Transport Characteristics of a Cocurrent Spray Dryer

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The design of an experimental cocurrent spray dryer and its method of operation are described. The rationale for the development of some new measurement techniques and modifications to existing ones is discussed. These techniques were used to obtain profiles at several dryer levels of the air velocity, air humidity, and spray mass velocity for the case of a 30% sodium nitrate solution sprayed into 100°C. air. Somewhat less detailed measurements of the spray moisture and radial turbulent diffusivity were also made.

The humidity and spray moisture measurements gave very nearly identical results for the progress of the evaporation along the length of the dryer. The axial injection of the spray was found to result in steep gradients for the air velocity, air humidity, and salt mass velocity but these were found to decay under the influence of turbulent mixing which is also generated by the spray injection.

Purely theoretical approaches to the drying of an assemblage of droplets have been taken by Tribus, et al. (*1*) and Benson (*2*). Although the mathematical expressions appear quite different, they reduce to the same expression for certain conditions. Sjenitzer (*3*) and Schlünder (*4*) have presented systems of equations which predict the drying of a spray whose droplets are injected into an air stream at higher than terminal velocity. Both these authors, expecially the former, considered quite simplified models for their analyses. Schlünder, in contrast to most workers in the field, also attempted to obtain a solution for the more difficult problem of a spray containing a solid solute, rather than one consisting only of a pure liquid.

The experimental investigation of the evaporation of water sprays falling at terminal velocity through a spray dryer has been carried out by Dlouhy (*5*) and Bose (*6*). The former found that small spray droplets, which have negligible terminal velocities, evaporate at the same rate as single droplets at rest in an infinite medium. He was also successful in applying an incremental procedure to the prediction of spray evaporation. Bose was able to demonstrate that the evaporation of coarser drops proceeds according to the correlations of Ranz and Marshall (*7*). Both Dlouhy and Bose made a number of simplifying assumptions with regard to the flow of the air and the spray. Manning (*8*) measured the evaporation rates of drops in the immediate vicinity of the atomizing nozzle and in spite of the high deceleration and rather close proximity of the drops in this region he found that the Ranz and Marshall correlations were still applicable. The measurement of the velocity of drops issuing from a nozzle is a problem of great technical difficulty, and it is probable that Manning's drop velocity-drop diameter data are of limited accuracy. Equations for the mechanics and evaporation of individual droplets leaving a nozzle have been worked out by Rawson, et al. (*9*) who, together with many other workers in the field, neglected the effects of the induced air flow.

Three experimental investigations have recently appeared in the literature dealing with the evaporation of droplets from the atomizer to the bottom of the chamber. All three employed simple atomizers producing coarse sprays. Gena (*10*) and Dietz (*11*) conducted very similar experiments; however, the latter was more successful in establishing that at some distance from the nozzle the evaporation rates were in general agreement with the Ranz and Marshall heat transfer correlation (*7*). His failure to obtain an agreement near the nozzle was probably due to neglect of the induced air flow, which led to an overestimation of the relative velocity. Arni (*12*) failed to predict the evaporation of the spray by means of the Ranz and Marshall correlation, but this may have been due, at least partly, to an incorrect estimate of the extent of evaporation.

All of the above experimental studies were performed in cylindrical dryers, usually of large aspect ratio, with the air flow fairly evenly distributed over the dryer cross section. Doumas and Huste (*13*) and Gluckert (*14*) established calculation procedures for the drying of sprays in more typically industrial dryers, but the success of their methods can be considered to rest more on their intimate familiarity with the operation of the commercial dryers they used rather than on the correctness of their approach. Cox (*15*) investigated the drying performance of a large dryer, but his findings provide mainly inferential understanding of the drying process.

It may be concluded that, in general, more attention has been devoted to the heat transfer rather than to the fluid mechanics aspects of the problem. Too often, the injection of the spray has been assumed to proceed without affecting the flow of the drying air. At least in the case of pneumatic atomization this is a very suspect simplification. In the opinion of the authors the failure of previous workers to achieve agreement between predicted and experimental results can be traced to their neglect of the momentum transfer between air and spray jet.

In the present study it has been attempted to characterize, as completely as possible, the flow behavior of air and spray, as well as to study the latter's drying rate.

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In order to keep the project within reasonable bounds, attention was limited to that portion of the dryer where the drops have attained their terminal velocities.

EXPERIMENTAL APPARATUS

The Spray Dryer

The test section of the spray dryer consisted of a 16 ft. vertical length of 8 in. I.D. aluminum pipe. The nozzle was inserted 17 in. below the top. Ports were provided at 5 in. intervals for five levels immediately below the nozzle, and at 12 in. intervals for the succeeding 8 ft., providing a working length of 121 in. The ports were circular and were closed with tight fitting plugs. The test section was surmounted by a flow straightener whose function it was to overcome the effect of upstream bends and other disturbances on the air flow, and to produce symmetrical velocity profiles. The principles underlying the design of the straightener together with its method of operation have been described in detail elsewhere (*16*). Figure 1 shows the results of four velocity traverses 45 deg. apart made 5 diam. below the straightener exit.

The air supply was provided by two blowers, one feeding into the system while the other was exhausting. The air rate was controlled by means of a gate before the first blower while a butterfly valve before the second controlled the static pressure in the dryer. The air flow was measured by means of a calibrated orifice. The principal source of heat was a cluster of four burners using natural gas, with electrical heaters being used for temperature regulation. Copper-constantan thermocouples gave the temperature of the air and feed at various points. The dryer was covered with a 3 in. layer of insulation.

Feed System and Atomizer

Considerable difficulty was encountered in the selection of a suitable atomizer. It was initially intended to use a pneumatic nozzle because nozzles of this type can produce fine sprays and have narrow cone angles, these features being important because of the small dryer dimensions. However, the very peaked velocity profile which these nozzles cause was deemed to be undesirable and attention was turned to pressure nozzles. The most difficult criterion to satisfy was that of a symmetrical spray pattern and after a considerable search the nozzle adopted was a Hago, type T, 0.75 U.S.G./hr. rating, 45 deg. spray angle.

