Cold Flow Mixing Rates in Confined, Recirculating Coaxial Jets with Angular Secondary Injection

The mixing of gases and particles in confined, coaxial jets with angular secondary steam injection into suddenly expanded mixing chambers was studied. The effects of secondary stream injection angle, mixing chamber diameter and length, primary jet solids loading, particle size, and secondary stream velocity on particle and gas mixing rates were determined. Gas mixing was much faster than particle mixing. Angular secondary injection significantly increased the initial gas and particle mixing rates but had little effect on the overall length of duct needed for complete mixing. The effects on initial gas mixing rate of combined angular secondary injection and increased secondary velocity were additive.

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SCOPE

An understanding of the mixing characteristics of gases and particles is important if the complex processes involved in pulverized coal combustion or entrained coal gasification processes are to be fully understood. The mixing of gases and finely divided powder in confined, nonreactive, coaxial jets has been studied at this laboratory as part of an overall program to develop an understanding of the complex fluid dynamic processes involved in the combustion or gasification of pulverized coal, but without the complications of the chemical reactions. The cold flow work has been an integral part of several studies that have involved pulverized coal combustion (Smoot et al., 1982), entrained coal gasification (Hedman et al., 1981), and the development of sophisticated computer codes to describe these complex processes (Smith et al., 1981; Fletcher, 1983).

The objective of this study was to collect jet mixing data in a particular geometry that has important application in entained flow reactors but that has been ignored in previous studies. The data are useful in determining the effect of various operating variables on gas and particle mixing rates and in providing a set of specific local data that can be compared directly to computer code predictions, thus providing a way of validating the computer codes being developed in companion research programs.

This study reports gas and particle mixing data obtained in confined, coaxial jets with angular secondary injection into a suddenly expanded mixing chamber. Flow conditions simulated operating conditions of pulverized coal combustors and entained coal gasifiers. The effects of secondary stream injection angle, mixing chamber diameter and length, solids loading in the primary jet, particle size and type, and secondary stream velocity on particle and gas mixing rates were determined from particle mass flux and gas tracer measurements. Reciprocal core length was used to characterize the initial mixing rate. The normalized length required to achieve complete mixing was used to provide a measure of the required size of a reaction vessel.

CONCLUSIONS AND SIGNIFICANCE

The test results have indicated that considerable control over initial gas and particle mixing rates can be gained by variations in inlet geometry and operating conditions. The results also show that a certain amount of independent control of gas and particle mixing rates is possible.

The initial gas mixing rate was 70 to 270% faster than the initial particle mixing rate depending on other test variables, except for the small silicon powder case where the initial gas and particle mixing rates were nearly the same. [Initial mixing rates are inversely proportional to core length $(z/_1)_c$; Smoot and Purcell, 1967.] The overall duct length required to obtain complete particle mixing was from 60 to 350% longer than that required for complete gas mixing.

Expanded recirculation mixing chambers enhanced initial gas and particle mixing rates over those observed in nonexpanded chambers. There was little difference in initial mixing rate seen between different size expanded chambers, however. Two exceptions were noted. A 30% increase in initial gas mixing

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rate was noted with the high-velocity angular-injection case when a large (343 mm) chamber was used in place of a small (206 mm) chamber. A 33% increase in gas mixing rate was also noted for the angular-injection coal powder case when the same substitution was made in mixing chamber size.

Angled secondary injection had a major effect on initial gas and particle mixing rates, increasing gas mixing by 110 to 230% and particle mixing by 60 to 100%. Angular secondary injection had essentially no effect on the overall duct length needed for complete gas or particle mixing.

The influence of primary solids loading on initial gas mixing rates and overall duct length for complete mixing was found to be small: 40% solids in the primary jet reduced the initial gas mixing rate by about 9% with no significant effect on the overall duct length required for complete mixing.

The use of a smaller silicon powder caused a modest increase in initial gas mixing rates (21%) and a decrease in duct length for complete mixing (27%). The initial mixing rate of the particle phase was increased by about 160% over the standard size powder. The initial gas and particle mixing rates were essentially the same for the small silicon powder case. The overall duct length for complete particle mixing for the small silicon power was only slightly decreased (17%) over the rate for the standard powder.

The use of pulverized coal powder rather than silicon powder resulted in 10 to 70% higher initial gas mixing rates. Initial particle mixing rates with coal dust were enhanced by only 10%. The overall duct length required for complete mixing for both the gas and coal particle phase was unaffected by power type.

Increased secondary velocity increased the initial gas mixing rates by about 80 to 160% with angular secondary injection. This increase is similar to that observed in previous parallel injection data. Increased secondary velocity with nonparallel secondary injection also increased the initial particle mixing by about 20 to 80%. With parallel secondary injection there was no significant increase in initial particle mixing with increased secondary jet velocity. The data suggest that the increase in initial gas mixing rate gained by angular secondary injection and that gained by increased secondary velocity are additive when the variables are combined.

