Cold Flow Mixing Rates with Recirculation for Pulverized Coal Reactors

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The mixing of particles and gases in confined, coaxial jets in the presence of recirculation was studied. Particle and gas mixing rates were measured for conditions simulating processes involving pulverized coal combustion and entrained gasification. The effects of mixing chamber diameter, gas velocity, particle size, and particle loading level on mixing rates were determined from particle mass flux and gas tracer measurements. In every case, the gas mixed much faster than did the particles. Introduction of an expanded mixing chamber of larger diameter (with recirculation zone) significantly increased both gas and particle mixing rates over that for a smaller mixing chamber without recirculation. However, this observed increase was not strongly dependent upon the diameter of the larger mixing chamber. Increasing secondary velocity also increased mixing rates significantly.

SCOPE

The mixing rates of particles and gases are important in such systems as entrained fuel gasifiers, pulverized coal combustors, catalytic fluidized beds, air breathing missiles, and many other processes where particulate solids and fluids are mixed. This particular cold flow study used a facility which could simulate test conditions for typical pulverized coal reactors. Laboratory reactors of this type were discussed in papers by Thurgood et al. (1976) and Skinner et al. (1976). Cold flow mixing rate data can be used to evaluate predictive codes in the absence of reaction. Further, such data indicate the extent to which test variables may influence mixing processes in reacting systems. Control of mixing rates in reactors can help to control reaction efficiency as well as limit pollutant formation in some combustion processes (e.g., ——, 1975).

The parameters of interest in this study were the mixing chamber diameter, the secondary jet velocity, the particle size, and the weight percent of particles (solids loading). The primary stream was air, with argon added as a trace gas, while the secondary stream was air only. Small (38 μm) and large (54 μm) diameter silicon particles at 0, 40, and 60% solids loading levels were added to the primary gas stream. The primary stream velocity was constant at about 31 m/s. The secondary jet velocity was set at either 38 or 61 m/s. Radial and axial measurements of argon concentration and particle mass flux in the mixing chamber gave profiles from which mixing rates were deduced, and effects of each variable on the gas and particle mixing rates were evaluated.

Chigier and Beer (1964) and Schulz (1977) conducted mixing studies using recirculation configurations similar to those of this study but with different flow conditions and without particles. Studies by Fejer et al. (1967), Beasley et al. (1970), and Durao et al. (1973) were similar in flow conditions but did not consider a recirculation zone. None of the cited work from other laboratories has investigated mixing rates in the presence of particles.

Previous work at this laboratory has investigated many aspects of particle laden, coaxial jet mixing. Work reported by Hedman and Smoot (1975), Smoot and Allred (1975), and Smoot and Fort (1976) considered parallel, nonparallel, and multiple portal injection of the secondary jet for various velocity ranges. Smoot (1976) has summarized and correlated the experimental data from these studies and from several other independent investigations. Most recently, Memmott and Smoot (1978) measured cold flow mixing rates for coal reactors with parallel and angled injection of the secondary jet but without flow recirculation. Much of the data from that study will be compared to the data presented here.

CONCLUSIONS AND SIGNIFICANCE

Radial and axial profiles of argon concentration and particle mass flux were measured. From these data, the center line axial decay profiles suggest the following conclusions about mixing rates:

1. Enlarging the mixing chamber diameter by a factor of 1.56 to permit recirculation increased gas and particle mixing rates significantly. Particle mixing rates increased by factors ranging from 1.2 to 1.8 and gas mixing rates increased by factors of up to 2.4.

2. A further increase in the mixing chamber diameter by a factor of 1.32 did not further affect gas or particle mixing rates appreciably, except to cause some decrease in mixing rates of larger particles.

3. Gases mixed from 1.6 to 3.7 times faster than particles for tests with expanded mixing chambers.

4. A high secondary jet velocity substantially increased the gas mixing rate (factor of 2) but had little effect on particle mixing rate.

5. The effect of particle size on gas mixing rates was small.

6. Increasing particle size caused decreases in particle mixing rates, especially in the largest mixing chamber.

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0001-1541-78-1720-1029-$00.85.

7. An increase in solids loading level caused small decreases in gas and particle mixing rates.

8. Addition of a wire screen near the primary stream exit improved particle distribution in the primary jet, particularly for the large particles, and also had a small effect on the particle and gas mixing rates.

