ln T at the critical point

γ = activity coefficient

δ = square root of nonpolar (dispersion) pressure $= \left(\frac{K}{V_{L_i}}\right.$ $\left.\frac{3}{4}\alpha_i h\nu_i\right)^{1/2}$ = Hildebrand's solubility parameter for nonpolar molecules, atm.$^{1/2}$

μ = dipole moment, esn. cm.

ν = dispersion frequency, sec.$^{-1}$

ϕ_i = effective volume fraction $\frac{X_i V_{L_i}}{\sum_{i=1} X_i V_{L_i}}$

∞ = square root of polar (orientation pressure $= \left(\frac{K}{V_{L_i}}\right)\left(\frac{2}{3}\right.$ $\left.\frac{\mu_i^4}{kT}\right)^{1/2}$ = polar pressure of van Arkel, atm.$^{1/2}$

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A Theoretical Correlation of Spray-Dryer Performance

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Spray dryers, because of their effective contact between heating medium and particles undergoing drying, are potentially applicable to the widest variety of materials. However their use has been retarded by the lack of reliable engineering procedures for scaling up and analyzing performance. Many studies have been made of the individual factors involved in the spray-drying process (*3, 7, 8*). To facilitate scale up and permit design from basic fundamentals a unifying theory has been needed to tie these factors together.

In this development of an overall correlation of spray-dryer performance the author has calculated the capacity heat transfer or production rate based on the heat transfer rate to the largest spray particles. The production rate, which also is calculated from heat and material balances, is limited by the requirement that the largest particles be dried during their flight from the atomizer to the chamber wall. The time of flight of the largest particles is determined from a consideration of the fluid dynamics of the process. Thus, from a theoretical analysis based on the computation of minimum heat transfer rates (for this case of gas-phase resistance limiting) at capacity conditions (as determined by incipient wall deposition), expressions have been developed which relate overall performance to the dryer geometry, drying temperature, atomizer type, and particle size of the material produced.

With these expressions agreement between predicted and measured heat transfer rates has been obtained for drying of sodium sulfate solutions in 1-, 2-, and 3-ft. diam. dryers and calcium carbonate slurries in the 2-ft. diam. dryer. The obtainable useful rates however are 52% above the minimum rates predicted by these expressions. This agrees with the observation that drops of sodium sulfate solution and calcium carbonate slurries do not require complete drying if they are to be free flowing and are not to stick to the dryer walls. Materials which exhibit less stickiness than sodium sulfate when partially dried have been processed at greater rates than sodium sulfate, whereas materials which exhibit greater stickiness have not.

The developed relationships will be useful for scale up, estimating the effect of small changes in operating conditions, or preliminary design for cost estimates. Extension of the techniques presented here should allow more effective designs of other spray processes, including spray combustion for furnace, jet engine, or rocket design.

THEORY

The theoretical development has been based on the following premises:

1. The rate of heat transfer to the entire spray equals the weight rate of flow of the spray times the rate of heat transfer per unit weight of the slowest drying portion of the spray multiplied by its time of flight.* The largest droplets, which dry most slowly are the limiting portion of the spray and are used therefore for this evaluation.

2. The time of flight of the largest drops before they impinge against the dryer wall is determined by integrating the equation for velocity decay of a free jet. Soo (*11*) has shown that momentum transfer in a two-phase stream, consisting of small particles carried by a fluid, very rapidly reduces the relative velocity between the solid particles and the other phase of the stream until the average velocity of the solid particles is essentially that of the fluid stream. The behavior of jets has been amply treated by Albertson et al. (*1*), Alexander et al. (*2*), and Taylor et al. (*12*). The location of wall impingement in spray dryers with sprays directed axially has been observed at 3 to 4 chamber diameters from the nozzle. This wall impingement stems from the expansion of the spray jet. The expansion has been reported by the above investigators to occur at a 15-to-20-deg. angle. The larger spray angles given in manufacturers' catalogues for pressure-nozzle atomizers have been found only to apply close to the atomizer.

3. The largest droplets in a spray population are assumed to be three times the surface per unit volume average size, $D_{sv} = \sum_j n_j D_j^3 / \sum_j n_j D_j^2$, as suggested from available data for centrifugal disk atomizers. The empirical correlation presented by Nukiyama and Tanasawa (*9*) is employed to determine the droplet size produced by two-fluid atomizers. The rule of thumb for drop size, $\overline{D_{sv}} = 500/\sqrt[3]{\Delta p}$, where Δp is the pressure across a single-fluid nozzle in pounds per square inches, is employed to determine the average drop size from single-fluid nozzle atomizers, and the relationships developed by Friedman, Gluckert, and Marshall (*5*) are employed to determine the maximum particle size produced by centrifugal disk atomizers.

4. A droplet Nusselt number equal to 2, corresponding to pure conduction to infinity, is used for evaluating the coefficient of heat transfer. Kesler (*6*) has studied experimentally the evaporation of drops and found that the evaporation proceeded approximately as predicted, based on the assumption that a Nusselt number of 2 is applicable. This is further substantiated by the analysis of Soo (*11*), who as noted before, has shown that the relative velocity between the particles and the gas stream is negligible despite the turbulent eddies, and by the experimental work of Dlouhy and Gauvin (*3*) and Manning and Gauvin (*7*).