INTRODUCTION

Previous work at this laboratory has investigated many aspects of particle-laden coaxial jet mixing (Hedman and Smoot, 1975; Smoot and Allred, 1975, Smoot and Fort, 1975; Memmott and Smoot, 1978; and Tice and Smoot, 1978). The cited reports of this work have included extensive literature reviews of jet mixing typical of pulverized coal reaction systems, as have reports of work by Tufts and Smoot (1971), Stowell and Smoot (1973), Ngai (1975), and Smoot (1976). A brief summary of relevant work found since the above reviews follows.

Moon and Rudinger (1977) have studied a single confined stream in which a sudden expansion induces recirculation. Drewry (1978) has investigated a similar system, but with higher velocities. Owen (1976) reports velocity and turbulence data for confined and free jets with recirculation. Pai et al. (1975) have performed a study of mixing for confined jets which were similar to the parallel configurations used at this facility but which were tested with different flow conditions. Other studies which have investigated jet mixing in parallel flows without forced recirculation include Catalano et al. (1976), Ribeiro and Whitelaw (1976), and Norris (1976). Antonia and Bilger (1976) report velocity and temperature data for a system with a heated primary jet. Fabris and Fejer (1974) report pressure, velocity, and turbulence data for a system with multiple primary jets and a common secondary flow. Bassiouni and Doasnjh (1979) conducted an experimental investigation of single round jet, single annular jet, and coaxial jet configurations. Measurements in a turbulent jet dumping into a coflowing free stream were obtained by Smith (1977). Kwan and Ko (1977) conducted a study to investigate vorticity formation at the primary and secondary jet exits. The jet and mixing chamber arrangements used by Habib and Whitelaw (1979) were very similar to one of the configurations used at this laboratory. Particle density effects were recently studied by Calabrese and Meddleman (1979). Hayashi and Branch (1980) conducted an experimental study on concentration, velocity, and particle size measurements in gas-solid two-phase flow. A study of Lilley (1973) addressed the issue of particle size effects on particle dispersion.

A number of other studies which deal with the analysis and modeling of jet mixing include Morgenthaler (1975), Al Taweel and Landau (1977), and Danon et al. (1977). Yuu et al. (1978) have developed a model for particle-gas dispersion. Peters and Phares (1978) have presented a theoretical analysis of homogeneous, confined jet mixing with recirculation. Hendricks and Brighton (1975) compare a theoretical mixing model with pressure and velocity data. Further, Tennankore (1978) investigated several turbulence models in single-phase confined jets in a nonexpanded mixing chamber. Another study concerning mixing of coaxial jets in a nonexpanded duct was made by Elghobashi (1977). A method for predicting velocity profiles and centerline velocity decay near the core region was presented by Middleton (1979). Astavin and Ryazantsev (1979) discussed a predictive approach to obtain concentration and temperature profiles for coaxial, confined jets.

Researchers at this laboratory have previously investigated the separate effects of angular secondary stream injection (Memmott and Smoot, 1978) and recirculation in expanded ducts (Tice and Smoot, 1978) in gas and particle mixing rates. The major objective of the present investigation was to study the combined effects of angular secondary injection into the larger secondary recirculation chambers on the gas and particle mixing rates. A second objective was to measure the effect of using pulverized coal (70%, −200 mesh) in place of the silicon dust used previously.

EXPERIMENTAL PROGRAM

The test facility used was that reported by Memmott and Smoot (1978) and Tice and Smoot (1978). Figure 1 shows schematic diagrams of the various flow configurations used. The 30° angular secondary injection hardware used by Memmott and Smoot (1978) was adapted to the recirculation chambers used by Tice and Smoot (1978) to obtain the mixing chamber hardware used in this study. The inlet flow areas of the primary and secondary jets were constant for all of the systems. Dry ambient air, argon, and silicon or coal powder formed the primary jet. The secondary jet was composed of dry ambient air.

