Heat and Mass Transfer to Decelerating Finely Atomized Sprays

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The rate of heat and mass transfer in the nozzle zone of water sprays produced by internal-mixing pneumatic nozzles and hollow-cone pressure nozzles was determined for both concurrent and crosscurrent drying air-flow patterns. The Nusselt numbers for the evaporating drops were correlated by means of the equation proposed by Ranz and Marshall for stationary drops in a moving air flow. Methods of measuring the physical properties of the water-air system were developed, and special attention was devoted to the determination of drop velocities and air humidity.

An increasing number of physical and chemical operations depend on atomization for the production of large contact areas between liquid and gaseous phases. Of the many complex problems which must be solved before the nozzle range of a spray can be fully characterized, the two most important are the rate of evaporation from the droplets and their rate of momentum transfer during deceleration. It is with the former that this paper is principally concerned.

The rate of evaporation from a single, stationary liquid drop suspended in stagnant or moving air streams has been widely investigated (for a fairly complete bibliography on this subject, see reference *1*). Of the several heat and mass transfer correlations proposed, those of Ranz and Marshall (*2*) are generally considered to be the most reliable:

$$N_{Nu} = 2.0 + 0.60\ (N_{Re})^{1/2}(N_{Pr})^{1/3} \quad (1)$$

$$N_{Nu'} = 2.0 + 0.60\ (N_{Re})^{1/2}(N_{Sc})^{1/3} \quad (2)$$

It should be mentioned that in his classic paper published fourteen years earlier Froessling (3) had presented an approximate solution for the Navier-Stokes equations which gave an expression for $N_{Nu'}$ of identical form, but with a coefficient of 0.552 instead of 0.60.

In contrast with the above, very little information is available on the evaporation from sprays or freely falling drops. The published literature on this subject can be divided conveniently into three classes. First there are the purely analytical approaches of Edeling (*4*), Sjenitzer (*5*), Miesse (*6*), and Daskin (*7*). Second there are several determinations of the evaporation rates under conditions of practically no relative velocity between the spray drops and the surrounding drying gases. The investigations of Dlouhy (*8*), Kesler (*9*), Kinzer and Gunn (*10*), and Marshall (*11*) have shown that the evaporation rates are analogous to those of stationary drops suspended in stagnant air; that is,

$$N_{Nu} = N_{Nu'} = 2.0 \quad (3)$$

Third there are several investigations in which the rate of evaporation from sprays injected into horizontal, turbulent, high-velocity air streams was determined. Coldren (*12*) recorded the heat, mass, and momentum fluxes in the drying air stream but did not attempt to measure the spray-drop velocities; he was thus unable to calculate the heat and mass transfer coefficients. Hanson (*13*) and Fledderman and Hanson (*14*) assumed that Froessling's equation could be applied to the spray drops, which permitted them to calculate indirectly the drag coefficient of fuel spray drops. Ingebo (*15*) measured the evaporation rates and drop velocities of *iso*-octane sprays injected against a high-velocity air stream.

It is believed that the present investigation constitutes one of the first attempts at measuring the heat and mass transfer rates from decelerating spray drops produced by typical atomizing nozzles, under conditions similar to those encountered in conventional spray dryers. Two flow patterns were studied: crosscurrent flow (with the drying air passing at right angles to the spray) and downward concurrent flow.

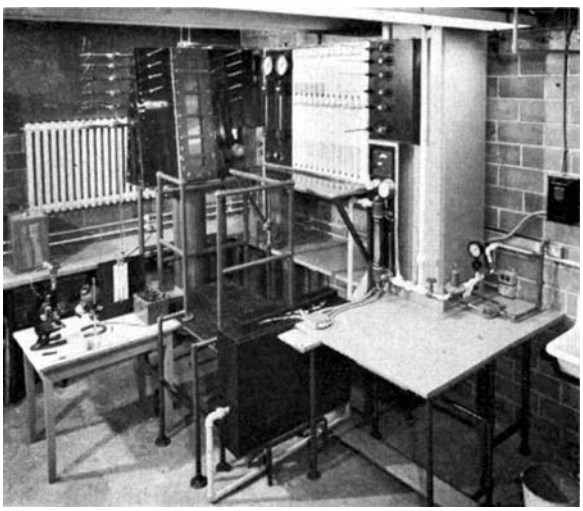

Fig. 1. Crossflow experimental equipment.

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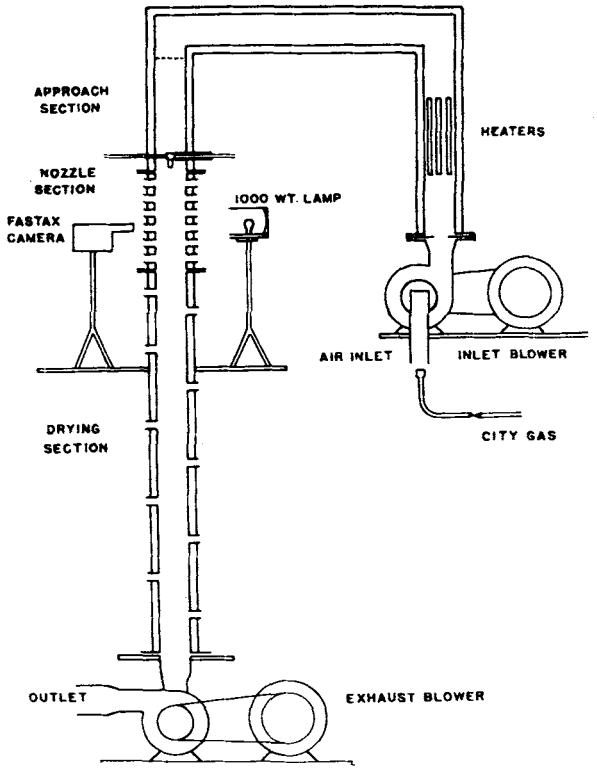

Fig. 2. Schematic diagram of concurrent-flow equipment.