5. Drying conditions are uniform throughout the drying chamber. The spray jet entrains several times its volumetric flow rate of the surrounding gas for each jet diameter away from its source; thus tremendous recirculation currents are set up in the dryer. This recirculation is so great that the entire chamber is essentially at the chamber outlet temperature. Temperature measurements made in a drying chamber indicated that the inlet temperature persists only a few jet diameters immediately below the gas inlet.

6. Drying occurs from the drop surface which consists of a liquid saturated with the solutes. The work of Duffie and Marshall (*4*) and Ranz and Marshall (*10*) on the drying of drops indicated that a saturated liquid film is established very rapidly at the drop surface and that the rate of evaporation corresponds to that of a saturated liquid. Thus in view of premise 5 above, the temperature driving force for drying is the difference between the drying gas outlet temperature and the adiabatic saturation temperature of a saturated solution of the material being dried.

7. The drop diameter is constant during drying. The drying from the surface mentioned above tends to form a surface shell which maintains the drop diameter essentially unchanged as drying proceeds. As has been borne out by experience with many systems, hollow particle beads are produced. If on the other hand it is assumed that the drop diameter decreases to zero, the time required for drying will be greater by a factor of 1.5 and the calculated performance correspondingly reduced.*

8. The performance of a spray dryer is determined by the heat transfer rate q that can be achieved between the drying gas and the spray without deposition or buildup on the dryer wall. The inherent stickiness of partially dried material will determine to a large extent the dryer performance, because many materials vary in stickiness with degree of dryness. The performance of the dryer is as if a characteristic drop were being dried. If the material is not sticky with a given residual moisture content, complete drying is not required and flight time to completely dry the largest drop is not needed. Instead time must be provided to dry the largest drop to a nonsticky condition or to completely dry a somewhat smaller or characteristic drop.

These premises have been employed to calculate the heat transfer q under capacity conditions in a spray dryer for the following three types of atomizers commonly used.

Two-Fluid Atomizers

A two-fluid atomizer produces an air jet which forms and carries the droplets with it. The trajectory of this spray has been computed from data obtained with jets of similar geometry (*1*). The falloff in center-line velocity V of a jet having an initial velocity in the neighborhood of 1,000 ft./sec., which is typical of two-fluid atomizers, is given by

$$\frac{V}{V_m} = 6.2\left(\frac{D_e}{x}\right) \tag{1}$$

Since $V = dx/d\theta$ (2)

$$\frac{dx}{d\theta} = 6.2\, V_m \left(\frac{D_e}{x}\right) \tag{3}$$

Separating variables one gets

$$d\theta = \frac{x\, dx}{6.2\, V_m D_e} \tag{4}$$

Integrating to obtain the total residence time in the jet of length x_t one obtains

$$\theta_t = \frac{x_t^2}{12.4\, V_m D_e} \tag{5}$$

The total volume v of the cylindrical dryer to the end of the spray jet will be

$$v = \frac{\pi D_c^2 x_t}{4} \tag{6}$$

The full cylindrical volume is useful because the volume outside the jet is actually required to recirculate air. The atomized material is projected downward in the chamber as a jet expanding at an angle of approximately 20 deg. This jet entrains the surrounding gas in order to expand, and it expands to the full chamber diameter at ap-

* All of the material sprayed is dried. Because of differences in particle size some portions of the spray are dried more rapidly than others, but each portion requires the same quantity of heat per pound for drying.

* Integration of the equation for the rate of heat transfer to a drop gives $Q' = \dfrac{12 k_f \Delta t_f \theta}{\rho (D)^2}$ if the drop diameter is constant. If the drop diameter decreases with evaporation,

$$Q' = \frac{8 k_f \Delta t_f \theta}{\rho[(D)^2_{\text{initial}} - (D)^2_{\text{final}}]}.$$

proximately 3 chamber diameters from its source. The source may be considered a point because the nozzle diameter is small compared with the chamber diameter. The location of wall deposition which occurs from operation of the dryer at greater than design capacity is 3 to 4 chamber diameters from the atomizer. The center line of a spray dryer of high length-to-diameter ratio (length/diam. = approximately 8) has been probed while the dryer operated at capacity conditions. It was found that material moving directly down the chamber of this dryer operating at capacity conditions is dry after moving 4 or 5 chamber diameters from the atomizer. Thus a desirable minimum number of chamber lengths is 4 ± ½ diam. This uncertainty has introduced an uncertainty of ± 15% in the coefficients of the correlating equations:

$$\frac{D_c}{x_t} = \frac{1}{4} \qquad (7)$$

which gives

$$D_c^2 = \frac{1}{16} x_t^2 \qquad (8)$$

Substituting for D_c^2 [Equation (8)] in Equation (6) one gets

$$v = \frac{\pi x_t^3}{64} \qquad (9)$$

from which

$$x_t^2 = \left(\frac{64}{\pi}\right)^{2/3} v^{2/3} \qquad (10)$$

Substituting this value for x_t^2 into Equation (5) one obtains

$$\theta_t = \left(\frac{64}{\pi}\right)^{2/3} \frac{v^{2/3}}{(12.4)\, V_m D_e} \qquad (11)$$

