Gas Mixing in a Square Duct: II

EUGENE MILLER and KURT WOHL
University of Delaware, Newark, Delaware

Instantaneous shadow photography is used to study the mixing of air flowing in a 2-in. square duct with a secondary stream of carbon dioxide entering sidewise from an orifice. Mixing is described in terms of four mixing parameters measured from the shadow photographs, penetration distance, bulk mixing distance, macromixing distance, and the quality of micromixing, as a functon of sidestream: mainstream mass velocity and volume flow ratios, main duct velocity, and the average orifice shroud velocity component parallel to the air flow in the main duct.

The first three parameters are reported quantitatively as a function of the variables mentioned. The latter parameter is reported semiquantitatively by means of a scale of grading the micromixing which describes the condition of the schlieren at arbitrary duct lengths downstream from the entrance of the gases. Comparisons are made with previous results from studies of the secondary gas entering sidewise from a tube.

Orifice discharge coefficients are correlated as a function of the orifice diameter, orifice Reynolds number, main duct velocity, and orifice shroud velocity. These are présented to aid in the description of the mixing and to be used in the design of similar mixing configurations.

There are numerous practical examples of the importance of gas mixing to the chemical industry and to combustion-engine technology. In the chemical plant good mixing is often a criterion for obtaining profitable yields. In the Diesel and Otto cycle engines, gas turbines, rockets, and ramjets gas mixing has an important bearing on performance. Moreover poor mixing often causes excessive corrosion or erosion of reactor or combustion chamber walls because of the presence of zones of extreme temperature or chemical concentration.

The present work is a continuation of efforts to define the factors controlling mixing in such equipment by studying mixing in relatively simple configurations. It has been possible to obtain a semiquantitative picture of gas mixing under this circumstance which may have industrial application.

In a previous paper by the present authors and associates (*1*) a study was made of the mixing of a mainstream of air flowing in a square duct with a stream of carbon dioxide entering at right angles from a cylindrical, square, or rectangular side tube. Mixing was described in terms of four mixing parameters primarily measured from instantaneous shadow photographs and confirmed by chemical sampling techniques, penetration distance, bulk, mixing distance, macromixing distance, and the quality of micromixing as a function of side stream: mainstream mass velocity and volume flow ratios, main duct scale, main duct velocity, and type and orientation of the sidestream duct.

The latter work is extended in the present paper to include the case of the sidestream gas entering through a sharp-edged orifice in the wall of the main duct. This has allowed confirmation of the validity of the parameters previously selected for describing gas mixing. Also it presents mixing results for another useful mixing configuration.

In the arrangement studied the orifice was placed in the wall of a 2-in. square duct so that the orifice plate was flush with the duct wall. The orifice plate formed the base of a rectangular shroud (see Figure 1) through which the sidestream gas was introduced into the orifice. The jet emerging into the main duct was given a velocity component parallel to the main duct axis, as well as perpendicular to it, by having an excess of the sidestream gas flow past the orifice in the shroud. Only the case of parallel flow of gases in the shroud and main duct was studied. As before carbon dioxide and air were used as the sidestream and mainstream gases respectively. Also instantaneous shadow photography was used again.

SCOPE OF WORK

The following parameters and experimental variables were independently controlled:

1. Main duct size D, 2-in. square, constant.
2. Main gas stream velocity V_D, 25 to 100 ft./sec.
3. Sidestream: mainstream mass velocity ratio R_m, 2:1 to 16:1.
4. Sidestream: mainstream volume flow ratio R_v, 1:50 to 1:6.25.
5. Average orifice shroud velocity V_s, 0 to 100 ft./sec. The average orifice shroud velocity is defined as the arithmetic average of the shroud gas velocities upstream and downstream of the orifice, at the shroud temperature and pressure.
6. The orifice diameter d was a dependent variable in the experiments, since R_m and R_v were varied independently; by definition

$$R_m = \frac{\rho_d}{\rho_D}\left(\frac{D^2}{\pi d^2/4}\right) R_v$$

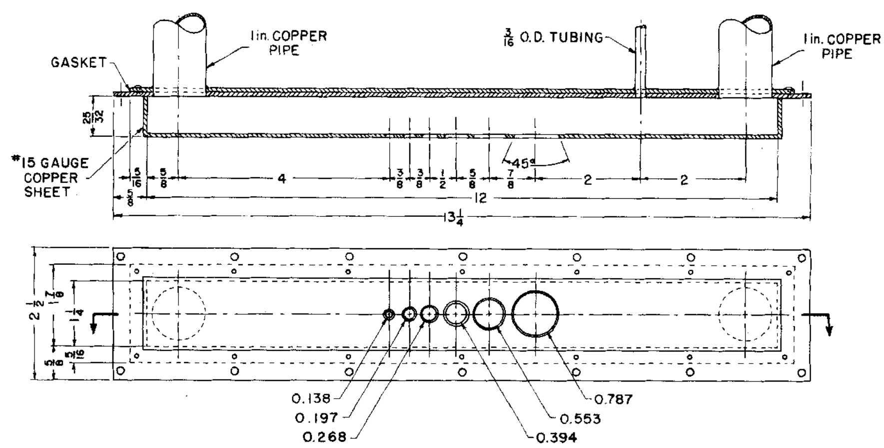

Fig. 1. Orifice shroud. All orifices not in use are sealed off with cellophane tape.