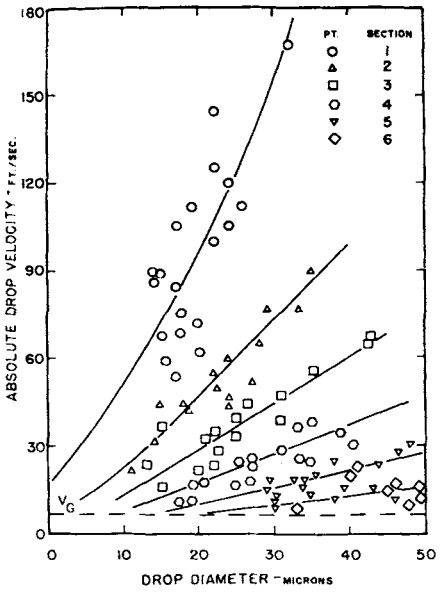

Fig. 3. Drop velocities for pneumatic nozzle JN number 12 in crosscurrent flow.

EXPERIMENTAL

Methods of Measurement

The accurate determination of the individual, local physical properties of the separate phases in a spray of droplets is fraught with experimental difficulties. The presence of the liquid phase in the form of a finely divided suspension renders the conventional methods of measuring the velocity, humidity, and temperature of the drying gases completely useless. Consequently several experimental techniques had to be developed and these are now reviewed briefly.

Drop-Size Distribution. Drop-size determinations were carried out on samples obtained by traversing the spray with an immersion cell containing Varsol. The cell consisted of a hollow aluminum cylindrical tube 0.25-in. O.D., 0.20-in. I.D., and 0.20 in. deep and was fitted with a glass bottom. The samples were photographed under a microscope, and the drop sizes measured to within 1 μ, with counts of up to 250 drops. Owing to the relatively high drop velocities, good impaction efficiencies were obtained, as shown by the large number of small drops (down to 1 μ) collected.

Spray Evaporation. The progressive evaporation from the spray in the nozzle range was followed by measuring colorimetrically the increase in concentration of a powerful red dye added to the feed water. Differences corresponding to one part in ten million could be accurately detected, which permitted the use of a very low dye concentration in the feed water, of the order of one part per ten thousand. Changes in the physical properties of the spray due to the presence of the dye were therefore negligible, and it was carefully ascertained that no surface active properties, such as depression of the surface tension, were imparted to the water.

Samples of the spray were collected under a nonvolatile silicone oil in small weighing bottles which were introduced into the spray by means of an aluminum holder. The holder was designed so that no evaporation of the drops could occur after collection.

Spray-Drop Temperature. There is considerable evidence in the literature to indicate that, once dynamic equilibrium conditions have been attained, evaporating spray drops remain at the wet-bulb temperature to the drying air (*2, 8, 10, 11, 12, 13, 15*).

In the nozzle range of a spray, however, an unsteady state period can be expected to occur before the drops attain a constant temperature. From theoretical step calculations El Wakil, Uyehara, and Myers (*16*) estimated that a 50-μ drop of octane, issuing from a pressure nozzle with an initial velocity of 100 ft./sec., would require about 0.23 sec. to reach constant temperature. For large drops of water (2.7 mm.) Kinzer and Gunn (*10*) showed experimentally that 4.3 sec. elapsed while the temperature of the drop, which was freely supported by an air stream with a wet-bulb temperature of 14.9°C., decreased from 22.4° to 17.6°C.

On the other hand Lyons (*17*) supplied in 1951 some experimental evidence which is much more pertinent to the present study. Using a copper-constantan thermocouple probe located ⅛ in. from the orifice of an internal-mixing pneumatic nozzle, he recorded the following observations.

(1.) With air alone passing through the nozzle a temperature drop of 7.3°C. was observed, in contrast with the much higher decrease which had been predicted by Fogler and Kleinschmidt (*18*).

(2.) With a feed-water temperature of 81°F. the wet-bulb temperature of the air (65°F.) was attained within the distance of ⅛ in., when the atomizing air pressure was sufficient to provide fine atomization. Coarser droplets, produced at lower atomizing air pressure, required a longer distance.

(3.) With increasing feed-water temperature and fine atomization, the wet-bulb temperature was again reached when the initial temperature did not exceed 102°F. The spray temperature was however 2°F. higher than the wet-bulb for a feed water of 114°F. and 12°F. higher for a feed water of 164°F.

These experimental results appear to indicate therefore that for fine droplets under the conditions prevailing in the nozzle range of a spray the unsteady state period is exceedingly short. It was assumed that, with feed-water temperature not too far removed from the wet-bulb temperature, the latter was probably attained by the droplets within 0.5 in. from the nozzle and certainly at higher distances.