The total mass flow rate through the atomizer will be

$$w_a + w_s = \frac{V_m \pi D_e^2 \rho_m}{4} \qquad (12)$$

The liquid being sprayed is accelerated by transfer of momentum from the atomizing gas and momentum is conserved. The initial momentum of the liquid is negligible:

$$V_a w_a = (w_a + w_s) V_m \qquad (13)$$

Replacing V_m in Equation (12) by V_a from Equation (13) one gets

$$w_a + w_s = V_a \frac{w_a}{(w_a + w_s)} \frac{\pi D_e^2}{4} \rho_m \qquad (14)$$

Solving for D_e

$$D_e = 2(w_a + w_s) \sqrt{\frac{1}{\pi w_a V_a \rho_m}} \qquad (15)$$

and replacing V_m in Equation (11) by V_a from Equation (13) one obtains

$$\theta_t = \left(\frac{64}{\pi}\right)^{2/3} \frac{v^{2/3}}{(12.4) V_a} \left(\frac{w_a + w_s}{w_a}\right) \frac{1}{D_e} \qquad (16)$$

Substituting the value of D_e from Equation (15) in Equation (16) one gets

$$\theta_t = \left(\frac{64}{\pi}\right)^{2/3} \frac{v^{2/3}}{(24.8)\, V_a w_a \sqrt{\dfrac{1}{\pi w_a V_a \rho_m}}} \qquad (17)$$

When one rearranges and collects terms

$$\theta_t = 0.532\, v^{2/3} \sqrt{\frac{\rho_m}{w_a V_a}} \qquad (18)$$

Because the liquid contributes little to the volume of the spray-gas mixture

$$\rho_m = \rho_a \left(\frac{w_a + w_s}{w_a}\right) \qquad (19)$$

Equation (18) can be written

$$\theta_t = 0.532\, v^{2/3} \sqrt{\left(\frac{\rho_a}{w_a V_a}\right)\left(\frac{w_a + w_s}{w_a}\right)} \qquad (20)$$

The rate of heat transfer to the largest drop is

$$\frac{dQ}{d\theta} = h\, A\, \Delta t_t = 2\pi k_f\, D_{max}\, \Delta t_t \qquad (21)$$

where $A = \pi(D_{max})^2$, $h = 2k_f/D_{max}$, and Δt_t is the difference between the drying gas and drop surface temperature.

The rate of heat transfer per unit initial mass of largest drop is

$$\frac{dQ'}{d\theta} = \frac{12\pi\, k_f\, D_{max}\, \Delta t_t}{\rho_s\, \pi\, (D_{max})^3} = \frac{12\, k_f\, \Delta t_t}{\rho_s (D_{max})^2} \qquad (22)$$

since the weight of the largest drop is $\rho_s\, \pi (D_{max})^3/6$. In the event that a solid filmlike structure is formed upon drying no appreciable change in drop diameter will be experienced during drying, and Equation (22) may be integrated to

$$Q' = \frac{12\, k_f\, \Delta t_t}{\rho_s (D_{max})^2}\, \theta_{max} \qquad (23)$$

The composition of the largest drop is assumed to be representative of the entire spray, and consequently the quantity of heat transferred per initial

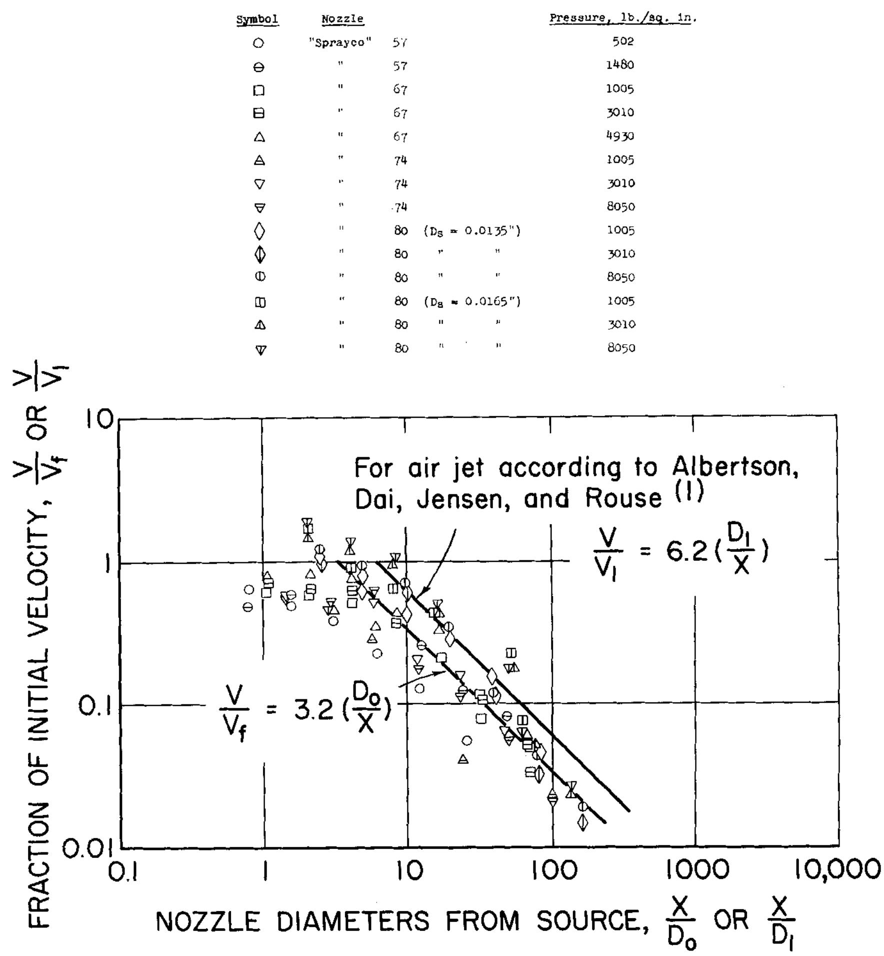


Fig. 1. Axial velocity of induced air from pressure nozzles.

