Greek Letters

α = relative volatility
γ = activity coefficient
ϕ = vapor fugacity coefficient
ψ = sum of vapor mole fractions

Subscripts

i = ith component in a mixture
r = reference component

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Simulation of Test Conditions for Typical Pulverized Coal Combustors

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INTRODUCTION

The mixing of heterogeneous phases of gas and particles has varied applications. Processes commonly encountered are the MHD power generation system, air breathing missiles, and catalytic reactors. Of interest to us, however, is the pulverized coal combustor where an air jet issues along with particles. This dust makes significant contribution to the mass and momentum transfer of the mixture and its study is of considerable value in estimating the extent to which the mixing is affected. Control of a pulverized fuel combustor is dependent on the effect of the particles on the eddies that generate the turbulence and influence the entrainment. A study of particle effects should include velocity and concentration profile measurements and a look at the distortion in the jet development due to the presence of particles.

Figure 1 shows a schematic diagram of a round air jet. The round jet is seen to be made up of a central potential core of constant velocity and this is surrounded by an annular region where the velocity profile decays to a value equal to zero at the jet edge. The velocity and concentration profiles are believed to be similiar in the annular shear layer and our aim is to check this similarity.

In recent years considerable study has been directed to the near field of a round jet. This surge in interest is due to a desire to comprehend and alleviate the jet noise problem and also due to a growing recognition of the fact that the large-scale structure in a turbulent jet is intimately related to the developmental stages of flow in the mixing layer. Browand and Laufer (1975) and Yule (1978) have shown that the emerging physical picture is interesting. The shear layer leaving the nozzle whether laminar or turbulent becomes unstable to form a train of vortex rings which become unstable to azimuthal disturbances and ultimately disintegrate into a large number of vortical fragments distributed across the jet.

The purpose of this research, however, is to study the turbulent shear layer with particles present under conditions that would simulate industrial pulverized coal furnaces and entrained gasifiers.

PREVIOUS WORK

Laats and Frishman's (1970) work is the only detailed study available on the development of a solid/air jet. They determined the mean velocity distribution for different particle sizes and concentrations, mainly in the fully developed region. The radius of the two-phase jet was found to be less than that of the single-phase jet. An increase in the axial concentration of solids close to the nozzle was observed for some case and a rapid decrease was observed in other experiments. The data reported, therefore, seem to be confusing.

Brush (1962) studied the diffusion of glass beads in a submerged

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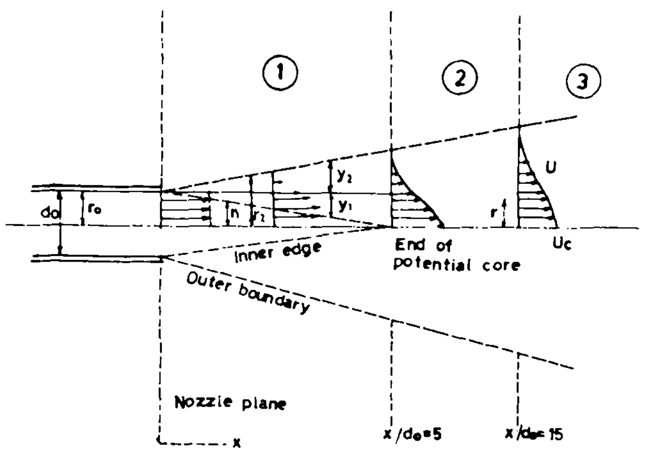

Figure 1. Schematic diagram for a round air jet.

Zone 1: Initial region

Zone 2: Transition region

Zone 3: Fully developed region

axisymmetric jet and found that Schmidt No. increases with particle size. Goldschmidt and Eskinazi (1966) measured the concentration distribution of aerosol droplets in a plane air jet and found Schmidt No. to be greater than unity. The Schmidt No., therefore, appears to depend on particle size and concentration and the mass transfer trends are not clear.