To measure the spray temperature, a thermocouple probe was constructed, with a No. 16 hypodermic needle for mounting. The soldered end of the thermocouple protruded slightly beyond the end of the hypodermic needle, and its tip was bent slightly downward. When the device was inserted into the spray through a port in the test chamber, the liquid drops accumulated at the tip and then fell off under the effect of gravity, thus keeping

the thermocouple junction at the spray temperature. The latter agreed closely (within 1.0°F.) with the wet-bulb temperature of the drying air.

Spray-Drop Velocities. Few attempts at measuring the velocity of spray drops from atomizing nozzles have appeared in the literature, and the only extensive experimental study is that of York and Stubbs (*19*), who used direct photography to obtain the velocities of spray drops produced by hollow-cone pressure nozzles. For the present investigation a direct method involving the use of high-speed cinematography was developed.

The drop-velocity determinations were all performed in 8-in.–diameter columns fitted with optical glass windows. The camera used was a 16-mm. one equipped with a *f*/3.5 lens. Illumination of the spray

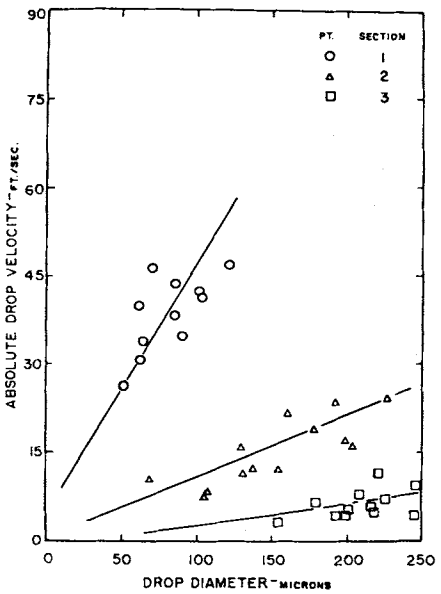

Fig. 4. Drop velocities for pressure nozzle LNN number 1 in crosscurrent flow.

was achieved by a 1,000-w. flood lamp. The optimum angle between the camera and the light beam was experimentally determined to be 135 deg.

The camera voltage and illuminating light was controlled, and a timing-light generator was incorporated into the circuit to activate the timing pulse of the camera, which flashed a light for the duration of a few microseconds every 1/100 or 1/1,000 of a second, so that the time which elapsed between successive frames might be measured.

The camera and illuminating light beam were directed onto the axis of the spray, and very small depths of focus could be photographed. No attempt was made to determine the velocity profile, radially. For the concurrent flow studies the velocity determinations were carried out in the drying chamber proper. For the crossflow studies, however, the measurements had to be carried out in an 8-in. Lucite column, since the drying chamber did not lend itself to direct observations. However the flow rates, temperatures, and pressures of the fluid streams to the nozzle were regulated to correspond with the values used during the actual evaporation tests.

A suitable camera voltage—and consequently speed—was selected for the spray drops to appear on at least three consecutive frames. One 100-ft. reel of motion picture film was taken for each spray-velocity determination. When it was developed, the drops appeared as black streaks on a light background and were analyzed. The grain of the high-speed film was 54 lines/mm. and did not permit drops smaller than 10 μ to be photographed clearly. Accordingly the measurement of velocities for the very small drops had to be abandoned. A cathetometer was used to measure the thickness of the streaks. The instrument was fitted with a moving cross hair on a vernier scale, and the magnification so produced enabled drop diameters to be measured within 2 or 3 μ. Corresponding velocities were easily calculated from measurements of the distance travelled between successive frames.

Air Velocity in the Spray. The direct determination of the air velocity in a droplet-laden system is extremely difficult. Since there is no accurate method of direct measurement, an indirect approach was used, based on the fact that small drops may be considered excellent tracers for gas velocities in turbulent systems. As both their terminal settling velocity and initial kinetic energy are extremely low, the absolute velocities of the smallest droplets approach those of the air stream at a relatively short distance from the nozzle. Consequently a fairly accurate estimate of the air velocities in the spray may be obtained from the intercept on the velocity axis of the drop-diameter–drop-velocity graphs obtained by the photographic method described in the previous section. The main source of error is the actual determination of the drop velocities in this range. The air-velocity profiles obtained from graphical extrapolation in this manner were in agreement with those reported in the literature (*12, 20, 21*). They were also quite similar to those produced by pneumatic nozzles, with no water flowing, as experimentally measured with a standard Pitot tube and a special wedge-shaped velocity probe developed by Stachiewicz (*22*).

Air Temperature in Spray. In the crosscurrent flow experiments mercury thermometers were used, protected by two concentric aluminum-foil shields. In the concurrent flow experiments the shielding of the thermometers was very similar to that used by Dlouhy (*8*). A somewhat larger aluminum-foil shield was used, and the insulation of the thermometer stem was improved by means of a double-jacketed glass shield. The whole device was attached to a transite plug carefully machined to fit the sample port and to follow the inner contour of the drying chamber exactly. A radial temperature traverse could easily be obtained with it.