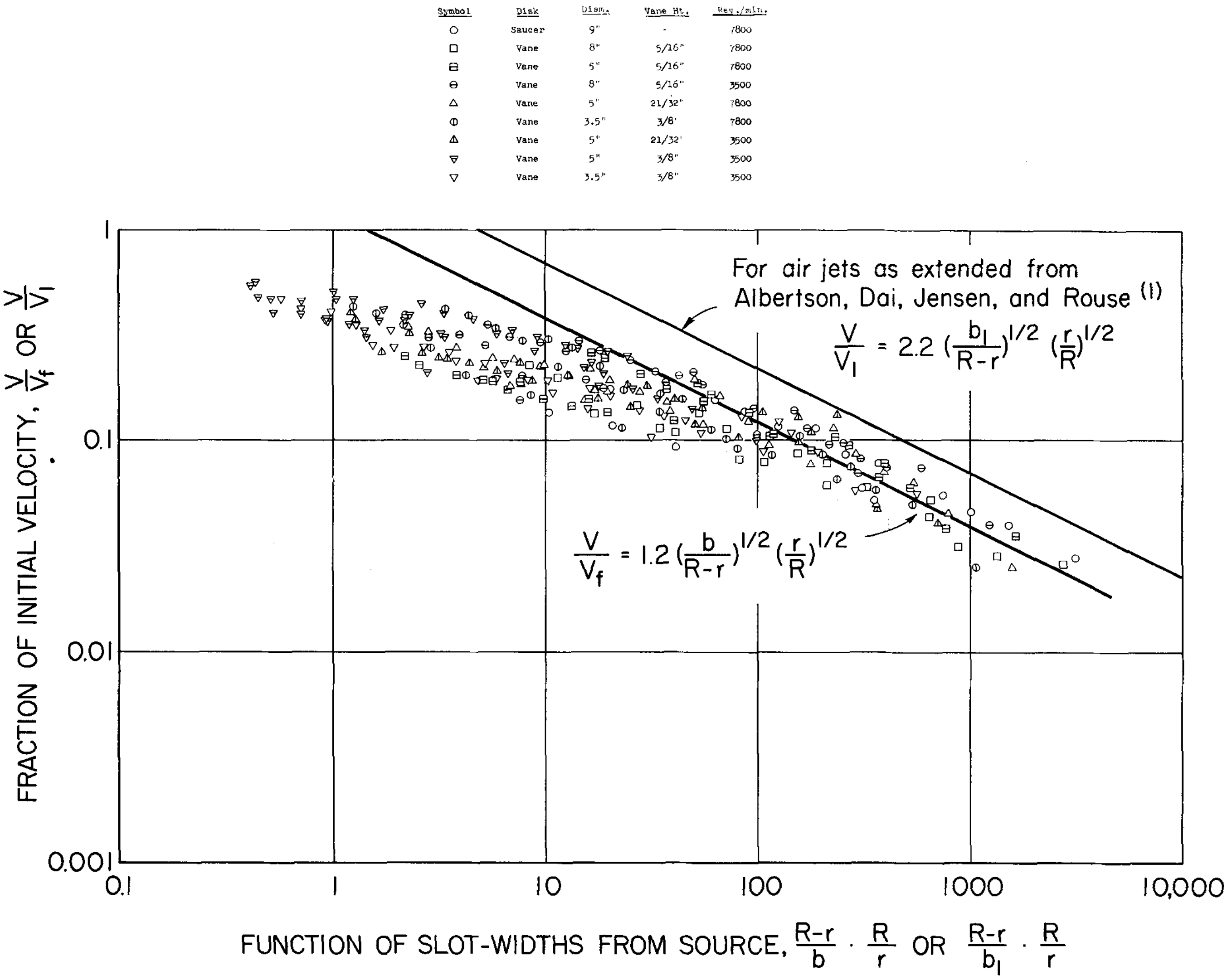


Fig. 2. Velocity of induced air from atomizing disks.

weight of spray also equals Q'. The rate of heat transfer per unit time for the entire spray therefore is given by

$$q = \frac{dQ}{d\theta} = Q' w_s \qquad (24)$$

or combining Equations (23) and (24) one gets

$$q = \frac{12\, k_f\, \Delta t_t\, w_s\, \theta_{max}}{\rho_s\, (D_{max})^2} \qquad (25)$$

Let θ_t equal θ_{max} and substitute the value of θ_t [Equation (20)] in Equation (21):

$$q = \frac{6.38\, k_f\, v^{2/3}\, \Delta t_t}{(D_{max})^2} \frac{w_s}{\rho_s} \sqrt{\left(\frac{\rho_a}{w_a V_a}\right)\left(\frac{w_a + w_s}{w_a}\right)} \qquad (26)$$

The heat transfer rate q given by Equation (26) is the maximum rate which can be achieved if the largest particles in the spray from a two-fluid atomizer are dried as they reach the dryer wall or bottom. Actually heat transfer rates somewhat higher than this calculated value can be achieved because it is not necessary to dry the largest drop completely but only to dry it until the drop is not sticky, that is dry the characteristic drop.