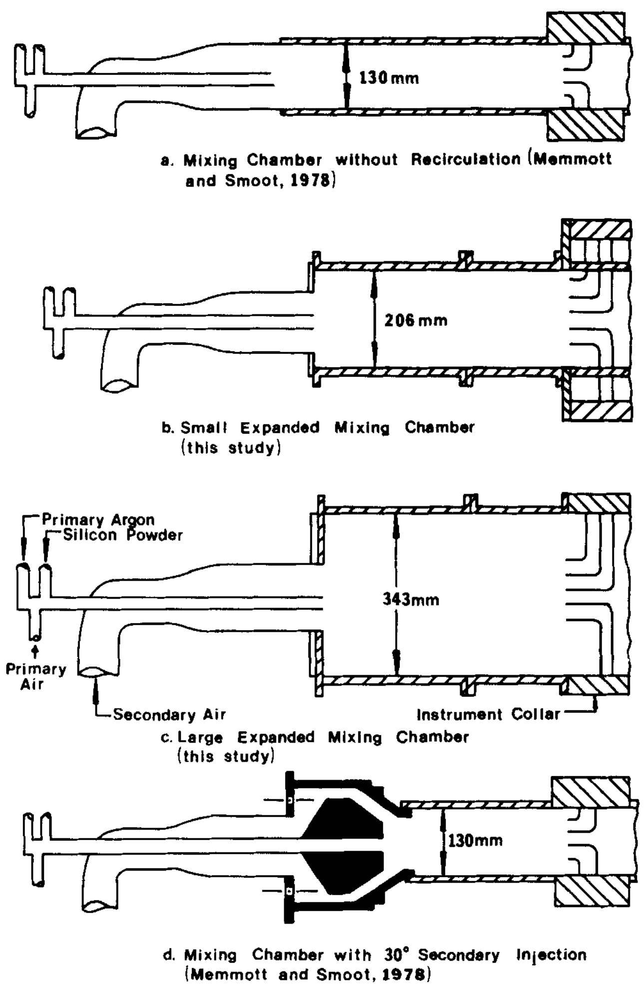
9. The gas mixing rates generally varied more with changes in test condition than did the particle mixing rates.

The test results have indicated that a certain amount of independent control of the gas and particle mixing is possible. Separate control of the gas and particle mixing processes may provide a basis for controlling nitrogen oxide pollutant formation in pulverized coal combustors and entrained gasifiers. To control nitrogen oxide formation in pulverized coal power generating furnaces, the rate of mixing of the primary coal-air stream and the secondary hot air stream is significantly reduced in order to promote low temperature, fuel rich combustion. To date, however, direct attempts at independently controlling gas and particle mixing rates have not been reported.

TEST FACILITY AND INSTRUMENTATION

The test facility used was that reported by Memmott and Smoot (1978) and described in detail by Hedman (1973). Figure 1 shows both the small (b) and large (c) expanded mixing chamber systems as well as the parallel (a) and nonparallel (d) configurations used by Memmott and Smoot. The inlet flow areas of the primary and secondary jets were constant for all of the systems. Air, argon, and silicon powder formed the primary stream, and the secondary jet was composed of air only.

Static and stagnation pressures in the chamber were measured on a 2.5 m manometer board and were used to calculate gas velocities. However, with this system it was not possible to measure gas velocities in the recirculation zones. Further, accuracy of velocity measurements was degraded in all regions where low velocities existed. Particle and gas samples were taken at different radial locations in the mixing chamber with up to eleven isokinetic collection probes. Particle samples were collected during a timed interval through probe openings of predetermined size and reported in terms of mass flux. The concentration of argon in the gas samples was determined by gas chromatographic analysis. Gas flow feed rates for the primary and secondary jets were established with choked flow control nozzles. A precalibrated, variable speed, particle feeder controlled the feed rate of silicon.



a. Mixing Chamber without Recirculation (Memmott and Smoot, 1978)

b. Small Expanded Mixing Chamber (this study)

c. Large Expanded Mixing Chamber (this study)

d. Mixing Chamber with 30° Secondary Injection (Memmott and Smoot, 1978)

Fig. 1. Schematics of flow systems with recirculation, with 30 deg secondary injection and without recirculation.

EXPERIMENTAL PROGRAM

The primary objective of this test program was to measure the effects that recirculating flow, induced by an expanded mixing chamber, have on gas and particle mixing rates. Effects of mixing chamber diameter, secondary jet velocity, particle size, and particle solids loading on gas and particle mixing rates were determined. For large particle and high solids loading tests, particles were not well distributed in the primary duct, and high particle flux material balance errors were observed. A screen inserted at the end of the primary tube did produce a smoother, more uniform particle distribution but increased the particle mixing rate slightly while causing a small decrease in the gas mixing rates.