The spray pattern was determined by inserting into the dryer, at the 25 in. level, a holder with 12 sampling tubes arrayed symmetrically about the drier diameter on ⅝ in. centers and weighing the dry sodium nitrate thus collected. Results of such a sampling are shown in Figure 2. Since no allowance was made for impaction efficiency, these results did not give a true picture of the spray flow in the dryer. However, because of the symmetry of the velocity profile it would be expected that the impaction efficiencies would be the same at points equidistant from the center. The feed temperature was maintained at 25°C. A streamline shape was fitted around the feed assembly in order to reduce the disturbance to the flow.

Operating Procedure

The possible variables in this work were air temperature, air rate, feed rate, feed concentration, and feed temperature,

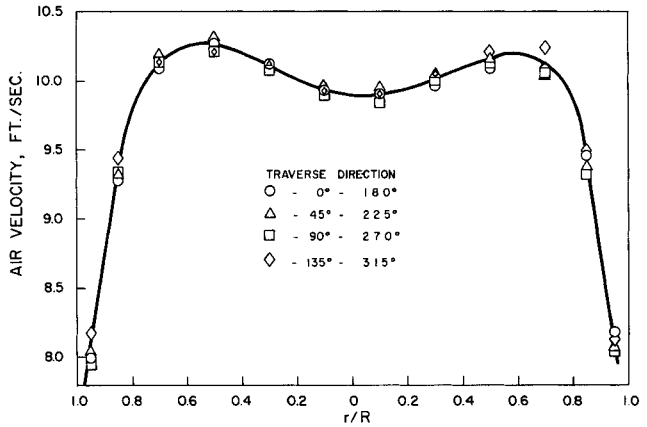

Fig. 1. Air velocity profiles downstream of straightener.

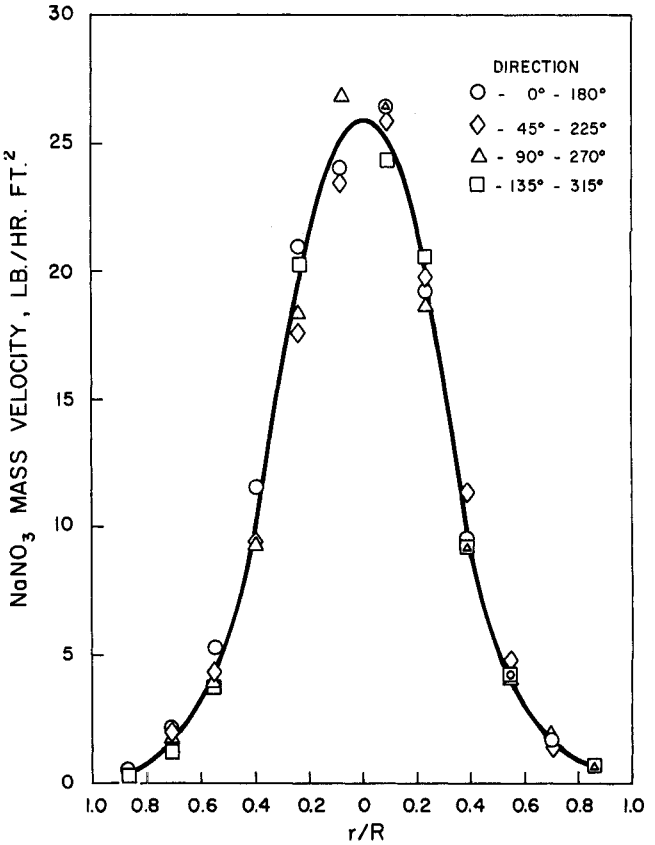

Fig. 2. Profiles of local salt mass rates as test of nozzle quality.

while other variations would include the solute and the type of nozzle. In the drying experiments all of the above were kept fixed. When water rather than solution was sprayed, its proper feed rate was established by a method to be mentioned in the section on air velocity. For measurements carried out at room temperature, the volumetric air rate was made to be the same as that of the hot air at the level of the nozzle. One experiment required the sampling of sodium nitrate drops in the absence of evaporation and to this end the air was humidified to correspond to the equilibrium vapour pressure of the solution. When spraying in hot air some of the spray impinged on the walls and there was an accumulation of dry salt in the form of fluffy deposits; since their adhesion was very weak, they were blown off the wall when still quite small so that only a very small fraction of the wall was covered by salt at any one time.

EXPERIMENTAL TECHNIQUES

Humidity Measurements

Air samples to be analyzed for humidity were collected by means of a sampling probe consisting of an inverted cup under which the inlet of an aspiration tube was located. The cup also had a conical skirt to preclude aspiration of drops. The moist air sample was led through a heated tube into 250 ml. sampling bottles. These were wound with resistance wire, and were heated to approximately 80°C. both during sample collection and later, during sample analysis, in order to prevent condensation from the more humid samples and to reduce the adsorption of water on the bottle walls. The samples were analyzed in an apparatus previously described by Dlouhy (*5*) which has since been modified by the authors in order to make its operation simpler and more reliable. The sample moisture is inferred from the reduction in volume caused by the quantitative absorption of the water by magnesium perchlorate. During a run, four air samples were collected along a diameter at each of six dryer levels, with the number of samples divided equally on either side of the axis. A duplicate sample of drying air was obtained in the chamber while the spray was off.

Spray Moisture

If a portion of spray containing a solute can be collected in

a spray dryer in such a manner that its evaporation is arrested immediately upon collection, the moisture content of the sample may be determined. Such a method makes it possible to determine the extent of evaporation independently of mass or heat balances and, in addition, such a technique should allow a better resolution of the drying process when the spray is *very nearly dry*. Of the few methods available in the literature the principle of immersion in an immiscible liquid upon capture, as employed by Dlouhy (5) and Manning (8), was considered as the most appropriate. It was decided to cool the sampling cell and its contents during collection so that the nearly dry particles would not impinge on a hot liquid surface. The cells were 6¼ in. long, 1¼ in. at their widest and 1 in. deep (Figure 3). A cover with an opening in its middle served to keep the inner cell walls free of spray above the collection liquid level. Cooling water was passed in the annulus.

Because of the small spray feed rates, which resulted in the collection of rather small amounts of spray, it was necessary to devise an analytical technique which would be able to measure small amounts of solid and even smaller amounts of water, both of these originally present under a layer of immiscible liquid. The method finally adopted was based on the fact that a small quantity of water generates an appreciable volume of vapor. Actually, rather than measure the change in volume of the water vapor evolved from the sample moisture, it was found preferable to measure the change of pressure in a confined space.