Pressure-Nozzle Atomizer

For pressure-nozzle–atomizer-spray drying the trajectory of the spray has been computed from measurements of air caused to flow by the momentum transfer to the air from the spray. The velocity of the air entrained by the spray, which by extension of the work by Kesler (*6*) and Soo (*11*) has been taken as a good approximation of the spray velocity, was measured in sprays from pressure nozzles and centrifugal disks along the axis of the spray jet. The measurements were made with a pitot constructed from a piece of ¼-in. copper tubing. A trap was employed between the pilot and registering manometer to prevent spray caught by the pitot from reaching the manometer and interfering with the pressure measurements. From the manometer readings of impact head the velocity of the gas moving with the spray was computed in the usual fashion. The data obtained for the axial decay of the air velocity in a pressure-nozzle spray jet is shown in Figure 1. The behavior is similar to that which has been shown for free air jets. The constants however have required some revision

$$\frac{V}{V_f} = 3.2\left(\frac{D_o}{x}\right) \qquad (1a)$$

From Equation (1*a*) the time required for the spray to travel from the pressure-nozzle atomizer to a position 4 chamber diameters from the atomizer has been calculated in a similar manner to that shown for two-fluid atomizers:

$$\theta_t = \left(\frac{64}{\pi}\right)^{2/3} \frac{v^{2/3}}{6.4\, V_f D_o} \qquad (2a)$$

D_o is the initial diameter of a jet of exit composition gas having the same velocity and momentum as the liquid jet which originates it. Since both the momentum and velocity of the initial liquid jet and this fictive initial gas jet are equal, the mass rates of flow are equal and

$$V_f = \frac{w_s}{\frac{\pi}{4}\rho_s (D_s)^2} = V = \frac{w_s}{\frac{\pi}{4}\rho_f (D_o)^2} \qquad (3a)$$

Solving Equation (3*a*) for D_o one gets

$$D_o = D_s \left(\frac{\rho_s}{\rho_f}\right)^{1/2} \qquad (4a)$$

When one substitutes the values of V_f and D_o [Equations (3*a*) and (4*a*)] in Equation (2*a*) and applies the result to Equation (25), the rate of heat transfer per unit time for the entire spray is as was shown for two-fluid atomizers:

$$q = \frac{10.98\, k_f\, v^{2/3}\, \Delta t_i}{(D_{\max})^2} D_s \sqrt{\frac{\rho_f}{\rho_s}} \qquad (5a)$$

The heat transfer rate q given by Equation (5*a*) is the maximum rate which can be achieved if the largest particles in the spray from a pressure-nozzle atomizer are dried as they reach the dryer wall or bottom. The same qualifications on rate as discussed under two-fluid atomizers apply in this case.

Centrifugal-Disk Atomizers

The theory for operation of a centrifugal-disk–atomizer-spray dryer has been developed in a similar fashion to that for two-fluid and pressure-nozzle–atomizer-spray dryers, except that the trajectory of the spray is outward from the disk. Measurements of air caused to flow by the spray from a disk, made in the manner described for pressure-nozzle atomizers, are shown in Figure 2. It will be noted that for a disk system the fraction of initial velocity of induced air is lower than it is for a jet alone from a slot orifice (a peripheral slot in a right cylinder) and that the difference is greater close to the disk. A portion of this difference is due to the interrupted pattern of the spray produced by vaned disks. (Very few data are available on saucer-shaped disks.) Because the difference tends to become less important at greater distances from the disk, more weight has been given to the impact head measurements made at greater distances from the disk than close to the disk in specifying the falloff in velocity of the sprays from a centrifugal disk. As shown in Figure 2 the observed trajectories of centrifugal-disk–atomizer-spray jets are represented by

$$\frac{V}{V_f} = 1.2\left[\left(\frac{b}{R-r}\right)\left(\frac{r}{R}\right)\right]^{1/2} \qquad (1b)$$

where b, the width of the annular jet from a centrifugal disk of exit composition gas having the same velocity and momentum as the liquid jet, is evaluated as follows:

The liquid jet velocity is the vector sum of the radial and tangential velocities

$$V_f = \sqrt{2}\; 2\pi r\; N \qquad (2b)$$

This equals the velocity of a fictive jet (width b) of exit composition having the same velocity and momentum (thus the same initial mass flow rate):

$$V_f = \sqrt{2}\; 2\pi r\; N = V = \frac{w_s}{\rho_f\, 2\pi r\, b} \qquad (3b)$$