Operating conditions for several pulverized coal furnaces and gasifiers were reported by Thurgood et al. (1976) and are summarized in column 1 of Table 1. This study was designed to simulate the operating conditions in these typical pulverized coal furnaces and gasifiers. The tests were nonreactive, however, and a silicon powder was used to simulate the pulverized coal. Five sets of operating conditions were selected for this test program and are also shown in Table 1.

Sixty one tests were completed at the five test conditions and with the instrument collar at various axial locations. The reference condition (1) had a primary jet velocity of 30.5 m/s, a secondary jet velocity of 38.1 m/s, and a 40 wt % solids loading of the silicon powder. The powder had a mass mean diameter of 38.6 μm. For each additional test condition, one parameter was changed from the reference condition 1. For test condition 2, the secondary jet velocity was increased to 61 m/s. For test condition 3, a larger silicon mass mean diameter of 54.1 μm was used. Particle size distributions of these test particles, together with a typical pulverized coal, were shown by Memmott and Smoot (1978). For test conditions 4 and 5, a 60 wt % solids loading with the larger particles and a 0% solids loading were evaluated, respectively. Data and results from Memmott and Smoot (1978) are also used in this study to establish the comparative effect of the expanded mixing chambers.

DATA REDUCTION AND PRESENTATION

Both the gas (argon) and particle (silicon) radial profile data were fit to empirical curves using a non-

TABLE 1. SUMMARY OF DESIGN TEST CONDITIONS

Test identification	P.C.F.*	1†	2	3†	4†	5
Primary stream						
Velocity, m/s	20-30	30.5	30.5	30.5	30.5	30.5
Temperature, °K	320-360	283	283	283	283	283
Particle size (mass mean diameter, μm)	40-60	38.6	38.6	54.1	54.1	—
Flow rate, g/s						
Air	—	5.2	5.2	5.2	5.2	5.2
Argon	—	16.9	16.9	16.9	16.9	16.9
Particles	—	14.7	14.7	14.7	33.1	0
% (mass) solids loading	35-40	40	40	40	60	0
% (mole) argon	—	70	70	70	70	70
Secondary stream						
Velocity, m/s	25-35	38.1	61.0	38.1	38.1	38.1
Temperature, °K	600	283	283	283	283	283
Flow rate, g/s	—	540	870	540	540	540
Sec/Pri ratios						
Velocity	—	1.25	2.00	1.25	1.25	1.25
Gas density	—	0.79	0.79	0.79	0.79	0.79
Total density	—	0.47	0.47	0.47	0.31	0.79
Gas flow	—	24.6	39.3	24.6	24.6	24.6
Total flow	—	14.7	23.6	14.7	9.8	24.6
Mixing chamber diameters (mm)						
Duct a	—	130**	130**	130**	—	130**
b	—	206	206	206	206	206
c	—	343	343	343	343	343

* P.C.F. refers to the range of test conditions commonly found in pulverized coal furnaces.
† These test conditions were also conducted with insertion of a small mesh screen near the primary exit to improve initial particle distribution.
** Tests conducted by Memmott and Smoot (1978).

linear, least-squares technique (Hedman and Smoot, 1973) which minimized the effects of test errors in the test data, such as hardware misalignment and those introduced by powder sampling techniques and variations in chromatographic analyses. Figure 2 shows a set of these curves for argon concentration data for one specific test condition at several axial locations. A reproduced test is shown at a reduced axial location of 12. Several other tests were also reproduced, and the agreement was excellent.

Data validity was checked by calculating mass flow rates from the empirical curves and matching the calculated values with the known input mass flow feed rates. A close agreement between the two flow rates indicated a valid test, although insensitivity in velocity measurements due to very low velocity values made some

