{0.67} \quad (32)$$

D_{av} = Average droplet diameter, m (which is 30.33dPi; D_p = max. droplet diameter)

The introduced air is delivered so as to cause swirl. For easy control of the drying process in the chamber, it is paramount that the swirl stabilizes within a short time after entering the chamber. A vane angle of 25° has been found to give a stable swirl within the chamber on long form spray dryer

CONCLUSION

The design of spray dryers consists of estimating the physical specification of each of the components within given performance constraints. Design methods for the atomizer and cyclone systems are fairly standardized. The design for the spray chamber is still largely empirical. Various model equations for the design of spray dryers have been presented in this paper. The equations and the sequences presented are very handy in the computer aided design and simulation of spray dryers.

LIST OF NOTATIONS

$A_{I,}$	=	inlet cross sectional area, m^2
B	=	height of vanes, m;
CD	=	coefficient of drag
d_m^d	=	mean droplet size, m
d_m^v	=	mean volume diameter, m
d, D	=	wheel/disk diameter, m
D	=	droplet diameter, m
D_c	=	diameter at end of constant rate/Diameter of chamber, m
D_o	=	diameter at beginning of content rate, m
D_{av}	=	Average droplet diameter, m
D_p	=	max. droplet diameter, m
F	=	cross-sectional area, m^2
g	=	acceleration due to gravity, m/s^2
G	=	liquid mass flow rate, kg s^{-1}
h	=	Heat transfer coefficient, W/m^2K
h	=	height of vanes, m
H	=	height of bed, m
H_c	=	Height of chamber, m
k, $K_{a,}$	=	thermal conductivity of air, W/mK
m	=	mass flow rate, kg/s
n	=	no. of vanes
N	=	rotary speed of atomizer, radian per sec
$N_i/\Delta d$	=	drop size distribution
q	=	quantity of heat, J
r	=	radius of the disk, m
SMD	=	Surface mean diameter, m;
t_c	=	time of drying during constant rate period, s
t_f	=	time of drying during falling rate period, s
$T_{a,}$	=	dry bulb temperature/ temperature of airflow, ^0C
T_w	=	wet bulb temperature of particle droplet, ^0C
T_{af}	=	temperature of air flow, ^0C

T_s	=	surface temperature of particle, ^0C
v_p, v_t	=	terminal velocity, m/s
v_o	=	initial velocity of the liquid jet at the disk/nozzle exit, m/s
v_c	=	constant velocity of the drying droplet, m/s
v_{po}	=	peripheral velocity of disk or nozzle exit, m/s
V	=	volumetric flow rate, m^3/sec
w_c	=	wieght of particle at the end of constant rate drying period, s
w_f	=	wieght of particle at the end of falling rate drying period, s
x,	=	wetted periphery, m,
$\in$	=	porosity
η, μ	=	viscosity of the feed, Ns/m^2
λ	=	latent heat of vaporization, J/kg
ρ	=	liquid density, kg/m^3
ρ_p, ρ_d	=	density of particle, kg/m^3
ρ_L	=	density of the feed, kg/m^3
ρ_w	=	density of water, kg/m^3
γ, t	=	surface tension, N/m

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