Eugene Miller is with Lockheed Propulsion Company, Redlands, California.

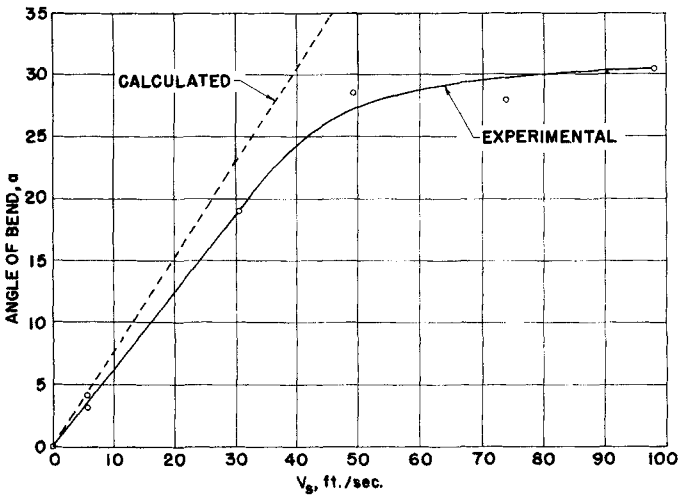

Fig. 2. Orifice jet angle of bend as a function of average orifice shroud velocity; orifice diameter, 0.268 in.; Reynolds number, 20,000.

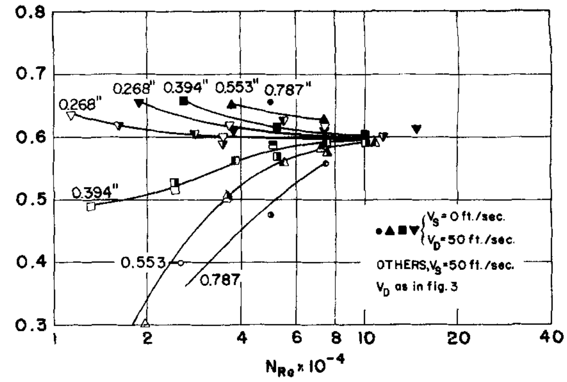

Fig. 4. Orifice coefficient of discharge as a function of Reynolds number, average orifice shroud velocity, main duct velocity, and orifice diameter.

In order to obtain the range of R_m and R_v indicated the orifice diameter was varied between 0.1978 and 0.787 in.

CRITERIA FOR MIXING

As described and discussed in detail in (*1*) four parameters were chosen for description of the mixing process.

Penetration distance is defined as the longitudinal distance between the upstream edge of the sidestream-jet shadow image at the sidestream port and the plane where the jet shadow just reaches the opposite wall. It is related to the problem of distributing the sidestream over the cross section of the duct.

Bulk mixing distance is defined as the longitudinal distance between the center of the sidestream port and the plane where the schlieren are distributed (but not necessarily uniformly) over the whole duct.

Macromixing distance is defined as the longitudinal distance between the center of the sidestream port and the plane where a roughly even distribution of the schlieren is accomplished over the cross section of the duct. The schlieren intensity and scale, that is graininess, are uniform over the duct cross section at this distance.

Instead of a distance parameter a scale of grading the quality of micromixing is used which provides a method for describing the micromixing in a semiquantitative manner.

Grade A: excellent; very faint schlieren present after 3.5 duct diameters and none at 7 duct diameters.

Grade B: good; distinct schlieren at 3.5 duct diameters and none or faint at 7 diameters.

Grade C: fair; medium-scale schlieren present at 7 duct diameters.

Grade D: poor; bulky, large-scale schlieren at 7 duct diameters.

As was shown in the previous studies these parameters are functions of the mass velocity and volume flow ratios of the two streams, duct size, and duct velocity. An added variable here is the average orifice shroud velocity. Shadowgraphs taken through the top and bottom duct walls (both of glass) indicated that the sidewise spreading and mixing of the sidestream jet with the mainstream were completed before completion of the mixing viewed from the side. Since the side plane thus represented the controlling plane of mixing, the major portion of the shadowgraphs were taken in this plane.

APPARATUS AND PROCEDURE

The mixing chamber consisted of a square wooden duct, 2-in. square by 55-in. long with two side walls of special plate glass for the last 20-in of length. Provision was made for introducing the mainstream air into one end of the square duct and for the sidestream carbon dioxide to enter through the top wall near the beginning of the glasswalled section, equidistant from the two side walls.

The orifice box or shroud was built in accordance with Figure 1. The box was placed in the top wall of the duct so that the orifice plate was flush with the wall.

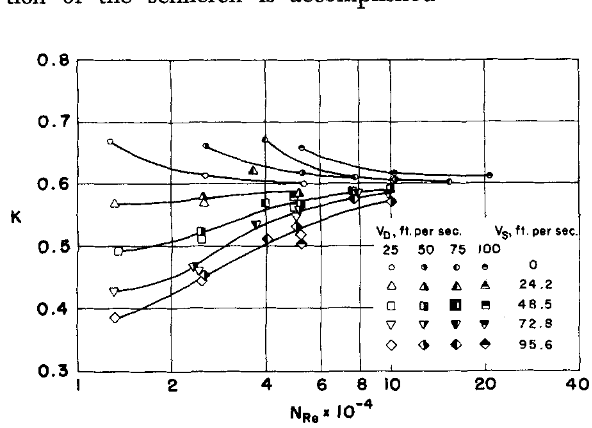

Fig. 3. Orifice coefficient of discharge as a function of Reynolds number, average orifice shroud velocity, and main duct velocity; orifice diameter, 0.394.