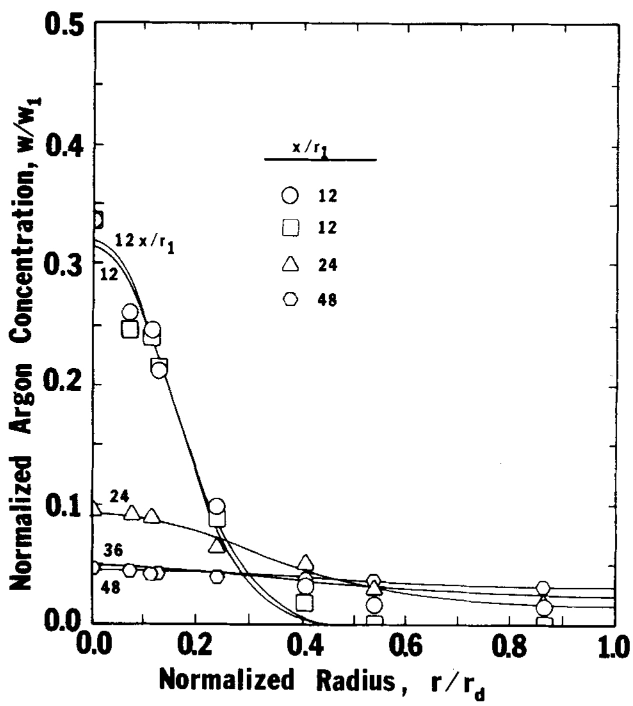


Fig. 2. Example of normalized radial profiles of argon concentration for the high solids, small expanded mixing chamber tests (test condition 4b).

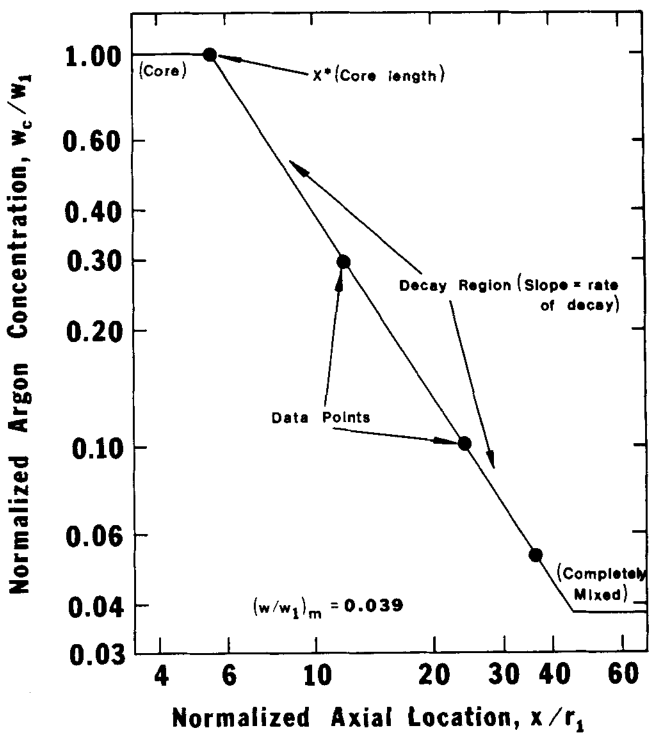


Fig. 3. Example of centerline decay plot for the argon gas (test condition 3b).

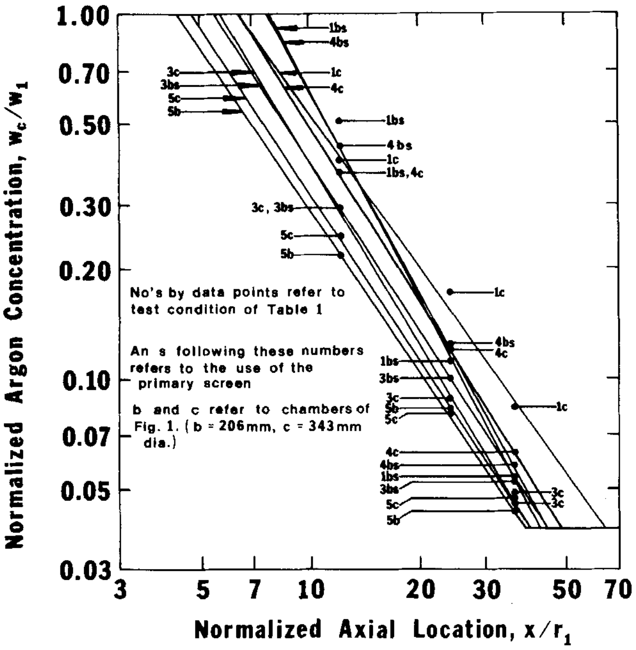


Fig. 4. Effect on gas mixing rates by solids loading level (3 vs. 4), particle size (1 vs. 3), mixing chamber diameter (b vs. c).