Determination of the Air Humidity. Owing to the small changes in drying-air humidity observed in this work (about 0.005 to 0.015 lb. water/lb. dry air), a considerable degree of accuracy was required for the humidity measurements. The accuracy provided by conventional hygrometers, the dew-point method, or the wet- and dry-bulb method was found to be inadequate. Other techniques, such as thermal-conductivity measuring devices or conductance cells made of palladium wires coated with lithium chloride, were found to suffer from the additional disadvantages of a narrow range of application and necessity of frequent calibration. A volumetric method of determining the humidity of the air was therefore developed, based on the removal of the water vapor by contact with magnesium per-

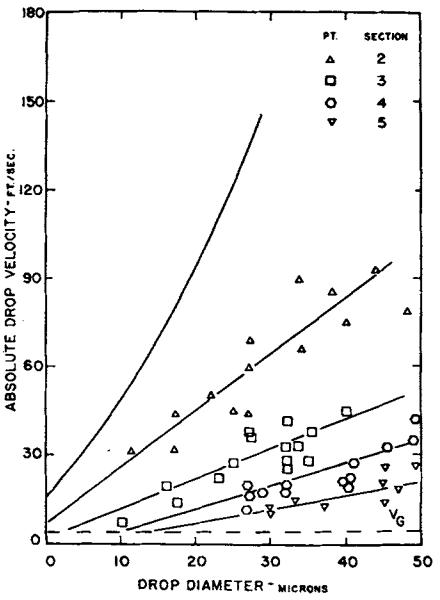

Fig. 5. Drop velocities for pneumatic nozzle JN number 12 in concurrent flow (low-atomizing air pressure).

chlorate. This dehydrating agent was chosen because of its high drying capacity and lack of absorption of carbon dioxide or other common gases.

Measurement of the air sample (collected through an impact separator to remove entrained droplets) was accomplished in a precision burette. The lowest and narrowest section (94 to 100 ml.) was graduated in 0.05-ml. divisions, and volume changes of 0.01 ml. could therefore be detected. The burette was surrounded by a water jacket in which a comparison tube was also installed. The latter was connected through a check valve and leveling tube to the burette. From the burette the air could be passed, by raising the leveling bulb, through the U tube containing the magnesium perchlorate and into a self-sealing mercury reservoir consisting of two interconnected

TABLE 1. COMPARISON OF SPRAY CHAMBERS

Section	Distance from nozzle, in.	Cross-sectional area available for flow: Crosscurrent equipment, sq. ft.	Cross-sectional area available for flow: Concurrent equipment, sq. ft.	Location of sampling ports, in. from nozzle: Cross-current equipment	Concurrent equipment: Pneumatic nozzles	Concurrent equipment: Pressure nozzles
1	0-3	0.050	0.350	1.5	—	0.5
2	3-6	0.066	0.350	4.5	4.0	4.5
3	6-10	0.115	0.350	8.0	8.0	8.5
4	10-14	0.0147	0.350	12.0	12.0	12.5
5	14-18	0.0175	0.350	16.0	16.0	16.5
6	18-24	0.304	0.350	21.0	20.0	20.5

chambers, mounted one above the other. The air entering the lower compartment forced the mercury into the upper section.

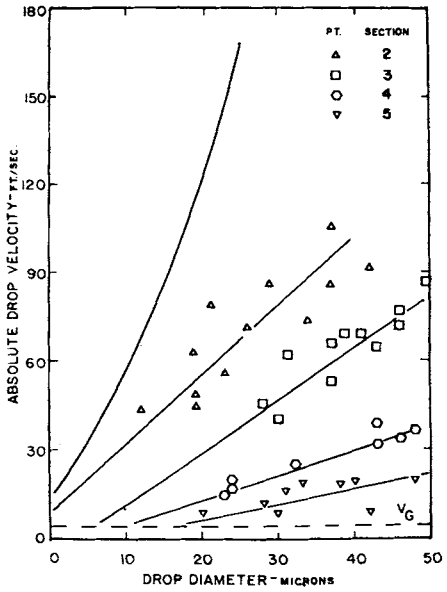

Fig. 6. Drop velocities for pneumatic nozzle JN number 12 in concurrent flow (high-atomizing air pressure).

When the air was sucked back into the burette, the mercury flowed back into the lower chamber. A fixed level of mercury in the lower chamber was obtained by means of a pilot-light circuit with contacts sealed into the mercury chamber. Three passes were found to be required for complete removal of the water vapor.

This method was tested painstakingly against a gravimetric determination, by means of molecular-sieve pellets attached to the end of a calibrated quartz spiral. This assembly was suspended in a 1.5-in.–I.D. by 50-in.–long glass tube, into which the air sample, containing the water vapor to be determined, was introduced. This method of determination was extremely accurate but was too ponderous for routine use. Since carbon dioxide was also absorbed, the apparatus was used for comparison only, by means of carbon dioxide–free air. The agreement between the two methods was excellent, as indicated by a number of comparative tests under various humidity conditions (*1*).

EQUIPMENT

Crosscurrent Flow Equipment

The use of a crosscurrent flow of drying air to measure the evaporation rates from a spray at small distances from the nozzle appeared to offer many advantages. Guiding the air at right angles to the vertical spray through horizontal compartments, in a specially constructed drying chamber, one might expect better contact and more rapid penetration of the spray by the drying air than could be achieved in conventional concurrent flow. The increase in the humidity of the drying air from each compartment would provide an accurate and simple method of determining the rate of evaporation at various distances from the nozzle.