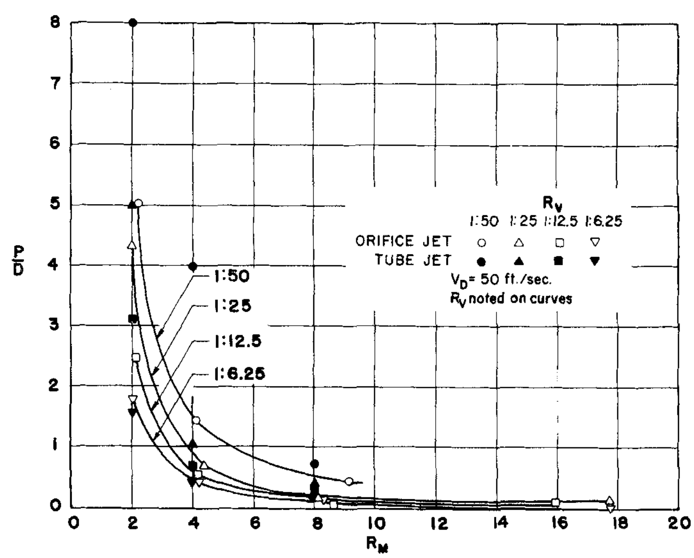

Fig. 5. Penetration distance: duct width as a function of mass velocity and volume flow ratios.

Flow of carbon dioxide in the shroud was in the same direction as air flow in the main duct. Another orifice shroud was used in conjunction with the orifice plate to give the condition of zero shroud velocity. In order to seal off the orifices not in use at any particular time ¾-in. wide cellophane tape was used.

EXPERIMENTAL RESULTS

Orifice Discharge Characteristics

In order to understand the mixing behavior of the orifice sidestream jet it is well to consider first the orifice jet discharge characteristics in relation to the shroud velocity and the main duct gas velocity. The general effect of the shroud velocity is illustrated by the case of the carbon dioxide issuing vertically from an 0.268-in. diameter orifice into still air. The free jet was given a constant port velocity of 72 ft./sec., and the average shroud velocity was varied from 0 to 100 ft./sec. Not unexpectedly it was found that the orifice jet is bent in the direction of the velocity vector of the gas inside the shroud. However as the shroud velocity is increased, a condition is reached at which the jet strikes the downstream beveled edge of the orifice, and a further increase in shroud velocity does not produce a proportionate increase in bend of the jet.

In Figure 2 the angle of bend of the jet from the vertical is plotted vs. the average shroud velocity for the experimental situation described. It will be noted that the angle of bend is proportional to the average shroud velocity for small shroud velocities but gradually reaches a limiting value of about 30 deg. The variation of angle of bend for the case of an infinitely thin orifice plate is also represented. It has been calculated from a vector summation of the average shroud and orifice velocities. The limiting value for this ideal case is, of course, 90 deg.

The shroud velocity not only bends the orifice jet but also has a marked effect on the orifice discharge coefficients. Since the discharge coefficient is related to the contraction of the jet, and hence subsequent point velocities in the jet, this is important to mixing. It was found also that the main duct velocity has an effect on the discharge coefficient. Suitable data were collected during the course of the mixing studies so that the coefficients of discharge could be computed. As will be seen they differ in general from those ordinarily used for pipe-centered orifices.

Although the usual working equation for the discharge coefficient

$$K = V/Y\sqrt{2gh}$$

is derived in that form for a pipe-centered orifice, an analogous equation can be derived for the present arrangement as well. The value of K for a pipe-centered orifice, for given pipe and orifice diameters, is only a function of the Reynolds number; the K value for the side-wall orifice, for a given duct size and orifice diameter, is a function of the average velocity past the orifice and the pressure drop across the orifice as well. It may be shown that

$$K = C\left\{1 + \theta^2\frac{(1+m^2/4)}{(1-m^2/4)^2} - \frac{m\theta}{2}\sqrt{(1+\theta^2)/(1-m^2/4)}\right\}^{1/2}$$

where

$$\theta^2 = (\overline{V}^2/2g)(1/\Delta pv)$$

The expansion factor for an orifice is available from empirical data obtained for pipe-centered square-edged orifices from the work of Beane et al. (2); it has been applied here for lack of better information. It is probable that the error involved in using this factor is within the precision of the present experimental measurements. Good agreement with pipe-centered orifice data was obtained at higher Reynolds numbers where the effect of the shroud velocity was small and also at zero shroud velocity where the orifice was essentially centered in the shroud. If this same expansion factor formula is used when utilizing the reported discharge coefficients, the product KY should be accurate enough for most applications.

Figure 3 shows a plot of the variation of K with N_{Re} with V_s and V_D as parameters for an orifice diameter of 0.394 in. Under the conditions of zero shroud and zero duct velocities the values obtained are about 0.60 within 1% of the accepted values. It may be seen that an increase in average shroud velocity results in a decrease in K. This occurs for two reasons. First the resultant orifice velocity vector is at an angle to the orifice axis and therefore encounters an equivalently smaller flow area. Secondly the orifice plate has a finite thickness; the jet impinges on it, producing friction and turbulent effects.