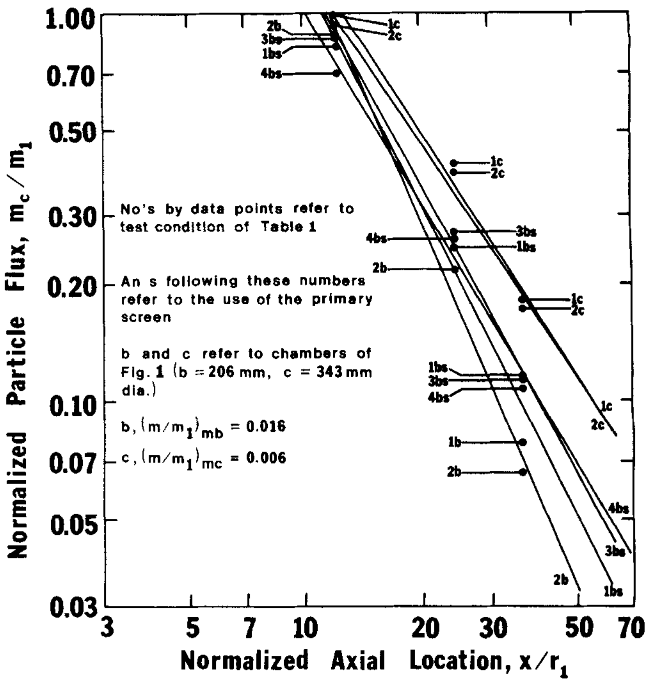


Fig. 5. Effect on particle mixing rates by changes in solids loading level (3 vs. 4), particle size (1 vs. 3), mixing chamber diameter (b vs. c), secondary velocity (1 vs. 2).

valid tests appear more uncertain than they actually were (Tice, 1977).

The major form of data presentation for this study was the center line axial decay plot. For a particular test condition, the center line data at different axial positions were plotted. When both the center-line value and axial distance downstream are normalized and plotted on logarithmic scales, a straight line usually results over a major part of the region of interest (Smoot, 1976). Figure 3 shows an example of an axial decay plot with features of the plot labeled. From this plot, the core length is the distance from the exit plane ($x/r_1 = 0$) to the point where the decay line intercepts the normalized concentration of 1.0. The core length is thus the length from the primary jet exit plane to the last point where the original composition of the primary stream still exists at the jet center line. Smoot and Purcell (1967) have shown theoretically that this core length is inversely proportional to a parameter known as the mixing coefficient (K) for coflowing, parallel, free jet systems. In the discussion that follows, the term rate of mixing is defined to be proportional to the mixing coefficient and thus inversely proportional to the core length.

A second important term is the rate of decay, which is the slope of the logarithmic line fitted to the data in the center line axial decay plot (Figure 3). For the case where the mixing coefficient K is independent of axial position, Stowell and Smoot (1973) have shown that this slope or rate of decay is not a function of the rate of mixing. Also, Hedman and Smoot (1973) and Smoot and Allred (1974) have shown experimentally that the decay slope does not change markedly as the core length is changed by increasing or decreasing mixing rates. Thus, the major variable characterizing the rate of mixing is taken to be the core length.

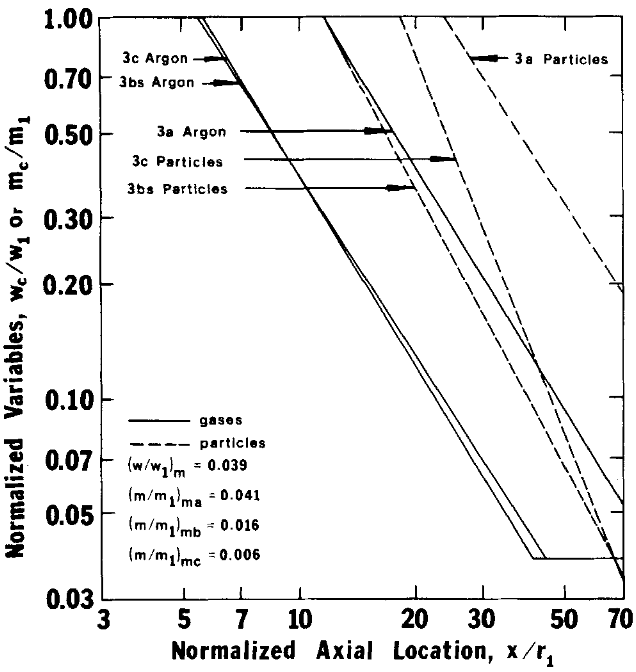


Fig. 6. Effect of mixing chamber diameter on mixing rates of gases and particles for test condition 3 (a vs. b vs. c).