Local gas velocities were obtained from probes within the test chamber. Gas and particle samples were taken at various radial and axial locations with up to 11 near-isokinetic collection probes. Local particle mass flux was determined from weighed particle samples, which were collected over a timed interval through probe openings of known size. The concentration of argon in the gas samples was used to determine the gas mixture fraction. Gas flow feed rates for the primary and secondary jets were established with

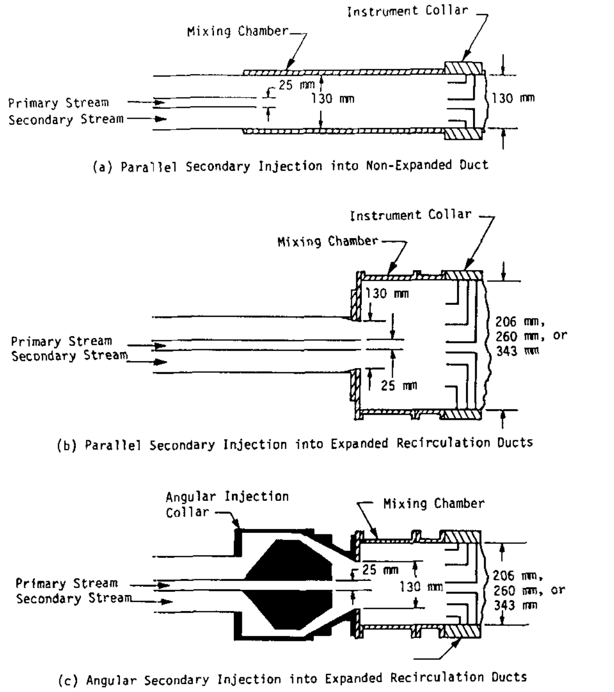

Figure 1. Diagrams of flow hardware used in this and cited previous studies.

choked flow-control nozzles. The coal or silicon particles were fed with a precalibrated particle feeder.

The flow conditions used for the tests conducted in this study are shown in Table 1. Particles used included a standard silicon powder (46 μm), a small classified silicon powder (24 μm), or a pulverized Utah bituminous coal (48 μm). The solids loading of the powder in the primary jet was about 40%. The flow conditions used simulated the flow velocities of typical pulverized coal furnaces or entained coal gasifiers as reported by Thurgood et al. (1976) and Skinner et al. (1976). Data from 96 separate jet mixing experiments are summarized, 20 with gas only, 44 with standard silicon powder, 4 with small classified silicon powder, and 28 with pulverized coal.

TABLE 1. SUMMARY OF EXPERIMENTAL TEST CONDITIONS†

Flow Property	Nominal Value Primary	Secondary
Velocity, m/s	30.5	38.1*
Air flow rate, g/s	5.3	520.0*
Trace argon flow rate, g/s	14.3	—
Particle flow rate, g/s	14.6**	—
Primary particle loading, wt. %	42.7**	—
Temperature, K	280	280
Pressure, kPa	87	87

* 61.0 m/s and 835 g/s in high secondary velocity case.

** Tests were performed with pulverized coal (48 μm mean dia.), a standard size silicon powder (46 μm mean dia.), a small classified silicon powder (24 μm mean dia.). Gas-only tests, without any particulate phase, were also conducted.

† Test condition notation: Secondary injection: *P*, parallel; *A*, angular. Duct size (dia.): 1, 206 mm; 2, 260 mm; 3, 343 mm. Particle type: *C*, coal; *S*, standard size silicon. Tests: *G*, gas only; *hi* v_2, high-velocity secondary; *sml*: small silicon powder.

The consistency of the radial profile data was checked by comparing gas and particle mass flow rates determined from the integration of the appropriate radial profile curves to the known input mass flow rates. Generally, there was very good agreement between the integrated and input particle flow rates. The comparison between integrated and input gas flow rates was not as good, however. Two factors were thought to be primarily responsible for the poor agreement. These were insensitive measurements at the low velocities in the mixing duct, and the compounding effect of very slight errors at the larger values of radius near the duct wall. Lack of good velocity data in regions of recirculation also caused some difficulty in getting good agreement between input and integrated mass flows. Generally, it was thought that the radial profile data, especially near the centerline were better than the mass balances would suggest (Leavitt, 1980; Sharp, 1981).

Free jet mixing data have traditionally used the exit radius of the jet to geometrically scale the results (e.g., Warren, 1957; Abramovich, 1963). Smoot (1976) used the scaled core lengths to develop empirical correlations for turbulent mixing coefficients

DATA REDUCTION AND PRESENTATION

Empirical curves using a nonlinear, least squares technique (Hedman and Smoot, 1975) were used to fit both the gas (argon) and particle (silicon or coal) radial profile data, as in Figure 2. This figure shows the Gaussian type profiles observed in jet mixing, demonstrates the flattening of the profiles (more complete mixing) with downstream location, and compares reproduced tests at a downstream location (z/r_1 = 37.7). Reproduced tests generally showed excellent agreement.

It was noted from the radial profile data in the angular injection cases that the peak particle flux or argon concentration would consistently lie a small distance off the geometric centerline of the duct, suggesting asymmetric flow. The problem was traced to slight deviations in the narrow anulus of the angular injection chamber (Figure 1a or 1c). Very careful mechanical alignment of the facility was unable to correct the problem. Since the 11 sample probes were used in two mutually perpendicular planes, it was possible—using nonlinear least-squares curve fitting techniques—to locate the mean flow center and transpose the radial mixing profiles for both gas and particles to that flow center. This approach gave more consistent results and reduced the data scatter significantly.