With an increase in orifice Reynolds number, or orifice velocity, the effect of the shroud velocity becomes smaller and the value of K approaches a value which would be obtained for a pipe-centered orifice, or for zero shroud velocity. An increase in duct velocity results in a large increase in the value of K at low Reynolds numbers with a shroud velocity of zero but in a relatively small increase with a shroud velocity of 25 ft./sec. or greater. Here again the effect of the duct velocity decreases as the orifice velocity is increased. The increase in the discharge coefficient due to the duct velocity is attributed to entrainment of the sidestream by the mainstream.

In Figure 4 typical data of K vs. N_{Re} are plotted for all the orifices used in the mixing experiments, for V_s of 0 and 50 ft./sec. The effects noted above for an orifice diameter of 0.394 in. are smaller for smaller diameter orifices and larger for larger orifice diameters at the same Reynolds number. Again, at Reynolds numbers over 100,000, the effects of shroud velocity and duct velocity are small.

In consideration of the factors of jet bending and variation of discharge coefficients with duct and shroud velocities it is to be expected that the mixing characteristics of the orifice jet will be more complex than those previously reported for the tube or slit jets.

Penetration Distance

The penetration distance data for all values of V_s and V_D were correlated

TABLE 1

V_s, ft./sec.	α	β
0	2.0	1.0
25	1.7	0.9
50	1.5	0.7
75	1.3	0.7
100	1.2	0.7

TABLE 2

V_D, ft./sec./V_s, ft./sec.	K_p 0	25	50	75	100
25	0.59	0.78	1.21	0.86	0.86
50	0.69	0.75	1.04	0.86	0.86
75	0.79	0.85	1.37	1.11	1.01
100	0.89	0.94	1.51	(1.26)*	(1.11)*

* Too few points.

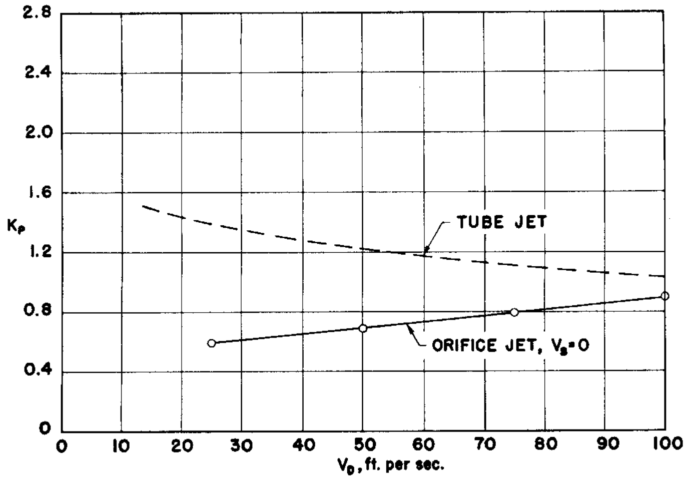

Fig. 6. K_p **as a function of duct velocity.**

by means of the equation previously derived by dimensional analysis:

$$P/D = K_p/R_m^{\alpha} R_v^{\beta}$$

The exponents α and β were found to be dependent on average shroud velocity but independent of duct velocity. K_p at a given value of shroud velocity varied with the duct velocity. The data may be summarized by means of Tables 1 and 2.

K_p values were obtained from the data by means of the method of least squares. Sigma values for the deviations of the calculated value of P/D from the actual values are 0.35, 0.21, 0.17, 0.24, and 0.27 in. at V_s values of 0, 25, 50, 75, and 100 ft./sec. respectively. The largest deviations from the correlation are found for the smallest and largest values of P/D. At the smallest distances the relative error is, of course, large, and at the largest distances dilution effects make the measurements relatively doubtful.

The present results are compared with those previously reported for the tube jet in Figure 5. Under all conditions the penetration distances for the orifice jet, at zero shroud velocity, are smaller than those for the tube jet. The exponents for the orifice jet equation under these conditions are the same as for the tube-jet equation. The K_p values for both are compared in Figure 6. The asymptotic values for both curves appear to be the same. So at higher values of V_D the penetration distance behavior of jets issuing from tubes or orifices with zero shroud velocity are predicted to be the same.

It is believed that the differences in penetration distance between the orifice jet with zero shroud velocity and the tube jet may be explained in terms of the contraction of the orifice jet at the vena contracta and subsequent mixing effects. The velocity of the jet is calculated from the volume flow and the port area. This yields an apparent R_m value which in the case of the orifice jet is lower than the value at the vena contracta. The orifice jet appears therefore to have a lower penetration distance than the tube jet at the same calculated values of R_m and R_v. An attempt at correcting the mass velocity ratios for the contraction of the orifice jet resulted in penetration distances for the orifice jet which were higher than the corresponding values for the tube jet. When one assumes that the coefficient of discharge corrected for expansion effects (KY) truly represents a contraction, since the boundary layer mixing of an orifice jet is more rapid than that of the tube jet, more rapid mixing of the orifice jet woud lead to a greater penetration distance. Thus there are at least two compensating factors involved in the penetration of an orifice jet, the vena contracta and boundary layer mixing.