TEST RESULTS

Figures 4 to 7 show the center line decay data for most of the tests. The complete set of detailed data and accompanying statistical analysis are reported by Tice (1977). Most of the gas data are summarized in Figure 4. The final value of normalized argon concentration $(w/w_1)_m$, indicating a totally mixed condition, is also shown on this plot. The majority of the particle mass flux data are summarized in Figure 5. Because of the three different mixing chambers used, each with different diameters, there are three different values for $(m/m_1)_m$, the totally mixed particle mass flux, as listed in Figure 6. These different values for the final state of particle mass flux alter the slope of the axial decay lines as seen in Figure 6, although core lengths (that is, mixing rates) were not significantly affected. The observations from the data about relative mixing rates which follow are based on the core length values obtained for each test condi-

TABLE 2. SUMMARY OF CORE LENGTH AND DECAY SLOPE VALUES

Flow condition	Mixing chamber†	Primary screen	Core length X^*	Core length interval†† ΔX^*	Slope/ interval††
			Gas data		
1	*a*†††	No	7.5	7.1-7.8	-1.4 ± 0.05
1	*b*	No	6.2	4.7-7.6	-1.7 ± 0.29
1	*bs*	Yes	7.8	6.8-8.7	-1.9 ± 0.24
1	*c*	No	6.4	4.6-8.1	-1.4 ± 0.29
2	*a*	No	3.5	1.7-5.4	-1.1 ± 0.28
2	*b*	No	3.3	2.8-3.8	-1.6 ± 0.12
2	*c*	No	3.2	2.9-3.6	-1.5 ± 0.08
3	*a*	No	9.2	8.7-9.8	-1.4 ± 0.06
3	*b*	No	6.1	5.9-6.2	-1.8 ± 0.03
3	*bs*	Yes	5.5	5.4-5.6	-1.6 ± 0.02
3	*c*	No	5.6	5.3-6.0	-1.6 ± 0.06
4	*b*	No	5.3	4.5-6.1	-1.5 ± 0.13
4	*bs*	Yes	7.7	7.4-7.9	-1.8 ± 0.05
4	*c*	No	6.5	6.4-6.6	-1.6 ± 0.02
5	*a*	No	10.6	8.0-12.8	-1.7 ± 0.35
5	*b*	No	4.3	3.9-4.8	-1.5 ± 0.09
5	*c*	No	4.7	4.5-5.0	-1.5 ± 0.05
			Particle data		
1	*a*	No	16.0	15.4-16.5	-1.1 ± 0.05
1	*b*	No	11.5	9.7-13.1	-1.7 ± 0.33
1	*bs*	Yes	11.1	9.3-12.8	-2.0 ± 0.34
1	*c*	No	12.6	10.2-14.5	-1.5 ± 0.36
2	*a*	No	20.4	18.9-21.7	-1.7 ± 0.27
2	*b*	No	11.7	9.7-13.4	-2.3 ± 0.47
2	*c*	No	11.8	9.0-14.0	-1.5 ± 0.41
3	*a*	No	21.3	17.9-23.6	-1.3 ± 0.36
3	*b*	No	12.4	11.8-12.9	-1.8 ± 0.08
3	*bs*	Yes	11.4	10.0-12.5	-1.8 ± 0.25
3	*c*	No	18.1	15.9-19.9	-2.5 ± 0.38
4	*b*	No	14.6	14.3-15.0	-1.8 ± 0.06
4	*bs*	Yes	10.1	7.6-12.0	-1.7 ± 0.41
4	*c*	No	21.3	20.2-22.3	-2.7 ± 0.26

† Letter *a*, *b*, or *c* refers to specific mixing duct as illustrated in Figure 1; letter *s* indicates presence of screen at primary duct exit.
†† For 70% confidence interval.
††† All *a* duct tests (diam = 130 mm) conducted by Memmott and Smoot (1978).

tion. A summary of core length values for all test sets is shown in Table 2.

Gas vs. Particle Mixing Rates

Results of this study confirm previous work at this laboratory, wherein the gas mixing rate was always faster than the particle mixing rate for all conditions tested. The gas mixing rate was usually about twice as fast as the particle mixing rate, with the ratio ranging from 1.6 to 3.7, as shown in Table 2 and illustrated by comparing Figures 4 and 5. These results clearly demonstrate that these particles do not move with the gas but lag significantly, owing to particle inertia. Special precautions were taken to insure that the particles and gas velocities were comparable at the primary nozzle exit; thus, the observed particle lag was induced during the mixing process itself.

The ratio of the gas mixing rate to the particle mixing rate was often smaller than that reported by Memmott and Smoot (1977). Thus, while the gas mixes more rapidly in the expanded mixing chamber, compared to the rate in chambers without recirculation, the particle mixing rate increases even more dramatically in the expanded chambers.