Solving for b one gets

$$b = \frac{w_s}{\sqrt{2}\,(2\pi r)^2 N \rho_f} \qquad (4b)$$

Since $V = dR/d\theta$ (5*b*), one obtains from Equation (1*b*)

$$\frac{dR}{d\theta} = 1.2\, V_f \frac{(br)^{1/2}}{[(R-r)R]^{1/2}} \qquad (6b)$$

Separating variables one obtains

$$1.2\, V_f\, (br)^{1/2}\, d\theta = [(R-r)(R)]^{1/2}\, dR \qquad (7b)$$

Integrating between limits of $\theta = 0$ to θ_t and $R = r$ to $R = R_c$ one gets

$$1.2\, V_f (br)^{1/2}\, \theta_t = \frac{(2R_c - r)[(R_c - r)(R_c)]^{1/2}}{4} - \frac{r^2}{8}\ln\left\{\frac{[(R_c - r)(R_c)]^{1/2} + R_c - \frac{r}{2}}{\frac{r}{2}}\right\} \qquad (8b)$$

For cases of interest $R_c > 5r$. Thus the approximation

$$\sqrt{(R_c - r)(R_c)} = \frac{(R_c - r) + R_c}{2}$$

will introduce an error of less than 1½%. Similarly the logarithmic term may be neglected without introducing more than a 5% error.

Making these approximations in Equation (8*b*), collecting the terms, and solving for θ_t one gets

$$\theta_t = \frac{\left(R_c - \frac{r}{2}\right)^2}{2.4\, V_f\, (br)^{1/2}} \qquad (9b)$$

When one substitutes Equation (4*b*) for b and Equation (2*b*) for V_f in Equation (9*b*) and applies the result to Equation (25), the rate of heat transfer per unit time for the entire spray is as was shown for two-fluid atomizers:

$$q = \frac{4.19\, k_f \left(R_c - \frac{r}{2}\right)^2 \Delta t_i}{(D_{\max})^2 \rho_s} \sqrt{\frac{w_s\, \rho_f}{r\, N}} \qquad (10b)$$

The heat transfer rate q given by Equation (12*b*) is the maximum rate which can be achieved if the largest particles in the spray from a centrifugal-disk atomizer are dried as they reach the dryer wall. The same qualifications on rate as discussed under two-fluid atomizers apply in this case.

EXPERIMENTAL PROCEDURE*

A series of tests in spray dryers of different sizes and with different atomizers was made to give a definitive test to the theories developed above. The experimental phase of the study was based principally on a series of runs drying sodium sulfate solutions to allow a cross comparison of the tests. Sodium sulfate solutions were selected as a test material because they are relatively difficult to dry and were easy to clean from the drying chamber when the capacity was exceeded. Calcium carbonate slurries proved impossible to feed to the 1-ft. diam. dryer through the small lines with which it was equipped.

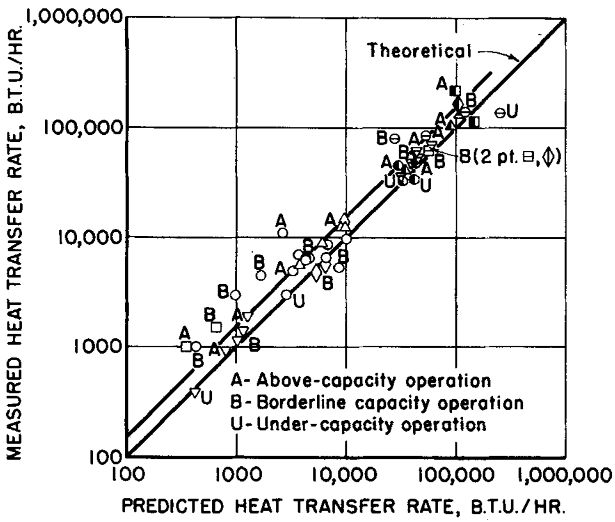
The rate of heat transfer to sprays of sodium sulfate solution was measured in spray dryers 1, 2, and 3 ft. in diameter, employing two-fluid atomizers; 2 and 3 ft. in diameter, employing pressure-nozzle atomizers; and 5 ft. in diameter, employing a centrifugal-disk atomizer. The rate of heat transfer to sprays of calcium carbonate slurries was measured in the 2-ft. diam. dryer with a two-fluid atomizer.

The 1-ft. diam. two-fluid atomizer spray dryer consisted of a vertical, cylindrical chamber 1 ft. in diameter and 5 ft. high. Feed slurry or solution was introduced in in a downward direction centrally at the top of the chamber. Atomizing gas (whch supplies part of the heat for drying) was discharged through an orifice concentrically around the feed point. Additional heat was supplied by lower-pressure gas introduced concentrically around the atomizing gas and feed. The moisture carrying drying gas and the dryed product were taken from the coned bottom of the dryer and separated in a bag filter.

The 2-ft. diam. two-fluid atomizer spray dryer consisted of a vertical, cylindrical chamber 2 ft. in diameter and 10 ft. high. Feed slurry or solution was introduced in a downward direction centrally at the top of the chamber. Atomizing gas (which supplied part of the heat for drying) was discharged through an orifice concentrically around the feed point. Additional heat was supplied by lower-pressure gas introduced concentrically around the atomizing gas and feed. The moisture carrying drying gas and the dryed product were

* Summaries of the experimental data have been deposited as document 7158 with the American Documentation Institute, Photoduplication Service, Library of Congress, Washington 25, D. C., and may be obtained for $1.25 for photoprints or for 35-mm. microfilm.