From Table 1 it may be seen that as the shroud velocity is increased the variation of penetration distance becomes less dependent on mass velocity and volume flow ratios. This is evidenced by a reduction in the exponents α and β with an increase in V_s. Further, from parametric plots of the penetration data, the following general conclusions may be drawn:

1. At all values of R_v, for $R_m \geqq 4$, the general trend is an increase in P/D with an increase in V_s.

2. At $R_m = 2$, and at $R_v = 1{:}50$, P/D also increases with V_s, but for $R_v > 1{:}50$, P/D decreases with V_s.

3. For $R_v > 1{:}50$ for $R_m > 2$, the effect of V_s on P/D is small. For $R_v = 1{:}50$, the effect of V_s is small for $R_m > 4$.

From studies of the effects of duct velocity the following conclusions hold:

1. The effect of V_D is greatest at $R_m = 2$ and/or $R_v = 1{:}50$.

2. At $R_v > 1{:}50$, V_D has little effect for $R_m > 2$.

3. Except at $R_v = 1{:}50$ and $R_m = 2$, P/D increases as V_D increases. At $R_v = 1{:}50$ and $R_m = 2$, the reverse is true.

A direct comparison of the mixing characteristics of the tube jet and orifice jet is complicated by the interrelated effects of V_s and V_D. However the following general conclusions may be drawn:

1. At $R_v \leqq 1{:}25$, $R_m \leqq 4$, the tube jet penetration distances are greater than those of the orifice jet at all V_s and V_D studied. At $R_m = 8$, the tube jet penetration distances are longer than those for the orifice jet at zero shroud velocity and all values of V_D. At higher values of V_D and V_s the penetration distances for the tube jet are the same or somewhat smaller than those for the orifice jet.

2. At $R_v = 1{:}12.5$ and $R_m = 2$, the tube jet P/D values are greater than the orifice P/D values at all V_s and V_D values. For $R_m \geqq 4$, the tube jet values are higher at $V_s = 0$, but at higher values of V_s and V_D they are somewhat less or about the same as the orifice jet values.

3. At $R_v = 1{:}6.25$ and $R_m \geqq 2$ and $V_s = 0$, the P/D values for both jets are about the same. For $V_s > 0$ and all values of V_D, at $R_m = 2$, the P/D values are about the same, and at $R_m \geqq 4$, P/D for the orifice jet is the same or greater at higher values of V_D.

The complex behavior of the orifice jet penetration distance is consistent with the discussion of the variation of the angle of bend of the jet with V_s and of the orifice discharge coefficients with V_s and V_D. It would be fruitless to try to explain the detailed variations of penetration distance in these terms alone however, since the mixing behavior of the jet with the duct flow adds another variable which cannot be explicitly described.

Bulk Mixing Distance

Bulk mixing is the next phase of the mixing of the sidestream with the mainstream. The bulk mixing distances are at least as large as the penetration distances but are usually larger.

Figure 7 is a graphical presentation of the variation of B/D with R_m and R_v at a duct velocity of approximately 50 ft./sec. Data are shown for orifice jets with shroud velocities of zero and 50 ft./sec. and compared with tube jet data.

Except at $R_v = 1{:}50$, no conclusive pattern can be established for the effect of orifice shroud velocity on B/D. At $R_v = 1{:}50$, the B/D value for an

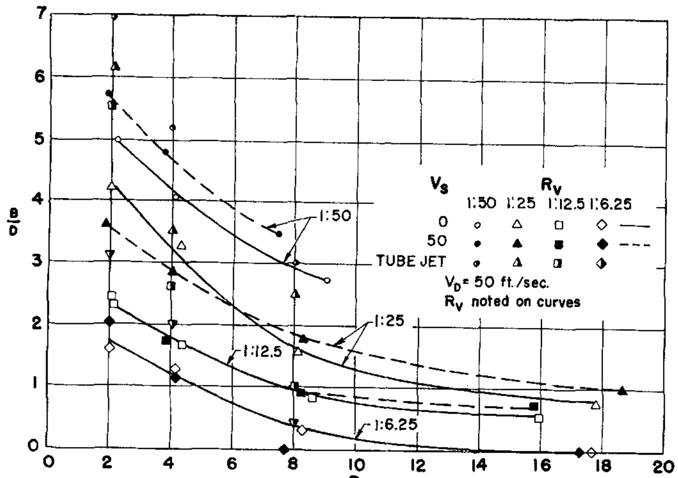

Fig. 7. Bulk mixing distance: duct width as a function of mass velocity, ratio, volume flow ratio, and average orifice shroud velocity.

orifice jet with a shroud velocity of 50 ft./sec. is consistently greater than for the orifice jet with zero shroud velocity. In general it may be concluded that shroud velocity has only a small effect on bulk mixing. The B/D variation with V_s follows the trends previously described for P/D for $R_v \leqq 1{:}25$; for $R_v \geqq 1{:}12.5$, B/D increases with an increase in shroud velocity at all values of R_m. Duct velocity has only a minor effect on bulk mixing and in general may be neglected.

For $R_m < 8$, the orifice jet consistently exhibits smaller B/D values than the tube jet. At greater values of R_m, B/D values of the two jets are probably the same. The discussion of the factors controlling P/D also apply to the behavior of B/D, since penetration precedes bulk mixing and strongly influences it.

As in the case of the tube jet (*1*) a logarithmic plot of B/D vs. R_m at constant R_v merely produces a family of nonlinear curves. Bulk mixing distance therefore is not a simple exponential function of mass velocity and volume flow ratios.