Effect of Mixing Chamber Diameter

Since most pulverized coal reactors provide for injection of the coal into a large combustion chamber, the mixing rates for expanded chambers are more applicable to design and performance evaluation of such systems. Use of the larger mixing chambers (206 and 343 mm) affected the gas and particle mixing rates significantly. The particle mixing rates in the larger mixing chambers were 1.2 to 1.8 times faster than the corresponding rates of the nonexpanded mixing chamber (130 mm diameter) as illustrated in Figure 6 and Table 2. Except for one case, the gas mixing rates for the expanded chamber systems were faster than for the nonexpanded chamber by factors of 1.2 to 2.4, as also shown in Figure 6 and Table 2. For the high velocity secondary jet, condition 2, the gas mixing rate of an expanded chamber was not greatly enhanced over that of a nonexpanded chamber; however, mixing rates for this case are already very high. Generally, both particles and gas are influenced by recirculation in the larger mixing chambers, with attendant enhancement in gross mixing rate and increases in residence time.

Rates of mixing of particles and of gases in the two larger chambers (206 and 343 mm diameter) were very similar. Once a recirculating flow was established, the size of the duct did not have a major effect on mixing rates. However, for tests with large particles (test conditions 3 and 4), use of the largest mixing chamber did retard particle dispersion to approximately 70% of that with the smaller expanded mixing chamber. The larger particles do not recirculate as readily as the smaller particles.

Effect of Secondary Velocity

The effect of increasing the secondary jet velocity from 38 to 61 m/s while maintaining the primary jet at 30.5 m/s was very similar to that reported by Memmott and Smoot (1978). The gas mixing rates nearly doubled when the secondary velocity was increased, but the particle mixing rates remained essentially unchanged, as shown in Figure 7 and Table 2. Since turbulent stresses in the gas are related to the difference in primary and secondary velocities, a significant increase is observed in gas mixing with a 60% increase of secondary velocity. However, the particles are apparently not able to respond to the more rapid gas mixing. Many of the pulverized coal combustors and entrained gasifiers use jet velocities in the range examined here. Thus, velocity is a parameter that can potentially be used to control the gas mixing processes of such systems without significantly affecting the particle mixing rates.

Effect of Particle Size

The average or standard silicon used in this study had a mass mean diameter of 38.6 μm (conditions 1 and 2). A larger size was also used (conditions 3 and 4) which had a mass mean diameter of 54.1 μm. Typical pulverized coal has mass mean diameters in the range of 40 to 60 μm but is of lower density than the silicon powders used in this study. Increasing the particle size at a fixed solids loading level caused the gas mixing rate to increase only slightly, as illustrated in Figure 4. When the small expanded mixing chamber was used, the large particles mixed slightly slower than the smaller particles as shown in Figure 5. Where the large expanded chamber was involved, however, the gas mixed nearly one and one half times faster than the larger particles as shown from Figures 5 and 6. It is to be expected that the larger particles will disperse more slowly than the smaller ones, since dispersion is caused by drag forces of the gas on particles which vary strongly with particle size.

Effect of Solids Loading

The particle solids loading of the primary stream was varied from 0 (condition 5) to 40% (condition 3) and to 60 wt % (condition 4). Typical pulverized coal gasifiers and furnaces use solids loading levels ranging from 40 to 90 wt %. While gas mixing rates did decrease as the solids loading level increased, test results in Figures 4 and 5 and Table 2 show that neither gas nor particle mixing rates were greatly affected by solids loading level. Thus, solids loading level was not an important variable in control of mixing rates, although at higher solids loadings, in the range of 90 wt %, the results may be quite different.

Correlation of Particle and Gas Mixing Rates

A correlation of the gas and particle mixing rates of this study and of Memmott and Smoot (1978) is shown in Figure 8. Since the reciprocal of the core length is proportional to the rate of mixing, the inverse of the particle core length, when plotted against the inverse of the gas core length, illustrates particle mixing rate vs. gas mixing rate.

For the parallel and expanded mixing chamber systems, the test variables appear to have a significant effect on gas mixing rates but much less effect on particle mixing rate. However, for the nonparallel system, both particle mixing rates and gas mixing rates appear to be affected significantly by the test variables investigated. This suggests that it may be possible to control the mixing of coal and gases independently in order to control the rates of chemical reaction and possibly pollutant formation rates within a combustor. For example, to increase gas mixing rates only, parallel injection with high secondary velocity in an expanded mixing chamber would be specified. To increase both gas and solids mixing rates, nonparallel injection with high secondary velocity in a nonexpanded mixing chamber would be specified.