Briefly, the analytical procedure was as follows: after sampling, the cover was removed from the cell and the annulus was dried thoroughly; the cell was then placed in a glass chamber of approximately ½ liter volume and the latter was immersed in a water bath at 50°C. After pressure in the chamber had become constant (1½ hr.) it was removed from the bath and the cell was heated for half an hour, causing the water in the sample to boil and to bubble through the collection liquid, thus passing into the air space above the cell. The chamber was again cooled to 50°C. and the new pressure was recorded. The mass of evolved vapor was then obtained by means of the gas equation. Depending on the exact size of the chamber, 1 mg. of water caused a pressure rise of 1 to 1½ in. of manometer fluid. The mass of dry salt was determined by washing off the collection fluid with a light hydrocarbon.

Although the principle of this procedure is fairly simple, its successful application was attended by several difficulties. Before attempting to apply it to actual spray samples the method was tried with prepared samples of known water and salt content. From these trials it was established that the most suitable collection liquid was "DuoSeal" vacuum pump oil, from which the light fractions were removed by distillation under vacuum. Its rather high viscosity and surface tension apparently did not hinder the rapid immersion of the spray particles. About one-tenth of the evolved vapour was adsorbed on the chamber walls and was corrected for by calibration.

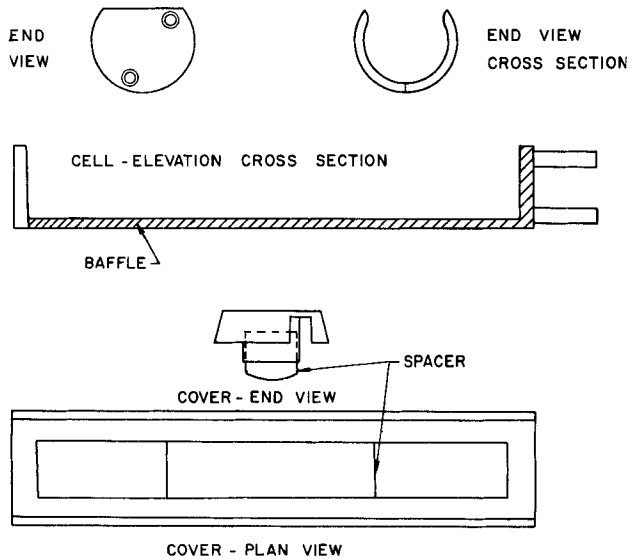

Fig. 3. Spray moisture sampling cell and cover.

With this procedure, it was possible to determine a 4 mg. water sample to within 2 to 3%. The upper limit in the sample size was determined by the height of the manometer tube, and by the necessity of keeping the humidity in the chamber below saturation.

Air Velocity

A Pitot tube cannot be used to measure the air velocity in a liquid spray because the droplets will coalesce and clog the dynamic and static pressure holes. This problem becomes accentuated when the spray contains a solid solute. The use of impact tubes in particulate flows, containing either droplets or solid particles, has been discussed by Dussourd and Shapiro (*17*) who, among other things, considered the effect of particle deceleration upstream of the tube on the stagnation pressure. When used in such flows an impact tube must be provided with a drain hole. As long as the area of the hole is less than 5% of the tube mouth area, the error in the stagnation pressure will be negligible. Such an impact tube was built and used in conjunction with a wall static hole drilled into one of the plugs used for the dryer ports. Velocity measurements in clear air made with the impact tube and a standard Pitot tube agreed with each other within the experimental error. The integrated air flow obtained in the presence of a spray, 25 in. below the nozzle was, at worst, within 3% of the orifice flow rate.

Velocity measurements for salt spray in hot air were irksome because the partially dry droplets accumulated on and in the tube in the form of a paste. A velocity profile was obtained at the 25 in. level, in 100°C. air, while spraying sodium nitrate solution, because at this level the spray was still quite wet. It was then attempted to reproduce the profile by injecting water in place of the solution. The closest approximation was achieved when the volumetric water rate was slightly in excess of that of the solution (Figure 4). The greatest difference between the two was 6% and it may be expected that this will be smaller at downstream locations since both profiles should tend towards the same shape, namely, a turbulent profile.

Local Spray Mass Velocity

In order to obtain a true measure of the rate of spray flowing through a given cross section, it was necessary to collect the sample while aspirating. The velocity of aspiration must be isokinetic, that is, it must equal the local air velocity at the point of sampling. As a result, the air velocities and spray mass velocities were obtained while spraying salt solution into air at room temperature in order to avoid the problem of salt encrustation on the probe. The latter consisted of a vertical tube of 0.343 in. I.D. and 0.005 in. wall thickness. The spray collected in the probe flowed into a trap. Following every sampling, the collected spray was washed out of the probe and trap into a tared dish, dried and weighed. At the 25 in. level, where wall deposition was negligible, the integrated salt mass flow was within 3% of the feed rate. A few samples were collected at the same level in hot air in order to check the results obtained in room-temperature air. The agreement was very satisfactory.

Drop Size Distribution

Of the many methods devised for drop size determination, the one deemed most suitable for this work was the immersion sampling method first described by Rupe (*18*). The drops were collected in a cell with a glass bottom and containing an immiscible fluid of lower density than the spray. The chief drawback of immersion sampling is that it discriminates in favor of the larger drops. This effect can be reduced by making the sampling cell smaller but there is a practical lower limit. An analytical study of impaction efficiency by Lewis and Brun (*19*) considered the trajectories of particles in a potential flow which impinges on a body of rectangular cross section and infinitely long in the direction of flow, so as to approximate the effect of the wake. The study suggested that impaction efficiency is lowest along the centerline and highest at the edges, and will approach 100% at the edge for particles above a certain size.

To this end, the sampling cells and holder were designed with the intention of considering only those drops which had been deposited in the immediate vicinity of the outer edges.