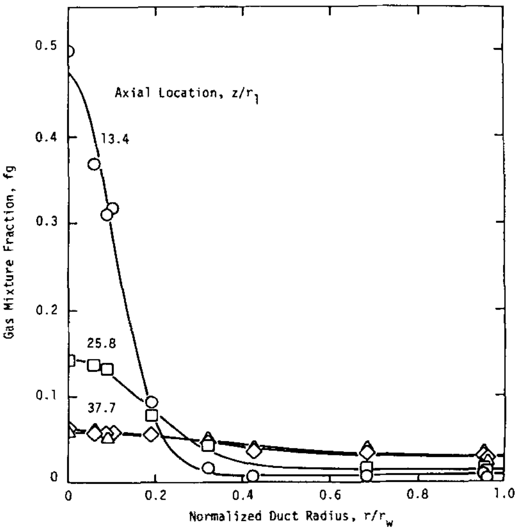

Figure 2. Example of gas mixture fraction radial profiles, test condition *P2S* (see footnote to Table 1).

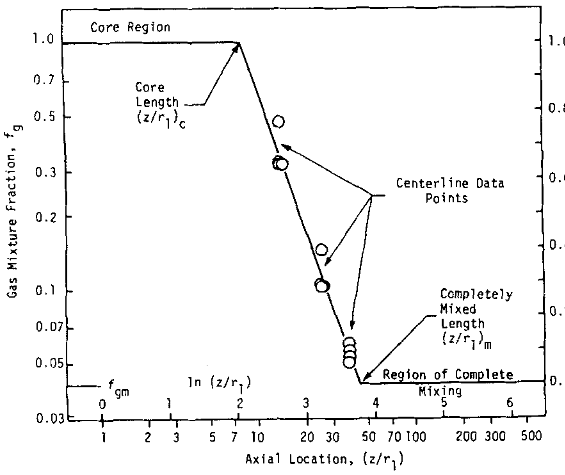

Figure 3. Example of gas mixture fraction centerline decay, test condition *P2S* (see footnote to Table 1).

for free and coflowing jets. The initial mixing rate data of this paper have also been reported in terms of the scaled core lengths $(z/r_1)_c$. A scaled, fully mixed length $(z/r_1)_m$ has also been introduced in order to determine the normalized length required for complete mixing, a measure of the size of the reaction vessel that may be needed.

The interpretation of the initial mixing rates for the gas and particles has made use of core lengths deduced from centerline decay profiles. When the centerline data and the axial distance are normalized and plotted on logarithmic scales, a straight line results over a major part of the region of interest (Smoot, 1976). An example of an axial decay plot obtained from a least squares curve fit of centerline data is shown in Figure 3, with major features of the plot indicated. The core length is defined by the intersection of the linear decay line and unity, the value which corresponds to the pure primary jet. The inverse of this core length $(z/r_1)_c{}^{-1}$ has been shown to be directly proportional to the initial rate of jet mixing for nonreacting free jets (Smoot and Purcell, 1967). The core length derived from these centerline decay plots has been used to evaluate the effects of geometry and operating variables on initial particle and gas mixing rates.

Thurgood et al. (1980) have noted the importance of determining the overall reactor length needed for complete gas and particle mixing. Extrapolation of the linear centerline decay line (Figure 3) to a fully mixed value determined from input stream flow rates defines a point where complete mixing has essentially occurred. Some data, which have been obtained at axial locations well into the completely mixed region, suggest that a relatively sharp break exists between the decay region and the completely mixed region in the same way a relatively sharp break exists between the core region and the decay region. Consequently, it has been found convenient to define a completely mixed length $(z/r_1)_m$, as is shown in Figure 3, to evaluate the effect of geometry and operating variables on the overall jet mixing process. The analysis of the data reported herein makes use of the core length to determine the initial mixing rate $(z/r_1)_c{}^{-1}$, and the completely mixed length $(z/r_1)_m$.