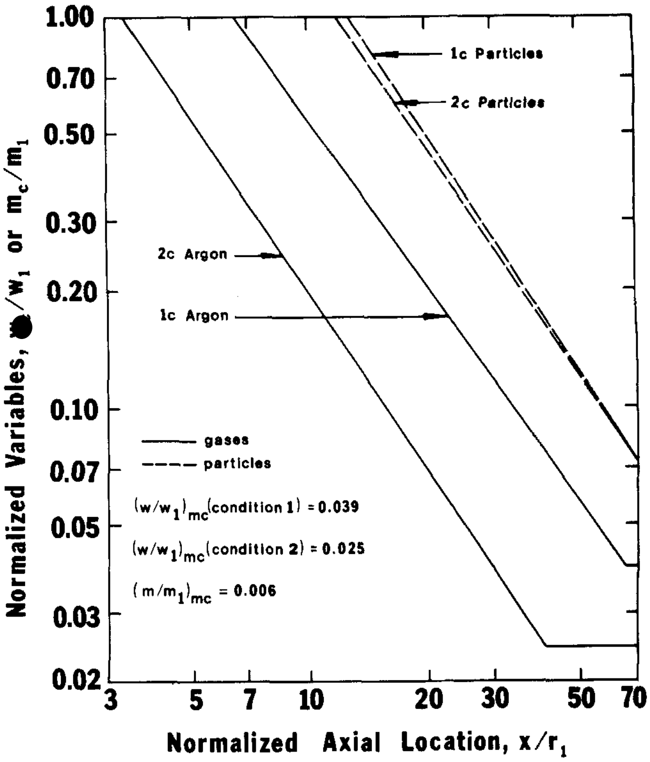


Fig. 7. Effect of secondary velocity on mixing rates of gases and particles (largest mixing chamber, 1 vs. 2.

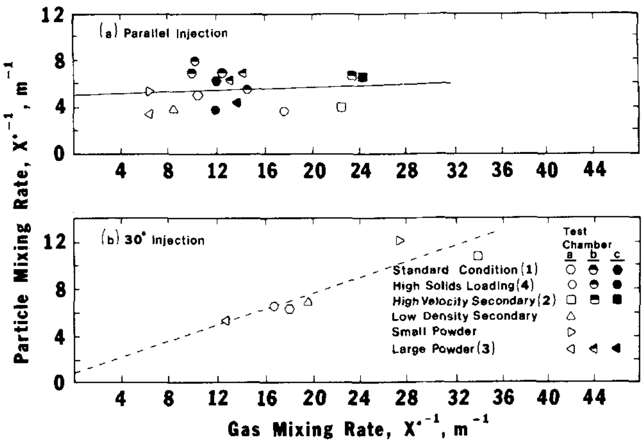


Fig. 8. Comparison of gas and particle mixing rates.

Acknowledgment

This work was supported by the Electric Power Research Institute, Palo Alto, California with Mr. John Dimmer as Project Officer and by the U.S. Department of Energy, with Dr. Robert Wellek, Project Officer.

NOTATION

a = 130 mm diam mixing chamber
b = 206 mm diam mixing chamber
c = 343 mm diam mixing chamber
K = turbulent mixing coefficient

m = particle mass flux, kg $m^{-2} s^{-1}$
r = radial position, m
w = argon mole fraction
X^* = core length, m/m
x = axial position, m
1, 2, 3, 4, 5 = test condition

Subscripts

1 = primary jet
c = center line
d = mixing chamber duct
m = completely mixed state

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Manuscript received October 21, 1977; revision received June 30, and accepted July 18, 1978.

Magnetically Enhanced Thermal Convection in Oxygen Gas

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The effects of static magnetic fields on heat transfer in oxygen gas have been measured at temperatures between 78 and 112°K and pressures between 2.01 and 4.77 kN/m². After the data are corrected for ordinary thermal conductivity behavior, comparison with theory suggests that the phenomenon is magnetically enhanced thermal convection.

SCOPE

When a magnetic field is applied to a dilute polyatomic gas transporting energy primarily by thermal conduction, the normal response is a small thermal conductivity decrease in the order of 1%. A much different result was found for oxygen gas at low pressures and temperatures near 80°K. The apparent thermal conductivity change was much larger than normal and opposite in sign.

This paper presents the results of a parametric study of the experimental variables in this new phenomenon. The objectives are to identify which variables are dominant, to determine their correlation with the observed effects, and to compare the results with existing theory.

A method is developed here for analyzing the total magnetically induced changes in heat transfer by correcting for the normal thermal conductivity effects. Relationships between the corrected data and each experimental variable are then determined. This information provides insight into the nature of the heat transfer changes which occur when the magnetic field is applied.

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