The cells were very nearly cubical, ¼ in. on a side, with walls made of 0.007 in. brass and the glass bottom was cut from microscope cover slides. The glass surface was treated with an antiwetting agent. The immersion liquid was a commercially available hydrocarbon mixture known as *Varsol* with a specific gravity of 0.77. No distortion was found due to flattening which may have resulted from the density difference between drops and Varsol. The distortion caused by the wetting of the coated glass surface has been reported by Rupe (*18*) and Hoffman (*20*) to be rather small.

The holder consisted of a bar ¼ in. wide and ½ in. high. Slots were cut into the bar just large enough to accommodate the individual cells. When the cells were brimful with Varsol the holder with cells presented to the flow the same configuration as the original solid bar. Thus, the cells in the bar presented a body for which Lewis and Brun had calculated the impaction efficiency. It is not likely that the drop size distribution of a spray will be uniform from the axis to the outer regions and for this reason four cells where arrayed along a diameter with the intention of combining the results of all the cells into one mean distribution. The cells were exposed to the spray for differing time intervals, the latter corresponding to the annular areas of the dryer cross section which the cells represented.

Following sample collection, the cells were removed from the holder and covered with a small glass plate in order to have a flat surface for viewing. The drops were photographed through a microscope, ten photographs being taken along each of the outer edges of the cell. In this manner the drops considered for the sample were lying in a strip about 0.015 in. wide, its width being 1/17 of the cell width. Prints with an overall magnification of 240× were made and analyzed with the help of a Zeiss particle size analyzer.

Turbulent Diffusion

The turbulent radial diffusivity of heat or mass existing in a fluid flowing in a duct has often been determined by employing the axial injection of a tracer. An extensive review of past work in the field, both of the theoretical and experimental variety, has been compiled by Bobkowicz (*21*).

Helium was used as the tracer and in order to avoid the accumulation of salt on the injector, which would have altered the aerodynamic conditions, the experiments were carried out in the presence of a water spray. The injector tube, which was aligned with the dryer axis, was 1⅜ in. long, with 0.084 in. O.D. and a 0.070 in. I.D. The horizontal feed tube had a 0.070 in. O.D. and was streamlined. The samples were collected along a diameter perpendicular to the feed tube and analyzed by gas chromatography. The integrated helium flow rate obtained from the traverses was always lower than the injection rate. The discrepancy ranged from about 20% at 1 ft. below the injector to about 10% at 3 ft. When some traverses were done in the direction of the feed tube the recovery invariably exceeded 100%. This effect was first noticed by Towle and Sherwood (*22*) who surmised that the helium was drawn into the line of low pressure created by the horizontal tube.

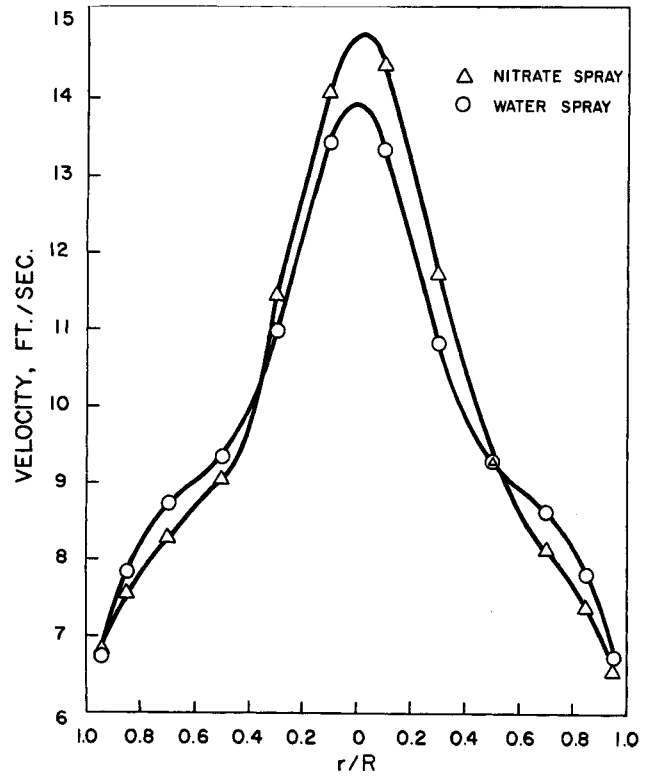

Fig. 4. Velocity profiles at the 25 in. level while spraying either water or 30% sodium nitrate solution.

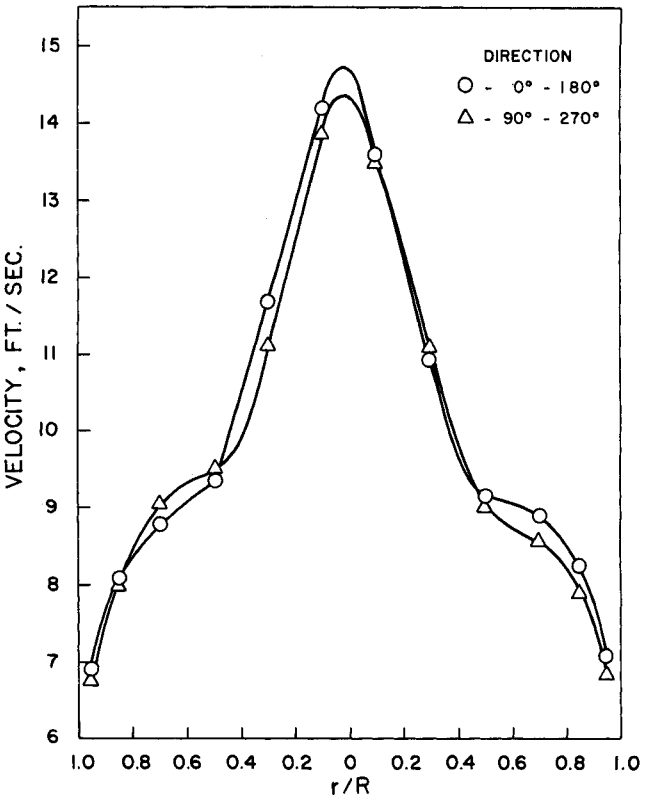

Fig. 5. Air velocity symmetry at the 25 in. level with spray turned on.