A trapezoidal drying chamber consisting of six horizontal sections was therefore constructed (Figure 1). It was insulated with an internal layer of transite made impervious to water with several coats of high-temperature aluminum paint. Dividing partitions of transite were fitted into the chamber so that six horizontal sections were formed, two of them 3 in. high, three of them 4-in., and one 6 in. high. Circular holes of increasing diameters were cut in the partitions to permit the spray to pass downward from the nozzle, which was installed in the center of the top surface of the chamber.

The spray could be visually observed through a Pyrex glass plate in the front sloping side of the spray chamber. Inlet and outlet drying-air ports were cut in the center of the ends of each of the horizontal sections, and additional ports were provided for temperature determinations. Table 1 gives the physical measurements of the six horizontal sections comprising the drying chamber.

Drying air from a surge tank was delivered to each of the horizontal sections through individual lines, each containing a globe valve, a calibrated orifice, and a thermometer. The exit-air flow rates from the horizontal sections were similarly controlled and metered. Provisions for the close control of the atomization conditions and flow rate of the feed completed the experimental apparatus.

In operation, flow rates were so adjusted in each section as to provide equal velocities of the drying air in all the horizontal compartments. Distortion of the spray and wetting of the walls were prevented by the use of relatively low flow rates.

Concurrent Flow Equipment

This apparatus, which is shown diagrammatically in Figure 2, consisted of a continuous 8-in.–I.D. steel duct, covered with 2 in. of magnesia insulation. In the approach section, directly above the nozzle, straightening plates provided a uniform velocity profile for the drying air, as shown by traverses taken with a Pitot tube and the wedge-shaped probe previously mentioned. The nozzle section was 2 ft. high and fitted with six pairs of sampling ports, located as indicated in Table 1. These ports were also used to photograph the spray under actual operating conditions. The lower section (or drying section) was 12 ft. long and also contained sampling ports, but spaced farther apart.

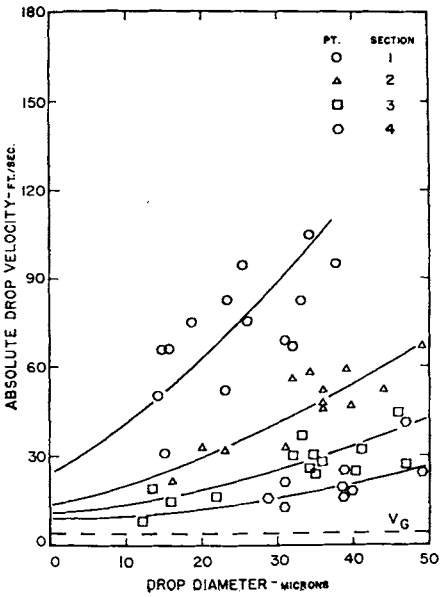

Fig. 7. Drop velocities for pneumatic nozzle JN number 228 in concurrent flow.

In addition to the conventional controls, a twelve-point temperature recorder was connected to copper-constantan thermocouples soldered at various points of the wall in the nozzle or drying sections. Any wetting of the wall by the spray or change in operating condition could thus be detected immediately. Provision was also made to heat the feed water containing the red dye over a wide range of temperature.

CALCULATIONS

In the crosscurrent flow experiment the rate of heat transfer to the spray from the drying air in each section was calculated from the increase in humidity of the individual drying-air streams, by means of an enthalpy balance on the system. When using pneumatic nozzles, one observed that the mass rate of outlet drying air was nearly always greater (particularly for the lower sections) than that of the inlet stream. This ef-

fect was due to the redistribution of the atomizing air and was of course absent when pressure nozzles were tested.

The surface area of the spray in a given section along the spray axis was calculated from the equation

$$A_s = W_s S_w \Delta x/3{,}600 V_D \qquad (4)$$

The average absolute drop velocity (that is, the absolute velocity of a drop of diameter equal to the Sauter mean diameter) was obtained from the graphs expressing the drop velocity in terms of the drop diameter for the appropriate nozzle operation, evaporation conditions, and the appropriate D_{vs}. Here the specific surface area was obtained from the particle count by substitution in

$$S_w = \Sigma nD^2/(\rho_L \Sigma nD^3/6) \qquad (5)$$

The driving force for heat transfer is the temperature difference between the average drying air and the evaporating spray. With pneumatic nozzles t_a was taken as the weighted average between the atomizing air and the drying air, while t_s was the average spray temperature in the section. Because of differences in the drying-air conditions between the various sections (temperature, heat losses, presence of atomizing air, etc.), t_s increased with distance from the nozzle but always remained at the wet-bulb temperature of the drying air in the section.

The heat transfer coefficient for the Sauter mean drop diameter of the spray was calculated from

$$h = q/A_s \Delta t \qquad (6)$$

The Nusselt number was calculated from its definition:

$$N_{Nu} = hD_{vs}/k_f \qquad (7)$$

Owing to the small content of water vapor in the surrounding gas film the thermal conductivity was taken as that of air alone at the arithmetic average temperature of the drying air and the drop surface (*11*).