Macromixing Distance

Subsequent to the completion of bulk mixing further evening of the distribution of the schlieren is observed on the shadowgraphs. Macromixing is considered to be complete where an even distribution of the schlieren is observed. In the published study of mixing with tube jets it was noted that macromixing was influenced by two factors, mechanical distribution (produced by the sidestream jet striking the opposite wall, spreading out in the plane of that wall to the side walls, then down to the wall in the plane of the port, and finally to the center of the duct) and turbulent mixing of the sidestream jet with the mainstream. In the case of tube jet mixing mechanical distribution predominated for $R_m > 8$ and turbulent mixing for $R_m < 8$. The result of this behavior was a reversal of the variation of M/D as R_m and R_v were changed. Below $R_m = 8$, M/D decreased with an increase in R_m and R_v, and for $R_m > 8$, M/D increased with an increase in R_m and R_v.

In the present situation a similar pattern of variation of M/D with R_m and R_v is observed, Figure 8, but with an important difference. The reversal occurs at lower mass velocity ratios, particularly at higher shroud velocities. At a zero shroud velocity the earlier reversal of M/D variation may be attributed to the contraction of the orifice jet at discharge, as was discussed in the section on penetration distance. As the shroud velocity is increased, the combination of jet contraction and bending results in an increase in M/D with R_v at values of R_m as low as 2:1 for $V_s \geqq 50$, although M/D continues to decrease with an increase in R_m until about $R_m = 8$. This is readily seen in Figure 8.

From a parametric plot of the orifice jet data some general conclusions may be drawn:

1. At $R_v \leqq 1{:}25$ and $R_m \leqq 4$, the trend is a decrease in M/D with an increase in V_s; at $R_m > 4$, M/D remains about the same or increases slightly with an increase in V_s.
2. At $R_v > 1{:}25$, the trend is an increase in M/D with an increase in V_s.
3. For $R_m > 2$, the effect of V_s on M/D is relatively small.

The variation of M/D with V_s and V_D is so interrelated that a general statement about the variation of M/D with V_D alone is not possible. As a first approximation it may be said that macromixing is independent of duct velocity.

Compare the situations illustrated in Figure 8 of M/D vs. R_m and R_v for V_s equal to 0 and 50 ft./sec. At zero shroud velocity for $R_v \leqq 1{:}12.5$ and $R_m < 6$, M/D is greater than that for $V_s = 50$. At $R_m > 6$ and $R_v \leqq 1{:}12.5$, the reverse is true. For $R_v > 1{:}12.5$, M/D for a shroud velocity of 50 ft./sec. is always greater than for the case of zero shroud velocity. By comparison the tube jet M/D values are always larger than for the orifice jet with zero shroud velocity, except for the case of $R_m > 6$ and $R_v = 1{:}6.25$ where the M/D variation reversal makes the orifice jet values greater than those for the tube jet.

For the condition of $V_s = 50$ at $R_v \leqq 1{:}12.5$, the tube jet M/D values are higher than those for the orifice jet. At $R_v = 1{:}6.25$ the earlier reversal of

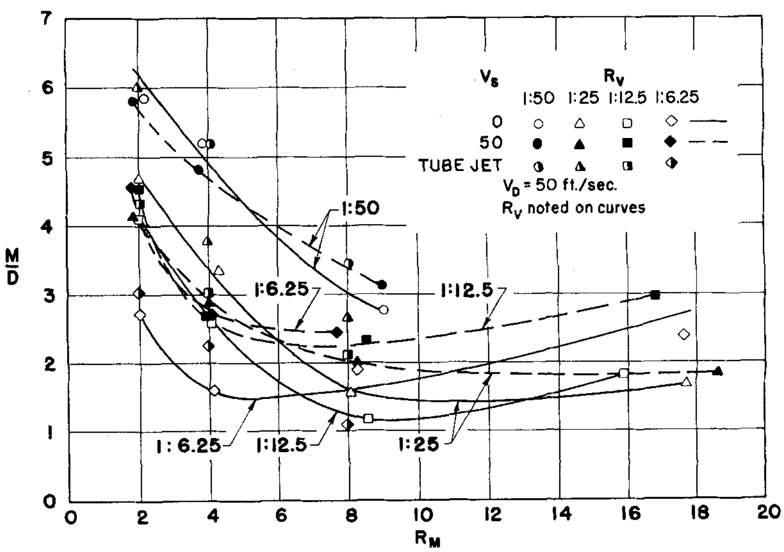

Fig. 8. Macromixing distance: duct width as a function of mass velocity ratio, volume flow ratio, and average orifice shroud velocity.