RESULTS

General Information

Since all the measurements necessary for a single run had to be performed over a period extending over several months, great care was taken to keep the experimental conditions as constant as possible. For measurements in hot air these conditions were

Air temperature at nozzle level	102°C.
Air flow rate at nozzle level	180 cu.ft./min.
Feed rate	7.28 lb./hr.
Feed concentration	30% sodium nitrate
Feed temperature	25°C.

When water was sprayed instead of sodium nitrate solution, the former's rate was 6.10 lb./hr., that is slightly in excess of 5.94 lb./hr. which represents the same volumetric flow rate as that of the solution. This was done for reasons previously discussed. Experiments in cold air (room temperature) were conducted with the same volumetric flow rate of air at nozzle level, which meant a 25% increase in the mass rate.

In order to check on the symmetry of injection and air flow pattern, nitrate solution was injected into cold air. As the nozzle feed line could be expected to disturb the flow, one traverse was made in the same vertical plane, at the 25 in. level, this being designated the 0 to 180 deg. direction, with another traverse in the 90 to 270 deg. direction. The air velocity profiles are shown in Figure 5

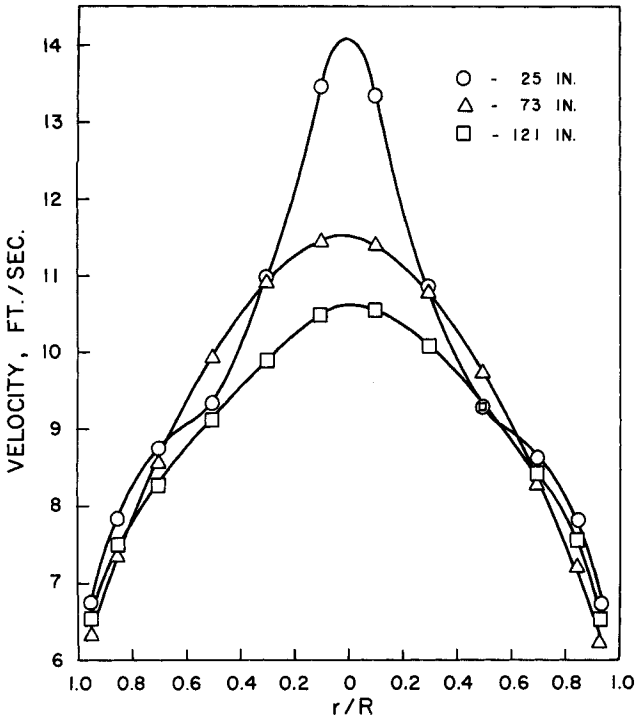

Fig. 6. Radial velocity profiles with spray turned on.

while the spray pattern has already been presented (Figure 2). The symmetry in both measurements was considered to be quite satisfactory so that all subsequent measurements were confined to the 90 to 270 deg. direction.

Air Velocity

Air velocity traverses were performed at nine levels. Water rather than sodium nitrate solution was injected since this simplified the procedure and as was shown in he section on experimental techniques, the errors introduced by substitution of the feed liquid are small. As no air temperature data were available, it was necessary to obtain an indirect estimate of the local temperature in order to calculate the velocity from the dynamic pressure, by way of the air density. For this purpose the local humidity values were used in a heat balance assuming adiabatic conditions

$$T_c = 250 - 4170H \qquad (1)$$

where T_c is in °F. and H in lb. water/lb. air.

Three representative velocity profiles are shown in Figure 6 from which it is evident that the air jet induced by the injection of spray persists for a considerable distance. In order to obtain the integrated air mass rate from the velocity profiles, the dryer cross section was divided into ten concentric zones whose outside radii are in arithmetic progression. The velocity and air density for each zone (annulus) were taken at the radial distances whose circles divide the annuli into halves. All the calculated mass flows were greater than 640 lb./hr., this rate being obtained from the orifice reading. The errors ranged from 2 to 5%.

Humidity

The humidity results consist of four-point traverses at six dryer levels. Because of the axial symmetry of the profiles, the samples at $r/R = 0.188$ and 0.625 were obtained on one side of the axis and those at $r/R = 0.438$ and 0.812 on the opposite side. These profiles are quite peaked near the nozzle but become flatter with increasing distance. This effect can be shown strikingly by cross plotting the profiles to show the variation of local humidity with downstream distance (Figure 7). This plot shows that the humidity at points near the axis decreases with distance from the nozzle while the humidity at points near the wall increases. Such a behavior suggests the existence of radial mixing.

The quantity of water vapour, W, at any level, was obtained from a numerical integration. The average humidity, $\overline{H}$, was obtained by dividing W by the corresponding integrated air rate. The increase in humidity, $\Delta\overline{H}$, was found by subtracting the inlet humidity, 0.00798 lb. water/lb. air, from $\overline{H}$, and the quantity of water evaporated, by multiplying ΔH by 640 lb. dry air/hr., the air rate at the orifice. The proportion of feed water evaporated, as obtained from this mass balance, vs. axial distance is shown in Figure 8. It is worth noting that three quarters of the water evaporates in the first 2 ft. and the remaining one quarter does not evaporate completely in the subsequent 8 ft. This behavior is not unexpected in spray drying and is due only in small measure to the gradual reduction in the driving force, and principally due to the early disappearance of the small drops which have high transfer coefficients and high specific surface areas.

Spray Moisture

Spray moisture samples were taken at the six lower levels (Table 1). At the bottom three levels the entire contents of the sampling cell were analyzed. The cell length was 72% of the dryer diameter. At the other three levels the portion of spray extending over either the central 31% of the diameter or the outer 41% was retained and analyzed. At first glance, it may seem that the reproducibility of the results may be unsatisfactory, but in view of the small size of the samples, 100 to 150 mg., and their low water content, the results are more than adequate. The last column of Table 1 shows that this method is capable of high resolution. At the upper three levels it was possible to distinguish a greater moisture content in the central spray portion although the difference was