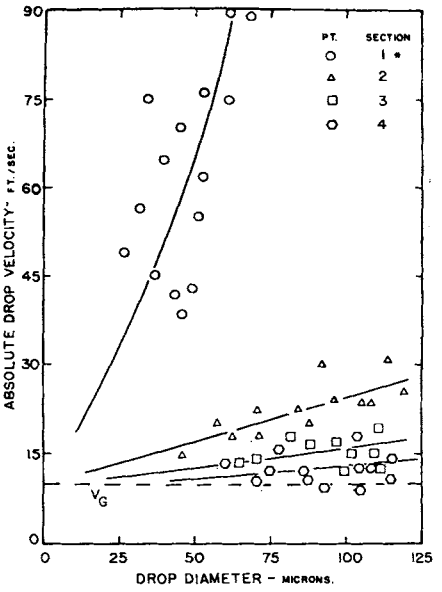

Fig. 8. Drop velocities for pressure nozzle LN number 1 in concurrent flow.

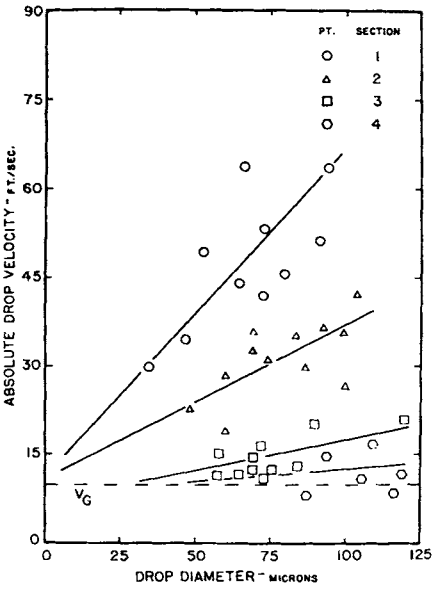

Fig. 9. Drop velocities for pressure nozzle LN number 1 in concurrent flow (high feed temperature).

The modified Nusselt number for mass transfer can be written as

$$N_{Nu'} = k_G D_{vs} RT/D_v = h D_{vs}/c_s D_v \rho_f \qquad (8)$$

or in terms of the Nusselt number:

$$N_{Nu'} = N_{Nu}(k_f/c_s D_v \rho_f) \qquad (9)$$

In the concurrent flow system analysis of the flow pattern was very much simpler, and calculations could be carried out more accurately. The evaporation was determined from the change in concentration of the dye dissolved in the spray. The average temperature of drops in spray remained constant at the wet-bulb temperature of the air. Values of the drying-air temperature, spray evaporation, Sauter mean diameter, and the velocity of a spray drop of the same diameter as the Sauter mean diameter, obtained at the various points shown in Table 1, were plotted against the distance from the nozzle as the abscissa. Average values of these quantities from section to section were obtained by the graphical integration of the area under the curve and the division of the values so obtained by the distance over which the integration was performed. These average values were then used for the calculations of h, N_{Nu}, and $N_{Nu'}$, as before.

RESULTS

A summary of the experimental conditions used is presented in Table 2. Two types of nozzles were tested in the crosscurrent flow equipment: an internal-mixing pneumatic nozzle and a hollow-cone pressure nozzle. The latter gave a much coarser degree of atomization.

These nozzles were again used in the concurrent drying chamber. In addition a second internal-mixing pneumatic nozzle was also used. This had a higher capacity and a somewhat larger spray angle.

In each of the seven sets of runs shown in Table 2, the atomizing air pressure and flow rate (for pneumatic

Table 2. Experimental Conditions

Run	1 to 12	13 to 20	21 to 24	25 to 30	31 to 34	35 to 38	39 to 43
Flow pattern	crosscurrent	crosscurrent	concurrent	concurrent	concurrent	concurrent	concurrent
Nozzle type	pneumatic	pressure	pneumatic	pneumatic	pneumatic	pressure	pressure
Nozzle no.	JN 12	LNN 1	JN 12	JN 12	JN 22B	LN 1	LN 1
Spray angle, deg.	12	60	12	15	20	60	60
Atomizing—air pressure, lb./sq. in. gauge	25	—	25	35	25	—	—
Atomizing air flow rate, lb./hr.	5.45	—	5.45	7.2	20.5	—	—
Liquid feed pressure, lb./sq. in. gauge	14.9	99	14.9	25	6	95	95
Liquid feed flow rate, lb./hr.	2.0	5.1	2.0	4.4	6.0	12	12
Liquid feed temperature, °F.	76-92	76-90	76-92	62-75	62-81	85-101	78-250
Drying air flow rate, lb./hr.	42-81	25-46	300	300	300	750	750
Inlet drying—air temperature, °F.	138-214	144-220	145-230	145-230	145-230	150-250	250
Total evaporation, %	19-55	2-7	72-84	72-86	40-50	9-27	14-56
Sauter mean diameter, μ	14.1-35	65-169	16-23	12-23	16-28	59-82	40-92
Drop—velocity data, Figure no.	3	4	5	6	7	8	8-9

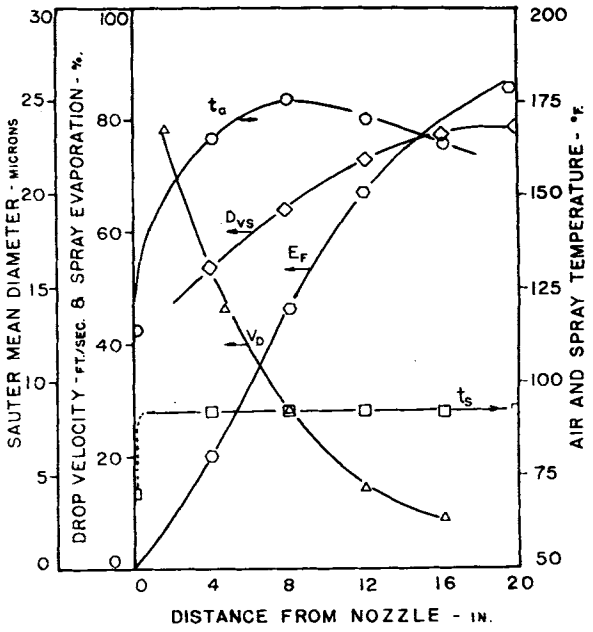

Fig. 10. Change in spray and air properties for run 29.