Comparison of different gas or particle decay lines on the log-log plots has proven awkward because the ceterline decay approaches different completely mixed values. This can cause a great difference in the slopes of the decay lines even though the core length and fully mixed lengths are the same. An improved method has been devised to present the centerline values so that the normalized value ranges from 0.0 for a completely mixed situation to 1.0 for

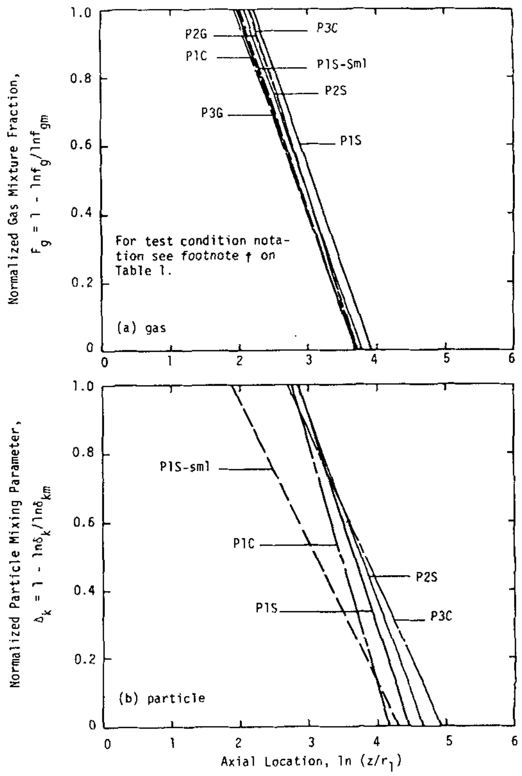

Figure 4. Gas and particle centerline decay for parallel secondary injection.

pure primary on a linear scale (Leavitt, 1980). The righthand ordinate scale in Figure 3 shows the revised normalized gas mixture fraction ($F_g = 1.0 - \ln f_g/\ln f_{gm}$). It can be seen that the linearity of the normalized centerline decay is maintained, and that there is a direct correspondence between the linear normalized gas mixture fraction scale and the actual gas mixture fraction shown on the log scale. Recasting the axial centerline decay data into this format (F_g or Δ_k) allows more direct comparison of gas or particle data, allows a more uniform presentation of the centerline results, and yields the exact same core lengths or fully mixed lengths that would otherwise be determined.

TEST RESULTS

A summary of the centerline decay lines obtained from least square curve fits of the gas and particle centerline data are shown in Figures 4 and 5 for the parallel secondary injection tests and the angular secondary injection tests respectively. The parallel injection data shown in Figure 4 reproduce some of the data reported by Tice and Smoot (1978) but include additional data for an intermediate duct size (260 mm dia.), for a small classified silicon powder, and for a pulverized Utah bituminous coal powder. The intercept of the decay plots with either the unity or zero ordinate values repectively defines the core lengths $(z/r_1)_c$ or completely mixed lengths $(z/r_1)_m$.

It can be seen that geometry and test conditions have varying effects on the gas and particle mixing rates. For example, Figure 4a shows that the range of conditions tested with parallel secondary injection had a relatively small effect on the initial gas mixing rate (reciprocal core length) or on the length required for complete mixing. Angular secondary injection however, had a major effect on initial gas mixing rate, as seen by comparing Figures 4 and 5 but

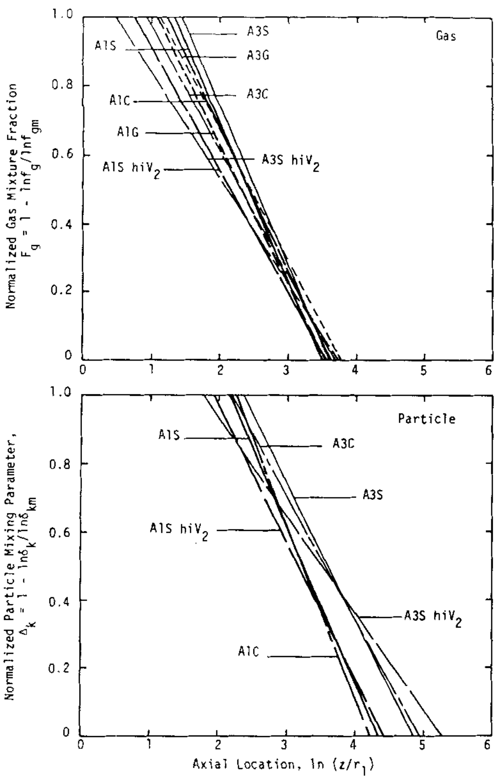

Figure 5. Gas and particle centerline decay for angular secondary injection.

a small effect on the overall gas mixing. It is also quite evident from Figure 5 that differences in condition have a considerable impact on initial gas mixing rate when used with angular secondary injection.

The particle mixing data shown in Figure 4 show little effect of test condition on initial particle mixing rate except for the small silicon powder. The initial mixing rate for the small powder case was about 160% faster than that observed for the standard size silicon powder. Comparison of the particle data in Figures 4 and 5 show that angular secondary injection had considerable influence on the initial particle mixing rate. The lengths for complete mixing with angular injection, however, overlap the fully mixed lengths for parallel injection. Considerable variation in overall particle mixing is attributable, however, to duct size, particle type, and particle size. In general, it appeared that angular injection had little effect on the overall mixing of the particle phase.