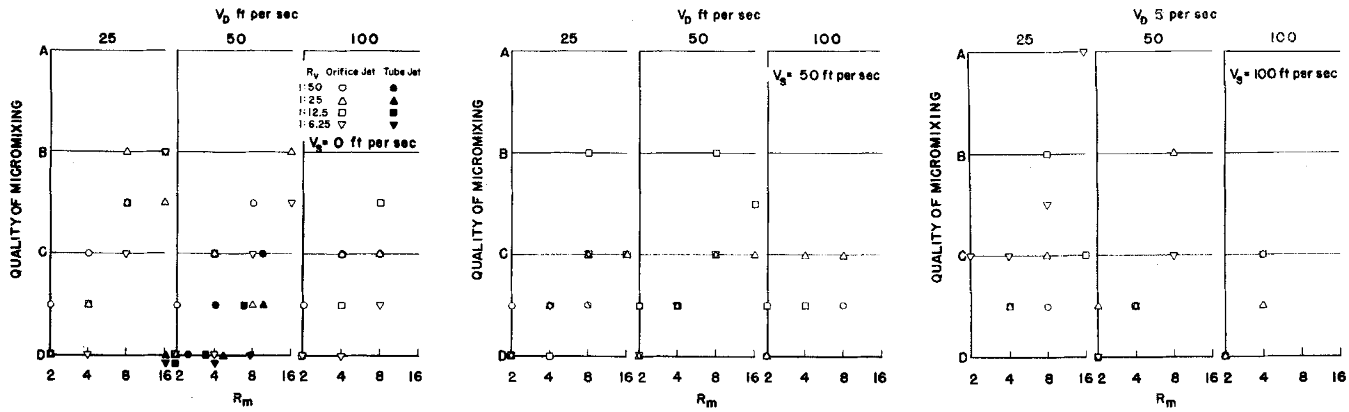

Fig. 9. Quality of micromixing as a function of mass velocity and volume flow ratios, duct velocity, and average shroud velocity: a. $V_s = 0$ ft./sec., b. $V_s = 50$ ft./sec., c. $V_s = 100$ ft./sec.

variation of M/D with R_m results in the orifice jet values being greater.

A consequence of the complex behavior described is that a correlation of the data with a simple exponential equation of the form used for the tube jet data (*1*)

$$M/D = K_m/R_m{}^e R_v{}^i$$

is not possible. A logarithmic plot of M/D vs. R_m at constant R_v, produces a family of nonlinear curves, even for the case of $V_s = 0$.

Quality of Micromixing

The final step is mixing, after macromixing is completed, is micromixing. The quality of micromixing for orifice jets at various values of R_m, R_v, V_D, and V_s is summarized in Figure 9. Tube jet data at a V_D of 50 ft./sec. are included for comparison.

It may be seen, as was observed in the previous tube jet study, that for an orifice jet with zero shroud velocity at constant R_v the quality of micromixing improves with an increase in R_m. At duct velocities greater than 25 ft./sec. as V_s was increased to 25 ft./sec., the quality of micromixing decreased or remained the same. The decrease in quality of micromixing was greatest at $R_v \leq 1{:}25$ for $R_m \geq 8$. As V_s was increased further, little effect on micromixing was observed. At $V_D = 25$ ft./sec. the variation of quality of micromixing was the same as at other duct velocities with the exception that at $R_v = 1{:}6.25$ the micromixing improved as V_s was increased, despite the increase in M/D previously noted. In general the effect of V_s on quality of micromixing is smaller than the effect of R_m.

As was the case with the tube jet the effect of R_v on the quality of micromixing is small compared with the effect of R_m. For zero shroud velocity, similar to the tube jet, the quality of micromixing improves with a decrease in R_v. The same trend is observed for the case of $V_s > 0$ for $R_m = 2$. For $R_m > 2$ and $V_s > 0$, a decrease in R_v leads to a decrease in the quality of micromixing, reflecting the behavior of macromixing under these conditions. There are indications that $R_v = 1{:}12.5$ is optimum at $V_s > 0$ for an $R_m = 8$.

Examination of the data shows that the duct velocity has a negligible effect on quality of micromixing. Since however an increase in duct velocity for given values of R_m and R_v means an increase in the amount of material mixing and a shorter time in which to mix for a given duct length, the independence of the quality of micromixing with duct velocity is an important observation. Slight improvements in quality of micromixing with duct velocity were previously reported in the tube jet mixing studies.

Despite the longer macromixing distances required when an orifice jet is used, the quality of micromixing is better or no worse than for the tube jet, even at the highest shroud velocities. It may be concluded therefore that the better jet boundary layer mixing and the higher velocity ratio produced by contraction of the jet results in improved micromixing which more than compensates for the initially poorer mass distribution indicated by longer macromixing distances.

In general, for the orifice jet, it appears best to use a low volume flow ratio with a high mass velocity ratio for best micromixing. An increase in shroud velocity produces some decrease in the quality of micromixing, but for practical purposes both shroud velocity and duct velocity have little effect on the quality of micromixing.

CONCLUSIONS

Mixing of a gas flowing in a square duct with a secondary gas entering sidewise from an orifice can be described in terms of the mixing parameters, penetration distance, bulk mixing distance, macromixing distance, and the quality of micromixing. These parameters may be expressed as functions of duct diameter, mass velocity ratio, volume flow ratio (sidestream: mainstream) of the two gases, main duct velocity, and average shroud velocity. Experimental penetration distance data are correlated by the equation $P/D = K_p/R_m{}^\alpha R_v{}^\beta$. The exponents α and β decrease with an increase in V_s. K_p increases with an increase in V_D. No simple equation can be used to correlate B/D or M/D.

The discharge and subsequent mixing behavior of the orifice jet is complicated by the effects of shroud velocity and duct velocity, particularly at low orifice Reynolds numbers. Bending of the jet caused by the shroud velocity is smaller than predicted because of interference from the finite thickness of the orifice plate. Discharge coefficients may be correlated as a function of orifice diameter, orifice Reynolds number, duct velocity, and orifice shroud velocity. These factors, bending of the jet and complex variation of discharge coefficient with the flow variables, strongly influence the subsequent mechanical distribution and turbulent and molecular mixing of the sidestream with the mainstream.