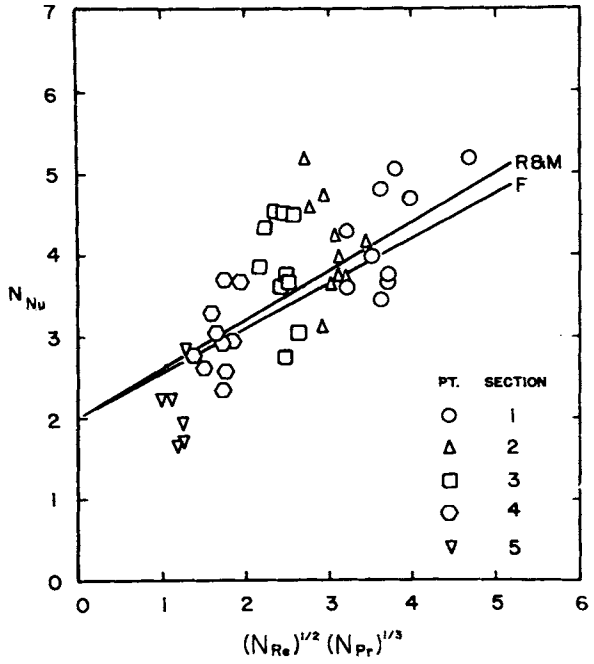

Fig. 11. Nusselt number for runs 21 through 30.

nozzles) and the liquid feed pressure and flow rate were kept constant. The variables studied were the drying-air flow rate and its inlet temperature. No attempt was made to control the feed temperature, which was allowed to fluctuate slightly from run to run, except in runs 39 to 43, where it was the variable studied. In run 39 the feed was preheated to 250°F. before the pressure nozzle and partially flashed at the nozzle opening.

The drop-velocity data are presented in Figures 3 to 9. In all these plots the air velocity is shown as a dotted line. The distances from the nozzle at which the measurements were made are indicated by the section number, as given in Table 1. Figures 3 to 8 cover the conditions shown in Table 2, as indicated in the bottom line. Figure 9 applies specifically to run 39, in which the feed was delivered to the nozzle at 250°F. Additional data can be found in reference *1*.

Typical changes in spray air and drop temperatures, percentage of spray evaporation, drop velocity, and Sauter mean diameter as a function of the distance from the nozzle are shown in Figure 10 for concurrent drying with a pneumatic nozzle (run 29). A typical plot of calculated Nusselt numbers vs. $(N_{Re})^{1/2} (N_{Pr})^{1/3}$ is shown in Figure 11 (runs 21 to 30), on which the two lines representing the correlations of Ranz and Marshall (R and M) and of Froessling (F) are also indicated. Similar plots could be drawn for the calculated modified Nusselt numbers.

Finally the effect of variations in feed temperature on the rate of evaporation from the spray is shown in Figure 12 (runs 39 to 43).

CONCLUSIONS

The development of suitable measuring techniques constituted an important phase of this investigation. Because of its importance in the calculation of heat and mass transfer rates, the determination of droplet velocities received particular attention. It is recognized, however, that the high-speed cinematographic method which was finally adopted presents a number of deficiencies, chief among which are its inability to determine velocities higher than about 180 ft./sec. or to permit measurements for drops smaller than 10 μ and the inherent inaccuracy in the estimation of the droplet diameter. It is also realized that, since the velocity of the droplet may depend to a significant extent on its radial position in the spray (*19*), the absolute droplet velocity at the axis of the spray (as measured in this work) is probably consistently higher than the true average velocity.

In spite of these various limitations, it was possible to make measurements as close as 1.5 in. from the pneumatic nozzle and 0.5 in. from the pressure nozzle. As expected, smaller drops and higher velocities are obtained with the pneumatic nozzles, and for a given nozzle the larger drops have a much higher initial velocity. The velocity data also indicate that the smaller droplets decelerate quite rapidly to the velocity of the air stream.

Generally speaking, an increased rate of evaporation, resulting from a higher inlet drying-air temperature, will decrease the distance of penetration of the spray under otherwise identical operating conditions, since the reduction in the mass of the spray also reduces its kinetic energy. The true situation is, however, somewhat more complicated; for a given droplet diameter measured at a given distance from the nozzle the initial diameter of the corresponding droplet issuing from the atomizer must have been larger under conditions of higher evaporation rate. Its initial kinetic energy or velocity must therefore have been higher. On the other hand, this is offset by larger drag forces. At an appreciable distance from the nozzle the cumulative effect of the latter results in a lower droplet velocity in the presence of higher evaporation rates. Closer to the nozzle the opposite behavior is observed.