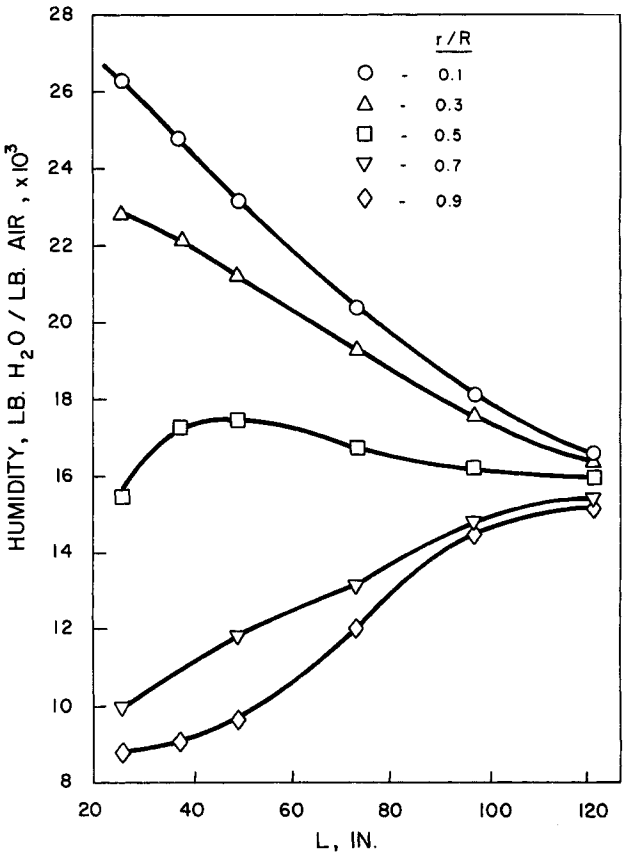

Fig. 7. Axial humidity profiles.

small. The extent of evaporation could be easily obtained from the spray moisture and the results are in excellent agreement with the humidity balance (Figure 8).

TABLE 1. SPRAY MOISTURE SAMPLES

L in.	Time min.	Portion analyzed	X lb.H_2O/lb. salt	$\overline{X}$ lb.H_2O/lb. salt	W lb./hr.
61	1.5	central	0.276		
				0.264	4.52
61	1.5	outer	0.252		
73	1.5	central	0.220		
				0.203	4.65
73	1.5	outer	0.186		
85	1.5	central	0.154		
				0.150	4.77
85	1.5	outer	0.146		
97	1.5	whole	0.094		
				0.104	4.87
97	2.0	whole	0.113		
109	2.0	whole	0.0848		
				0.0772	4.93
109	2.0	whole	0.0695		
121	2.0	whole	0.0624		
				0.0631	4.96
121	2.5	whole	0.0638		

Spray Mass Velocity

Traverses of the local sodium nitrate mass velocities were made at five levels (Figure 9). The sampling was performed with isokinetic aspiration in cold air and for this purpose velocity profiles in cold air were obtained. Once again, the distribution from one half of the dryer was superimposed on the other half. The aspiration rates were determined by using calibrated constrictions and at all sampling points the aspiration velocity was matched exactly to the air velocity. Some samples were collected in hot air at the 25 in. level and it was seen that at this level, at least, the air temperature does not seem to affect the profile.

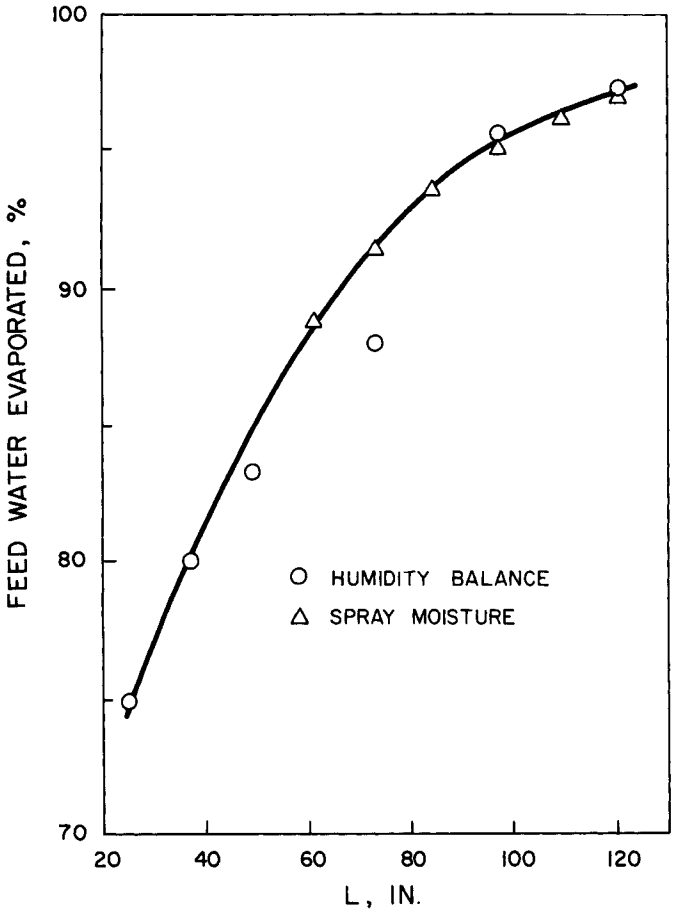

Fig. 8. Spray evaporation as a function of axial distance.

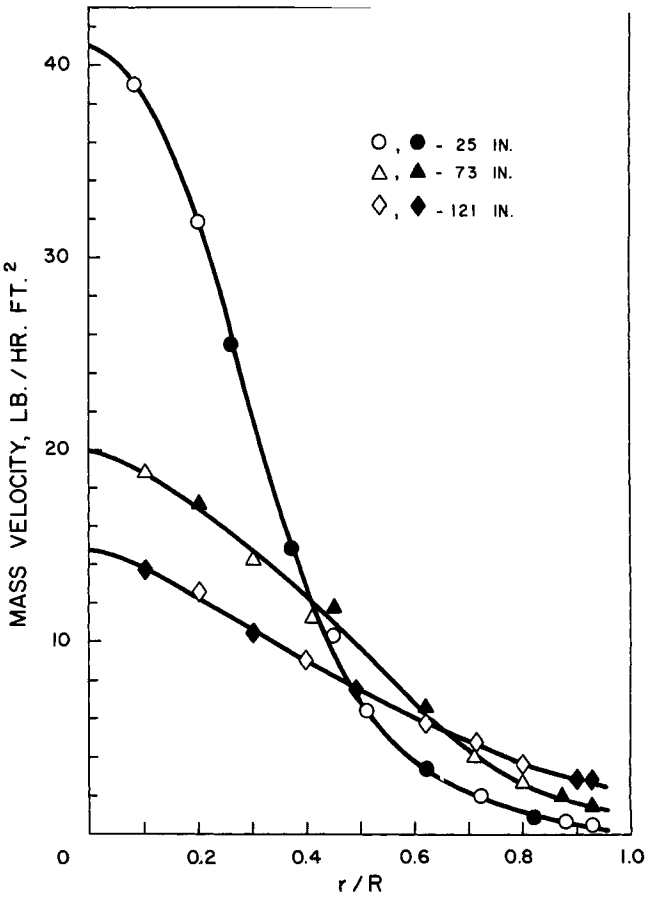

Fig. 9. Radial salt mass velocity profiles.