The gas and particle core lengths and fully mixed lengths determined from the centerline decay plots are summarized in Table 2 for all of the tests conducted. The observations about the relative initial or overall mixing rates which follow are based on comparisons of reciprocal core length of length required for complete mixing for each test condition. Reference to observations from previous studies are made where appropriate.

TABLE 2. SUMMARY OF CENTERLINE CORE LENGTHS AND FULLY MIXED LENGTHS

Reference*	Test Condition**	Gas Mixing (F_g) $(z/r_1)_c$	Gas Mixing (F_g) $(z/r_1)_m$	Particle Mixing (Δ_k) $(z/r_1)_c$	Particle Mixing (Δ_k) $(z/r_1)_m$
S	*P2G*	8.50	40.9	—	—
L	*P3G*	6.89	39.8	—	—
S	*P1S*	9.15	49.9	17.3	84.6
S	*P2S*	7.99	44.2	16.9	103.9
S	*P2S-sml*	7.59	39.2	6.6	72.5
L	P1C	7.34	39.9	15.6	63.2
L	*P3C*	8.61	41.0	14.9	135.5
S	*A1G*	3.02	34.1	—	—
S/L	*A3G*	3.07	43.2	—	—
S	*A1S*	3.84	33.6	8.7	75.8
S/L	*A3S*	4.28	38.8	10.7	127.2
L	*A1C*	3.44	37.8	9.6	68.1
L	*A3C*	2.58	41.0	8.9	141.6
S	*A1S-hi* v_2	2.14	35.4	7.0	83.6
S	*A3S-hi* v_2	1.65	42.9	6.0	194.4

* S, Sharp (1981); L, Leavitt (1980).
** Test condition notation is shown in footnote of Table 1.

TABLE 3. COMPARISON OF GAS AND PARTICLE MIXING RATES

Test Condition*	Initial Mixing Rate (Gas/Particle)	Overall Mixing Length (Particle/Gas)
P1S	1.89	1.70
P2S	2.11	2.35
P1S-sml	0.87	1.85
P1C	2.12	1.58
P3C	1.73	3.31
Group Avg.	1.74	2.16
A1S	2.28	2.26
A3S	2.50	3.28
A1C	2.80	1.80
A1C	3.46	3.45
A1S-hi v_2	3.26	2.36
A3S-hi v_2	3.65	4.53
Group Avg.	2.99	2.95
Overall Avg.	2.42	2.59

* Test condition notation is shown in footnote of Table 1.

Gas vs. Particle Mixing Rates

A comparison of initial gas and particle mixing rates and overall gas and particle mixing was obtained by appropriately ratioing the core or overall mixing lengths. The resulting ratios are summarized in Table 3. These ratios show that the rate of initial gas mixing was always faster than the rate of initial particle mixing (except for the small silicon powder case) by about 70 to 270%. The ratio for the small silicon powder case was slightly less than one suggesting nearly the same initial mixing rates for both gas and powder. It is unlikely that the powder mixed faster than the gas, and the difference shown probably represents a measure of the absolute data accuracy. These data for initial mixing confirm the results observed by Memmott and Smoot (1978) and Tice and Smoot (1978), where gas mixed faster than particles by 200 to 500% and 60 to 270%, respectively. Precautions were taken to insure that the particle and gas velocities were comparable at the primary nozzle exit. Consequently, these results clearly demonstrate that the particles do not move out radially with the gas but lag significantly due to particle inertia. On average, initial gas mixing is about 70% faster than initial particle mixing with parallel secondary injection. With angular secondary injection, the initial gas mixing is about 200% faster than the particles. This suggests that angular injection can be used effectively to vary the initial mixing rate between gas and particles.

Table 3 also compares the overall length required for complete particle mixing to that for complete gas mixing. In general, the overall length required for complete mixing of the particles is seen