The orifice jet with zero shroud velocity produces smaller penetration and bulk mixing distances than the tube jet does. Also the macromixing distances for the orifice jet are smaller at low mass velocity ratios than those for the tube jet, but since a reversal in variation of M/D with R_m and R_v occurs earlier for the orifice jet than for the tube jet, at higher mass velocity ratios the orifice jet produces longer macromixing distances. The quality of micromixing is better for the orifice jet than for the tube jet under all conditions studied.

The general effect of an increase in average shroud velocity, neglecting particular variations, is an increase in all the mixing distances used and a reduction in the quality of micromixing. The general effect of duct velocity on the mixing parameters is small. The best micromixing is obtained with the highest R_m and lowest R_v.

NOTATION

- B = bulk mixing distance
- C = orifice velocity coefficient
- d = diameter of orifice
- D = diameter of main duct
- g = gravitational constant
- h = head of fluid
- K = orifice discharge coefficient
- K_m = constant in tube jet macromixing–distance correlation
- K_p = constant in penetration–distance correlation
- m = area ratio
- M = macromixing distance
- p = pressure
- P = penetration distance
- R_m = ratio of mass flow rate of sidestream per unit area of orifice to the mass flow rate of mainstream per unit area of main duct
- R_v = ratio of volume flow rate of sidestream per unit area of orifice to the volume flow rate of the mainstream per unit area of main duct
- v = volume per unit mass
- V_D = average main-duct velocity
- V_s = average orifice shroud velocity
- $\bar{V}$ = average velocity in orifice discharge coefficient equation = $V_3 + (V_2/2)m$; subscripts 3 and 2 refer to the shroud velocity downstream from the orifice and the orifice velocity respectively
- Y = expansion factor
- ρ_d = density of sidestream gas
- ρ_D = density of mainstream gas

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COMMUNICATIONS TO THE EDITOR

On the Use of the Activity Driving Force in Rate Equations

ERNEST J. HENLEY
Stevens Institute of Technology, Hoboken, New Jersey
and
JOHN M. PRAUSNITZ
University of California, Berkeley, California

It is often stated that the proper driving force for the diffusion equations is chemical activity, rather than concentration. To test this theory one needs both diffusion coefficients and equilibrium data. The recent paper by Rogers, Stannett, and Swarc (*1*) affords both. In Table 1 the columns have the following meaning:

1. Diffusing vapor
2. Concentration, g./g. polymer
3. Activity, p/p_o, calculated from the solubility data given
4. Thermodynamic activity coefficient, $\gamma = a/C$, with $\gamma \rightarrow 1$ as $C \rightarrow C$ (pure)
5. Integral diffusion coefficient,

   $$D = 1/C \int_0^C D_o(C)\, dC$$

   D_o being the diffusion coefficient at $C = 0$ and $D_o(C)$ denoting the concentration dependence, which is usually exponential.
6. See 5.
7. As has been suggested by Kuppers and Reid (*2*), the activity coefficients can be predicted by

$$D_o\, d[\gamma'(C)C] = D(C)dC$$

$$\gamma'(C) = \frac{1}{C}\int_0^C \frac{D(C)}{D_o}\, dC = \frac{1}{D_o}\int_0^C \frac{D_o e^{-\delta C}}{C}\, dC = \frac{\bar{D}(C)}{D_o}$$

$\gamma'(C)$ was calculated in this fashion; these however are not the values recorded in Column 7. The γ' calculated from the Kupper-Reid equation is defined differently insofar as $\gamma' \rightarrow 1$ as $C \rightarrow 0$. The correction to a common thermodynamic base was made by obtaining γ^∞ with a linear relationship between log γ and C assumed over the range in question and with $\gamma^1 = \gamma/\gamma^\infty$, where γ is thermodynamic and γ' Kupper-Reid.

8. The γ^∞ used in making the corrections for Column 7.

TABLE 1. ACTIVITY COEFFICIENTS OF VAPORS IN POLYETHYLENE

1	2	3	4	5	6	7	8
Vapor, (0°C.)	$C(10^2)$, g./g. polymer	a	γ(thermodynamic)	$\bar{D}(10^9)$, sq. cm./sec.	$D_o(10^9)$, sq. cm./sec.	γ, predicted from diff. data	γ^∞
Benzene	1.6	0.035	2.2	3.3	1.9	4.25	2.5
	7	0.1	1.4	10.5	1.9	13.80	
Hexane	1.3	0.19	15	2.2	1.2	33	16
	6.8	0.7	10.1	12.7	1.2	169	
Methyl bromide	1.1	0.255	23	12	8.5	33.6	24
	13.2	1.8	14	53	8.5	199	

A comparison of Columns 4 and 7 shows clearly that there is no apparent connection between thermodynamic and kinetic activity coefficients. This conclusion is especially apparent if one examines the variation of activity coefficient with concentration. Equation (7) in the reference by Kuppers and Reid is

$$\gamma' = \frac{e^{\delta C} - 1}{\delta C} \qquad (1)$$

In nonpolar systems we know that the (thermodynamic) activity coefficients decrease with increasing concentration, and yet Equation (1) predicts that γ'

(*Continued on page 141*)