The initial increase in the value of the Sauter mean diameter of the spray with distance from the nozzle, as shown in Figure 10, may at first appear unusual. This is actually to be expected with a wide distribution in drop sizes, since the smaller drops evaporate much more quickly than the larger ones (*8*).

The equations proposed by Froessling (*3*) and by Ranz and Marshall (*2*) for stationary drops suspended in moving air streams were found to be generally applicable for correlating the Nusselt numbers in terms of the dimensional groups $(N_{Re})^{1/2} (N_{Pr})^{1/3}$, as shown in Figure 11. The scatter of the experimental data appears to be considerable but may be ascribed at least partially to the fluctuations inherent to the system: by this it is meant that in any part

of the nozzle zone drops of a given diameter, or of a given D_{vs}, may have different velocities depending on the effect of the turbulent-velocity fluctuations during deceleration. In Equation (4), however (and thus in the other equations which follow from it), only one average V_D value was used, read from the curves given in Figures 3 to 9. It might be expected that the intensity of turbulence encountered might result in an increase in the heat transfer rate (*14, 23*), but such effects are relatively small and thus are not likely to be apparent in the range of Reynolds numbers investigated.

The limited experimental data on the effect of an increase in feed temperature on the evaporation rate are summarized in Figure 12. The marked increase in the latter can be attributed to three separate factors: First, there is a certain amount of flashing as the drop temperature decreases to the wet-bulb temperature of the surrounding gas; second, the decrease in the liquid-surface tension and viscosity at higher temperatures produces a decrease in the drop size (*24, 25, 26*) which results in an increase in the specific surface available for heat and mass transfer; third, there is a decrease in the drop velocity (Figures 8 and 9), which increases the residence time and hence the evaporation.

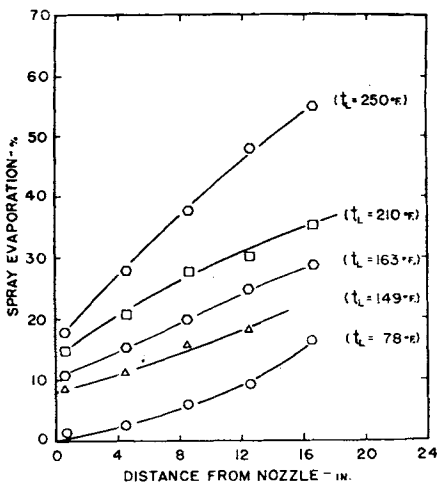

Fig. 12. Effect of feed temperature on evaporation.

Dlouhy (*8*) has shown that the evaporation and drying time of a spray can be predicted with good accuracy from step-by-step calculations, with a procedure similar to that proposed by Marshall (*11*), provided that the droplet-size distribution at the atomizing nozzle is known. A similar method, modified to take the changing drop velocity into account, can obviously be used to calculate the rate of evaporation in the nozzle range of a spray. Such calculations were carried out on five of the crosscurrent runs and four of the concurrent ones and were generally in good agreement with the experimental values.

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NOTATION

A_s = average total surface area of the spray drops, sq. ft.
C_D = drag coefficient
c_s = average humid heat of the gas film, (B.t.u.)/(lb. dry air) (°F.)
D = diameter of drop, μ
D_{vs} = Sauter mean diameter of spray drops, μ
D_v = diffusivity of surrounding gas film, (sq. ft.)/(hr.)
E_f = fraction of spray evaporated
h = heat transfer coefficient, (B.t.u.)/(hr.) (sq. ft.) (°F.)
k_f = average thermal conductivity of the gas film surrounding drop, (B.t.u.)/(hr.) (ft.) (°F.)
k_G = mass transfer coefficient, (lb.-mole)/(hr.) (sq. ft.) (Δp)
n = number of drops
N_{Nu} = Nusselt number, hD_{vs}/k_f
$N_{Nu'}$ = Modified Nusselt number, $k_G M_m D_{vs} p_f / D_v \rho_f$
N_{Pr} = Prandtl number, $C_p \mu_f / k_f$
q = rate of heat transfer, (B.t.u.)/(hr.)
R = gas constant 1,545 (ft.-lb. force)/(lb. mole) (°R.)
N_{Re} = Reynolds number, $D_{vs} V_R \rho_f / \mu_f$
N_{Sc} = Schmidt number, $\mu_f / \rho_f D_v$
S_w = specific surface area of spray drops, (sq. ft.)/(lb.)
Δt = driving force = $t_a - t_s$, °F.
t_a = average temperature of the drying air in the spray, °F.
t_s = average temperature of drops in spray, °F.
t_L = temperature of liquid feed, °F.
V_D = absolute velocity of drop, (ft.)/(sec.)
V_G = absolute velocity of drying air, (ft.)/(sec.)
V_R = velocity of drop relative to drying air in spray, (ft.)/(sec.)
W_s = average mass flow rate of spray water in a section in crosscurrent flow, lb./hr.
x = axial distance from the source of the spray, ft.
μ_f = absolute viscosity of gas film surrounding drop, (lb.)/(ft.) (sec.) or (lb.)/(ft.) (hr.)
ρ_f = average density of the gas film surrounding drop, (lb.)/(cu. ft.)
ρ_L = density of liquid feed, (lb.)/(cu. ft.)

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