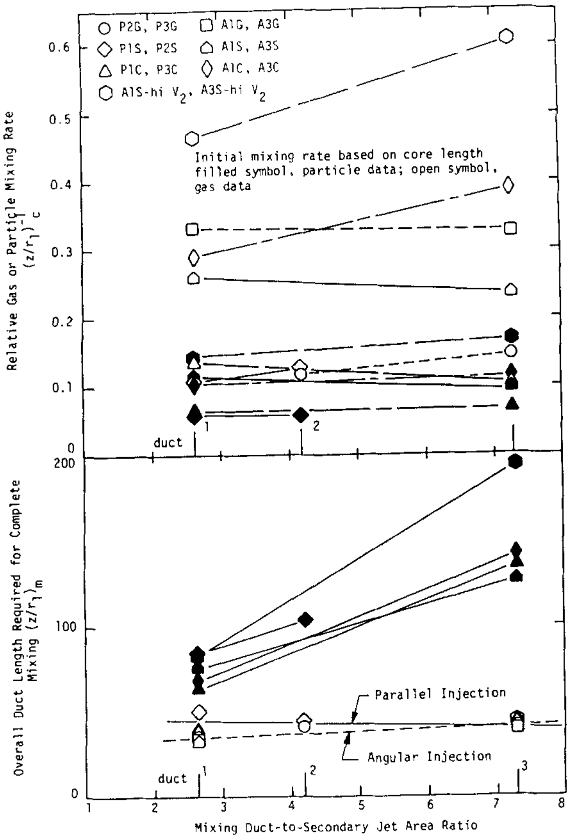

Figure 6. Effect of duct size on initial gas and particle mixing rate and overall duct length required to obtain complete mixing.

to be about 160% longer than that for gas. The ratios ranged from about 1.6 (60%) to 4.5 (350%), however, depending on geometry and condition. As with initial mixing rate, the average particle to gas mixing length ratio for nonparallel injection was significantly greater (195%) than that observed for parallel injection (116%). This suggests that angular injection can be used to vary the relative overall mixing between gas and particles as well.

Effect of Mixing Chamber Diameter

Tice and Smoot (1978) showed a significant effect of a sudden expansion mixing chamber on the gas and particle mixing rates over those observed in nonexpanded chambers. They observed particle mixing rate increases of 20 to 80% and gas mixing rate increases of 20 to 140%, except for the high secondary velocity case.

They noted however, that there was little difference in initial gas or initial particle mixing rates for the two larger chambers tested (206 to 343 mm dia.).

The initial mixing rate data from this study are plotted in Figure 6 for both gas and particles as a function of the area ratio between mixing duct and secondary jet. In general, the initial mixing rates observed are greater than the initial mixing rates obtained by Memmott and Smoot (1978) without the expanded duct. The general effects observed by Tice and Smoot (1978) are also confirmed, i.e., little variation in initial mixing rate over the range of expanded duct sizes tested. The effect of other operating variables is clearly evident but little change is seen as a function of duct size. There are two exceptions to this observation. Increasing duct size caused a significant increase in initial gas mixing rate for both the angular secondary injection, pulverized coal case and the angular secondary injection, high secondary velocity case.

Variation in test condition had a significant effect on the overall length required for complete gas mixing in the small expanded duct (206 mm dia.), less effect in the intermediate duct (260 mm dia.), and little effect in the large duct (343 mm dia.). The overall length required for complete particle mixing was sensitive to test condition and showed a uniform increase with increasing duct size.

Table 4. Effect of Secondary Injection Angle on Gas and Particle Mixing Rates

Test Conditions*	Nonparallel-to-Parallel Ratio: Initial Mixing Rate, Gas	Initial Mixing Rate, Particle	Overall Mixing Length, Gas	Overall Mixing Length, Particle
A3G vs. *P3G*	2.24	—	1.09	—
A1S vs. *P1S*	2.38	1.99	0.67	0.90
A1C vs. *P1C*	2.13	1.63	0.95	1.08
A3C vs. *P3C*	3.34	1.67	1.00	1.05
Average	2.52	1.76	0.93	1.01

* Test condition notation is shown in footnote of Table 1.

Table 5. Effect of Primary Solids on Gas Mixing Rate

Test Conditions*	Solids-to-Clean Gas Ratio: Initial Mixing Rate	Overall Mixing Length
P2S vs. *P2G*	1.06	1.08
P3C vs. *P3G*	0.80	1.03
A1S vs. *A1G*	0.79	0.99
A3S vs. *A3G*	0.72	0.90
A1C vs. *A1G*	0.88	1.11
A3C vs. *A3G*	1.19	0.95
Average	0.91	1.01

* Test condition notation is shown in footnote of Table 1.

Effect of Secondary Injection Angle

The effect of secondary injection angle was determined by ratioing the appropriate core and fully mixed lengths for angular secondary injection (Table 2) to their corresponding parallel lengths. These ratios are presented in Table 4. It can be seen that secondary injection angle enhanced both the gas and particle initial mixing rates in every case. Initial gas mixing rates were increased by about 110 to 230% depending on the condition, while initial particle mixing rates were increased by about 60 to 100%. This increase in initial mixing rate compares well with the results obtained by Memmott and Smoot (1978). They reported increases of approximately 100% for both gases and particle in a nonexpanded duct.

Angular secondary injection had little effect on the overall length required for complete gas or particle mixing, as noted in Table 4. On the average there was no significant effect on the overall particle mixing rates and only a 12% decrease in average overall gas mixing length, approximately within the data scatter. It is evident that the initial mixing rates of both gas and particles can be markedly enhanced by angular injection, but that the overall length of mixing chamber needed is not significantly changed by angular injection into an expanded recirculation chamber.