Symbol	Dryer	Material	Atomizer	Conditions
○	1-ft. diam.	10% Na_2SO_4	2-fluid	
▽	1-ft. diam.	10% Na_2SO_4	2-fluid	
□	1-ft. diam.	10% Na_2SO_4	2-fluid	Cold atomizing air
◇	1-ft. diam.	10% Na_2SO_4	2-fluid	Low atomizing air pressure
△	1-ft. Diam.	18.4% Na_2SO_4	2-fluid	Medium atomizing air pressure
◐	2-ft. diam.	10% Na_2SO_4	2-fluid	
▲	2-ft. diam.	10% Na_2SO_4	Pressure-nozzle	
◧	2-ft. diam.	40% $CaCO_3$	2-fluid	
◆	2-ft. diam.	5% $CaCO_3$	2-fluid	
⊖	3-ft. diam.	10% Na_2SO_4	2-fluid	
△	3-ft. diam.	10% Na_2SO_4	Pressure-nozzle	
▽	3-ft. diam.	10% Na_2SO_4	Pressure-nozzle	Low pressure
⊟	5-ft. diam. Bowen	10% Na_2SO_4	Centrifugal-disk	No side air
◇	5-ft. diam. Bowen	10% Na_2SO_4	Centrifugal-disk	



TWO-FLUID ATOMIZER:

$$q = \frac{6.38\, k_f\, v^{2/3}\, \Delta t_t}{(D_{max.})^2} \frac{w_s}{\rho_s} \sqrt{\left(\frac{\rho_a}{w_a V_a}\right)} \left(\frac{w_a + w_s}{w_a}\right)$$

PRESSURE-NOZZLE ATOMIZER:

$$q = \frac{10.98\, k_f\, v^{2/3}\, \Delta t_t}{(D_{max.})^2} D_s \sqrt{\frac{\rho_t}{\rho_s}}$$

CENTRIFUGAL-DISK ATOMIZER:

$$q = \frac{4.19\, k_f\, (R_c - r/2)^2\, \Delta t_t}{(D_{max.})^2\quad \rho_s} \sqrt{\frac{w_s\, \rho_t}{rN}}$$

Fig. 3. Comparison of measured and predicted transfer rate in spray dryers.

taken from the coned bottom of the dryer and separated in a bag filter.

The 3-ft. diam. two-fluid atomizer spray dryer consisted of a vertical, cylindrical chamber 3 ft. in diameter and 27 ft. high. Feed slurry or solution was introduced in a downward direction centrally at the top of the chamber. Atomizing gas (which supplies part of the heat for drying) was discharged through an orifice concentrically around the feed point. Additional heat was supplied by lower-pressure gas introduced concentrically around the atomizing gas and feed. The moisture carrying drying gas and the dryed product was taken from the coned bottom of the dryer and separated in a cyclone and bag filter.

The 3-ft. diam. pressure-nozzle–atomizer-spray dryer which employed the same chamber as the two-fluid atomizer dryer was 27 ft. high. However the spray nozzle was mounted on the end of an extended feed pipe 15 ft. from the bottom of the dryer.

The 2-ft. diam. pressure-nozzle-atomizer-spray dryer employed the same chamber as the two-fluid atomizer dryer. The pressure nozzle replaced the central feed and atomizing gas pipes and discharged downward concentrically within the drying gas supply orifice.

The 5-ft. diam centrifugal-disk-atomizer-spray dryer consisted of a 5-ft. diam. vertical, cylindrical chamber 7 ft. high including a 60 deg. cone bottom. The ceiling of this chamber was essentially flat. The feed was introduced from a centrifugal-disk atomizer located centrally. The drying gas was introduced concentrically to the disk through vanes imparting a swirl to the gas and optionally through four inlets at the periphery of the chamber.

The performance, as defined under theory, of these several experimental spray dryers was determined from the maximum evaporation or heat transfer rate q which could be achieved without deposition of partially dried material in the drying chamber. The specific value of dryer performance was determined as follows. The dryer was operated at selected temperatures with a given low value of the drying gas flow rate, and the evaporation rate or heat transfer rate q measured. Then the drying gas flow rate was increased, and again the evaporation rate or heat transfer rate q was measured. The increase in feed rate required to maintain the same temperatures resulted in a larger maximum drop size from two-fluid and centrifugal-disk atomizers. To obtain the necessary increase in feed rate with a pressure-nozzle atomizer a larger nozzle was required which, if operated at a reduced pressure, produced a larger maximum drop size. When the proper conditions were selected for the test the larger drops produced upon increasing flow rates did not dry. Alternatively the drying-chamber temperature was reduced in steps until there was insufficient Δt_t to dry the larger drops. Inspection of the drying chamber between runs identified the heat transfer rate for which negligible wall deposition was experienced (under capacity) and another greater rate which produced wall deposition (over capacity). In many instances it was difficult to determine whether or not the dryer was operating at less than capacity conditions. The runs for which this condition existed have been designated borderline.

The measured rates of heat transfer for the above described runs with several dryers and atomizers at essentially capacity conditions have been compared in Figure 3 with the heat transfer rates predicted by the theory presented. The points show a deviation of from +41% to −25% from their average which is 52% above the theoretical line for minimum heat transfer rate at capacity conditions. It should be noted that the points on Figure 3 cannot be expected to fall exactly on a line. They might fall more or less lower (under capacity) or higher (over capacity) than a line representing the optimum heat transfer rate set by the precise rate at which the largest drops of the material being sprayed are just dried to a nonsticky condition or the rate at which the characteristic drop is dried. The predicted heat transfer rate is a minimum rate; in the case of sodium sulfate solution drying it is 52% low. However the diameter of the spray dryer chamber necessary for a given drying rate with material such as sodium sulfate could be specified from the theoretically predicted minimum rate to within about 20% because the chamber diameter varies approximately as the square root of the heat transfer rate. A limited number of runs (not reported here) of proprietary materials such as dyes, pigments, surface active agents, etc. have indicated that the theory is generally applicable.