The extremely steep gradients, especially at the upper levels, suggest that the spray mixes only gradually with the air. In addition, a large portion of the spray is in a region where both the air velocity and the humidity are greatest so that both the residence time and the driving force are least. As a result the spray will dry to a lesser extent in practice than has been predicted by researchers using the assumptions of complete radial mixing and plug flow.

The integration of the mass velocity profiles of salt initially in the feed which is still suspended suggested that there takes place a gradual reduction in the amount of salt suspended in the air stream with increasing distance from the nozzle and that about 10% of the spray is lost by deposition on the dryer walls during its 10 ft. descent.

Turbulent Diffusivity

The turbulent diffusivity of the drying air was determined by axial injection of a tracer, helium, into the stream. These experiments were conducted while spraying water in hot air. Profiles of the helium concentration were obtained at three downstream levels (Figure 10). The peaks of the concentration profiles did not always coincide with the dryer axis but the displacement was never greater than 0.06 in. The integrated helium flow rate was always smaller than the rate of injection although the former increased with increasing distance from the source, the discrepancy being due to the flow disturbance generated by the horizontal helium feed tube. The sampling was always at right angles to the feed tube direction but the flow disturbance caused the greater portion of the

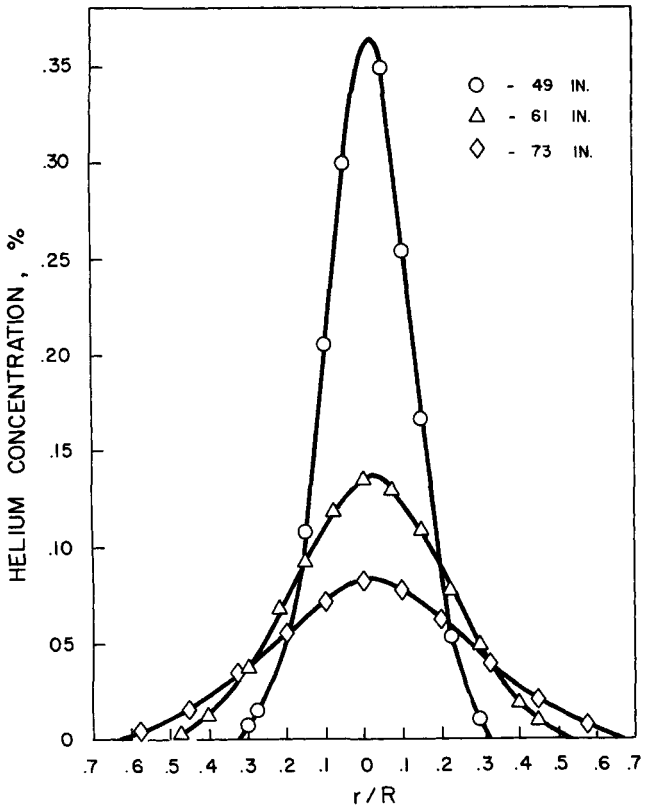

Fig. 10. Helium concentration profiles. Injection at 37 in.

helium to be in the plane which extended downwards from the tube.

The first step in the determination of the turbulent diffusivity, D_t, is the calculation of $\overline{Y^2}$, the mean square radial displacement of the tracer particles from the axis

$$\overline{Y^2} = \int_0^R r^3(c/c_{max})\,dr/2 \int_0^R r(c/c_{max})\,dr \qquad (2)$$

where R = radius of dryer, r = distance from center line, c = tracer concentration at distance r, and c_{max} = maximum tracer concentration. With $\overline{Y^2}$ calculated for several levels, D_t is given by:

$$D_t = \overline{Y^2}/2\tau \qquad (3)$$

where τ = time of diffusion for sufficiently large τ so that the plot is linear.

The above procedure applies strictly to a system with flat velocity profiles. In the present case not only were the profiles not flat but they varied with distance along the axis. As the tracer diffuses outward it enters regions of progressively lower velocity with the result that for a given rate of outward diffusion the tracer will become less diluted with increasing r than would have been the case for uniform velocity across the diameter. This can be expected to affect the concentration profiles, and, consequently, $\overline{Y^2}$. In an attempt to correct for this, Equation (2) was modified to read

$$\overline{Y^2} = \int_0^R r^3(c/c_{max})\,(V/V_{max})\,dr/2 \int_0^R r(c/c_{max})\,(V/V_{max})\,dr \qquad (4)$$

The integrations were performed graphically.

Other corrections which had to be applied dealt with the outward transfer of tracer by the expanding jet and the contribution of the molecular diffusivity. It was also necessary to obtain a weighted time of diffusion for the tracer at a given distance from the injector because of the curved velocity profiles. The corrected values of $\overline{Y^2}$ were then plotted vs. τ (Figure 11). This was done for two dryer zones, near the nozzle and near the exit, and as can be seen from Figure 12 the two lines have identical slopes so that the two diffusivities are also identical. The radial component of the fluctuating velocity was obtained through the expression

$$v' = (\Delta Y^2/2\,\tau_L \Delta\tau)^{1/2} \qquad (5)$$

where τ_L = Lagrangian time scale; intercept on abscissa of $\overline{Y^2}$ vs. τ plot. Although v' for the upper portion of the dryer was somewhat higher, the errors and corrections inherent in the process and the uncertainty in the determination of τ_L do not permit any conclusions as to the significance of this difference. In any case the radial turbulence intensity is about the same for both cases, namely 5%, since it is related to the centerline velocity which is higher in the upper zone.