Effect of Primary Solids on Gas Mixing Rate

The influence of primary solids on both initial and overall gas mixing rates, which was determined by ratioing the appropriate

TABLE 6. EFFECT OF PARTICLE TYPE ON GAS AND PARTICLE MIXING RATES

Test Conditions*	Coal-to-Silicon Ratio: Initial Mixing Rate, Gas	Initial Mixing Rate, Particle	Overall Mixing Length, Gas	Overall Mixing Length, Particle
P1C vs. *P1S*	1.25	1.11	0.80	0.75
A1C vs. *A1S*	1.12	0.91	1.13	0.90
A3C vs. *A3S*	1.66	1.20	1.06	1.11
Average	1.34	1.07	1.00	0.92

* Test condition notation is shown in footnote of Table 1.

core or overall lengths, was found to be small, as shown in Table 5. The initial gas mixing rate was reduced an average of about 9% with no significant change in overall gas mixing. The presence of particles might be expected to slow gas mixing because of inertial effects or damping of gas phase turbulence, but the data show that the effect is very small. This is consistent with the results reported by both Memmott and Smoot (1978) and Tice and Smoot (1978).

Effect of Particle Size on Gas and Particle Mixing Rates

One limited comparison on the effect of particle size was made from the data presented in Table 2. Comparison of the initial mixing rate and overall length required for complete mixing for case *P1S-sml* to that of *P1S* shows enhancement of the initial gas mixing rate by 21% and reduction in the required overall length by 27%. The initial particle mixing rate was increased by about 160%. The overall length required for complete particle mixing for the small powder was 17% shorter than that observed for the standard powder. Thus, the use of a smaller powder was seen to have a major effect on the initial mixing rate of the powder but had only a small effect on the initial gas mixing rate and on the overall length required for complete mixing of gas and particles.

Effect of Particle Type

The effect of particle type, shown in Table 6, was determined by dividing the appropriate length (core or overall) for the coal tests into the corresponding lengths for the silicon powder tests. The initial gas mixing rates in the small chamber (206 mm dia.) were only slightly affected, a 25% and a 12% increase for parallel and angular secondary injection, respectively. A more significant increase of 66% in initial gas mixing rate was observed with angular secondary injection into the large mixing chamber. The effect of particle type on initial particle mixing rates was very slight—only 11% faster in the small chamber parallel injection case and 9% slower in the small chamber angular injection case. The initial coal mixing rate for the large chamber angular injection case was 20% faster than the corresponding rate for the silicon powder.

The observed effect of particle type on the overall length required for complete gas and particle mixing was very small, generally within the data scatter. It was concluded that particle type had only a small effect on overall mixing.

Effect of Secondary Velocity

A limited analysis of the effect of secondary velocity was obtained for angular secondary injection into the small and large chambers. Increasing the secondary velocity (also mass flow) increased the initial gas mixing rate by about 80% with the small chamber and 100% with larger chamber. Particle mixing rates were increased by about 20% and 80% with the small and large chambers respectively. Tice and Smoot (1978) report an increase of about 100% in gas mixing with increased secondary velocity and parallel injection, but essentially no effect on initial particle mixing rate. These data support the observed increase in initial gas mixing rate. They also suggest that enhanced particle mixing can be obtained by using both the secondary velocity and angular injection. The increase in secondary velocity and the corresponding increase in secondary mass flow rate caused a general increase in the completely mixed lengths for both gas and particles, indicating a reduction in the overall gas and particle mixing rates.

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NOTATION

- A = angular (30°) secondary injection
- C = pulverized coal powder
- F_g = normalized gas mixture fraction
- f_g = gas mixture fraction, $m_p/(m_p + m_s)$
- f_{gm} = fully mixed gas mixture fraction
- G = gas only
- $hi\ v_2$ = high secondary velocity
- m_k = local particle mass flux, kg/m^2
- m_{k1} = primary jet particle mass flux, kg/m^2
- m_p = mass of gas from primary jet, kg
- m_s = mass of gas from secondary jet, kg
- N = nonparallel (30°) secondary injection
- P = parallel (0°) secondary injection
- r = radial coordinate, m
- r_1 = primary jet radius, m
- r_w = mixing duct radius, m
- S = standard size silicon powder
- S-*sml* = small size silicon powder
- z = axial coordinate, m
- 1 = small 206 mm dia. duct
- 2 = medium 260 mm dia. duct
- 3 = large 343 mm dia. duct

Greek Letters

- Δ_k = normalized particle dispersion parameter
- δ_k = particle dispersion parameter, m_k/m_{k1}
- δ_m = fully mixed particle dispersion parameter

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