CONCLUSIONS

An overall correlation of spray-dryer performance has been developed. Subject to the limitations discussed under theory, a spray-dryer design can be specified by substituting the values corresponding to the required duty of the dryer and selected values of drop size D_{max} and the temperature driving force Δt_t in the appropriate equation [Equation (26) for two-fluid atomizers, (5a) for pressure-nozzle atomizers, and (10b) for centrifugal-disk atomizers] and solving for the dryer volume or dimensions. In an analogous manner the maximum capacity achievable in an existing dryer can be determined for various conditions. It will be noted that for a specified duty only Δt_t and D_{max} can be freely selected. Temperature driving force Δt_t is a function of drying air temperatures, drying air rate, and spray rate. For two-fluid–atomizer-spray dryers D_{max} is a function of atomizing air quantity w_a and velocity V_a; for pressure-nozzle atomizer spray dryers D_{max} is a function of nozzle orifice size D_s; and for centrifugal-disk–atomizer-spray dryers D_{max} is a function of disk radius r, speed N, and spray rate w_s.

The degree to which the largest drop must be dried to render it nonsticky and the puffing, shrinking, or disintegrating of the drop during drying will cause differences in the drying rate of various materials. The effect of these factors is best determined by experiment. Thus the developed relationships will be useful principally for scaleup, for estimating the effect of changes in operating conditions, and for first design for cost estimates. The experiments required can be carried out in small equipment and scaled up to large production equipment with confidence.

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NOTATION

A = area for heat transfer, sq.ft.
b = $\dfrac{w_s}{\sqrt{2}\,(2\pi r)^2 N \rho_t}$, fictive width of annular jet from centrifugal-disk atomizer of exit-composition gas having same velocity and momentum as the initial liquid jet, ft.
b_1 = width of annular-slot air orifice, ft.
D = diameter of spray drop, ft.
D_1 = diameter of air nozzle or orifice, ft.
D_c = diameter of dryer chamber with pressure nozzle or two-fluid atomizer, ft.
D_e = effective diameter of atomizer orifice, ft.
D_j = diameter of drop of class j, ft.
D_{max} = maximum drop diameter, ft. (assumed to be three times the surface per unit volume average size)
D_o = $D_s(\rho_s/\rho_t)^{1/2}$, diameter of a jet of exit-composition gas having same velocity and momentum as the liquid jet, ft.
D_s = diameter of pressure-nozzle discharge orifice, ft.
D_{sv} = surface per unit volume average drop size, $\sum_j n_j D_j^3 / \sum_j n_j D_j^2$, μ
h = heat transfer coefficient, B.t.u./(hr.)(sq.ft.)(°F.)
j = class assigned to drop size range selected for consideration
k_f = thermal conductivity of gas film surrounding drop, B.t.u./(hr.)(sq.ft.)(°F./ft.) (evaluated at average temperature between dryer gas and drop temperature)
N = rate of rotation of centrifugal disk, rev./hr.
N_{Nu} = Nusselt number, $h\,D_{max}/k_f$, based on largest drop
n = number of drops
n_j = number of drops of class j
Δp = pressure drop across pressure nozzle, lb./sq.in.
Q = heat, B.t.u.
Q' = heat transferred per unit weight of spray, B.t.u./lb.
q = rate of heat transfer to spray, B.t.u./hr.
r = radius of centrifugal-disk atomizer, ft.
R = radial distance from center of dryer chamber with centrifugal-disk atomizer, ft.
R_c = radius of dryer chamber with centrifugal-disk atomizer, ft.
Δt_t = temperature driving force, °F. (temperature difference between dryer gas at exit conditions and the drop surface)
v = volume of dryer chamber, cu.ft.
V = axial velocity of air in a jet, ft./hr.
V_a = velocity of atomizing air at atomizer, ft./hr.
V_f = velocity of liquid leaving atomizer, ft./hr.
V_m = velocity of the spray jet at the two-fluid atomizer, ft./hr.
V_1 = initial velocity of air from orifice or nozzle, ft./hr.
w_a = weight rate of flow of atomizing air, lb./hr.
w_s = weight rate of flow of liquid, lb./hr.
x = distance from atomizer, ft.
x_t = distance from atomizer to position four chamber diameters away, ft.

Greek Letters

θ = time, hr.
θ_{max} = time required for maximum size drop to dry, hr.
θ_t = time required for spray to travel from a two-fluid or pressure-nozzle atomizer to a position 4 chamber diameters away from the atomizer or from a centrifugal-disk atomizer to the chamber wall, hr.
ρ_a = density of atomizing air, lb./cu.ft.
ρ_m = density of the spray jet at the atomizer, lb./cu.ft.
ρ_s = density of sprayed material, lb./cu.ft.
ρ_t = density of gas at exit conditions, lb./cu.ft.
Σ = operator indicating summation

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