The diffusivity of the air stream was also found in the absence of spraying. The $\overline{Y^2}$ values were also plotted on Figure 11 where it can be seen that the spreading of helium was much less rapid under these conditions. It was readily apparent that the turbulent diffusivity and the intensity of turbulence are greatly enhanced by the act of spray injection. This is in contradiction to the earlier findings of Longwell and Weiss (23) that injection of fuel oil into an air stream has no effect on the turbulent diffusivity. In their case, however, the air velocity was about 300 ft./sec. so that in spite of the high liquid feed rate the turbulent energy of the stream may have been too high to be affected by the injection. On the other hand, it seems safe to assume that the enhanced turbulence in the present case is the result of spray injection rather than the presence of the drops themselves, since Soo, et al. (24) have demonstrated that for loadings similar to those used in this study, and particle sizes smaller than 250μ, the turbulence of the stream is not affected by the presence of the particles.

CONCLUSIONS

Early in this investigation, the importance of a complete

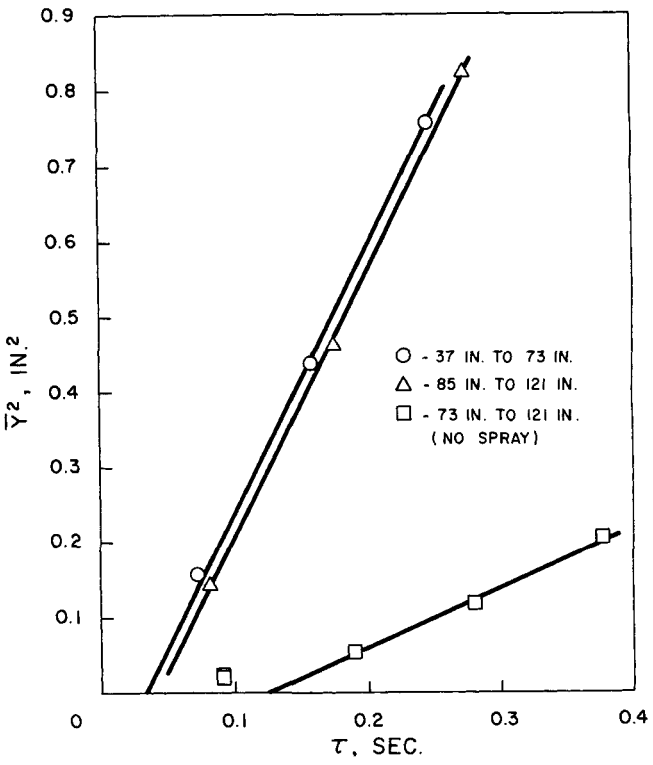

Fig. 11. $\overline{Y^2}$ vs. τ.

characterization of the flow pattern on all phases of the dryer performance was realized and every attempt was made to obtain as symmetrical a distribution as possible. That this attempt was successful was amply demonstrated by the excellent agreement obtained between the various mass balances, in spite of the complexity of the measurement techniques and the possible errors introduced by the very nature of the integrating methods of analysis which had to be used.

Generally speaking, the most striking effect noted during the study was the governing influence exerted by the spray injection on the major variables, such as velocity, humidity, and spray mass velocity, and their distributions through the length of the drying chamber. This effect would undoubtedly be less pronounced in a large commercial chamber, but it might be replaced by other, equally important factors, such as convection currents, which might also influence the flow pattern in a marked manner. An indication of the complexity of the flow pattern in a commercial dryer even in the absence of spray injection, is provided by the findings of Chaloud, et al. (25) and Place, et al. (26). Whatever their origin, these factors must certainly be accounted for before mass balances can be attempted as a first step towards an intelligent design procedure. As already mentioned, the assumption of complete radial uniformity, so prevalent in prediction techniques which have appeared in the literature so far, is quite unsound.

The helium tracer technique was found very useful in characterizating yet another important factor in the flow behavior, namely the turbulent diffusivity. As far as is known no previous information exists on this major aspect of the flow behavior of a spray dryer. The present study was admittedly too limited to provide detailed information but it does show that for the air velocity levels employed, quite typical of industrial practice, the expanding spray has a decided effect on the turbulence level. Again, the information is incomplete but it does appear that the decay of the turbulence is only gradual.

More specifically, for the conditions of air entry and spray injection of the experimental spray dryer, the following conclusions may be drawn:

1. The axial injection into the air stream results in a peaked velocity profile. The profile becomes flatter with increasing distance.

2. The injection of the spray jet causes a marked increase in the radial turbulent diffusivity and radial intensity of turbulence of the air stream. The increased diffusivity can be expected to produce enhanced radial mixing.

3. At a distance of 2 ft. from the atomizer there exist very steep radial gradients in the spatial concentration of the spray with the maximum at the axis. The gradients become weaker with increasing distance but are still quite marked at a distance 10 ft. from the atomizer.

4. As a result of the above gradients there are corresponding but considerably weaker, gradients in the air humidity.

5. The spray moisture is greatest at the axis and decreases towards the dryer walls.

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NOTATION

c = helium concentration, volume %
c_{max} = maximum helium concentration, volume %
D_t = turbulent diffusivity sq.in./sec.
H = air humidity, lb. water/lb. air
$\overline{H}$ = mean humidity across dryer, lb. water/lb. air
M = mass of sodium nitrate collected, mg.
r = radial distance from axis, in.
R = dryer radius, in.
R' = maximum radial penetration of helium, in.
T_c = air temperature, °F.
v' = radial component of fluctuating velocity, ft./sec.
V = air velocity, ft./sec.
V_L = weighted velocity of helium across dryer, ft./sec.
V_L = centerline velocity, ft./sec.
x = axial distance from injector to sampler, in.
X = spray moisture, lb. water/lb. salt
$\overline{Y^2}$ = mean square radial displacement of tracer, sq.in.
$\overline{Y_V^2}$ = mean square radial displacement of tracer due to jet expansion, sq.in.
w_c = air mass rate, lb./hr.
w_s = sodium nitrate mass rate, lb./hr.
W = water vapor mass rate, lb./hr.

Greek Symbols

ρ_c = air density, lb./cu.ft.
τ = diffusion time, sec.
τ_L = Lagrangian time scale, sec.

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