Memmot and Smoot (1978) reported the mixing rates of particles and gases in confined, coaxial jets. Effects of inlet velocity, density, particle loading level and particle size on the rates of mixing were determined. Dispersion of particles lagged that of the gas in all cases investigated. They later extended their study to an investigation of mixing rates with recirculation for pulverized fuel combustors (Tice and Smoot, 1978). Shinichi Yuu et al. (1978) studied the turbulent diffusion mechanism of particles in a round air jet paying particular attention to the relative velocity between particles and the fluid. Their results indicate that the particle diffusivity decreases with increase of the particle inertia. Our previous work (1982) considers particles of sand issuing along with an air stream as a concentric jet and the particle effects are examined.

ANALYSIS

The jet dimensions can be represented by the following equations:

$$\frac{r_1}{r_o} = 1 - K\frac{x}{r_o} \text{ (potential core boundary)} \tag{1}$$

$$\frac{r_2}{r_o} = 1 + M\frac{x}{r_o} \text{(jet edge)} \tag{2}$$

$$\frac{b}{r_o} = N\frac{x}{r_o} \text{(half-width line)} \tag{3}$$

Particles affect the jet development. This effect can be estimated using the boundary layer theory of Abramovich (1963).

The slope of the inner edge of the boundary layer is given by

$$\frac{y_1}{2b} = \frac{1}{2}\int_o^2 \frac{\rho}{\rho_o} d\eta - \int_o^2 \frac{\rho}{\rho_o}(1-f)d\eta + \frac{1}{2}\int_o^2 \frac{\rho}{\rho_o}(1-f)^2 d\eta \tag{4}$$

where

$$\frac{\rho}{\rho_o} = \frac{1+\psi}{1+\psi_o}, \quad \eta = \frac{r-r_1}{b} \tag{5}$$

and

$$f = \frac{U}{U_o} = \frac{1}{2}\left(1 + \cos\frac{\pi\eta}{2}\right) \tag{6}$$

Assuming that the concentration distribution is linear in the boundary layer

$$\eta = \frac{2(\psi_o - \psi)}{\psi_o} \tag{7}$$

Therefore, Eq. 4 becomes

$$\frac{y_1}{2b} = \frac{0.38 + (0.29\psi_o)}{1 + \psi_o} \tag{8}$$

and

$$\frac{db}{dx} = 0.135\left(\frac{1 + \rho_a/\rho_o}{2}\right) \tag{9}$$

where

$$\frac{\rho_a}{\rho_o} = \frac{1}{1+\psi_o} \tag{10}$$

Therefore,

$$\frac{db}{dx} = \frac{0.0675(2+\psi_o)}{(1+\psi_o)} \tag{11}$$

This gives

$$K = \frac{0.135(2+\psi_o)(0.38 + 0.29\psi_o)}{(1+\psi_o)^2} \tag{12}$$

$$M = \frac{0.135(2+\psi_o)(0.26 + 0.71\psi_o)}{(1+\psi_o)^2} \tag{13}$$

$$N = \frac{0.0675(2+\psi_o)}{(1+\psi_o)} \tag{14}$$

ENTRAINMENT

From the principle of conservation of mass, the entrainment of ambient fluid in the initial region of a jet can be written as

$$E = \frac{\int_o^{r_1} 2\pi r U_o dr + \int_{r_1}^{r_2} 2\pi r U dr}{\pi r_o^2 U_o} - 1 \tag{15}$$

$$= \left(\frac{r_1}{r_o}\right)^2 + \left(\frac{2}{r_o^2}\right)(b^2F_1 + bF_2r_1) \tag{16}$$

where

$$F_1 = \int_o^2 \eta f(\eta)d\eta = 0.59 \text{ (for a cosine profile)} \tag{17}$$

$$F_2 = \int_o^2 f(\eta)d\eta = 1 \text{ (for a cosine profile)} \tag{18}$$

Using Eqs. 1 to 3 and 12 to 14 in Eq. 16

$$E = A\left(\frac{x}{r_o}\right) + B\left(\frac{x}{r_o}\right)^2 \tag{19}$$

where

$$A = -2K + 2N \tag{20}$$

$$B = K^2 + 1.18N^2 - 2NK \tag{21}$$

EXPERIMENTAL PROGRAM

The jet issued vertically downwards through a 25.4 mm diameter tube at a Reynolds number equals to 2.5×10^4. Sand particles of size 150–180μm were fed from a hopper through copper cones having orifices from 1 mm diameter onwards. The particle concentration at the exit was determined using an isokinetic sampling probe (detailed by Salzman and Schwartz,

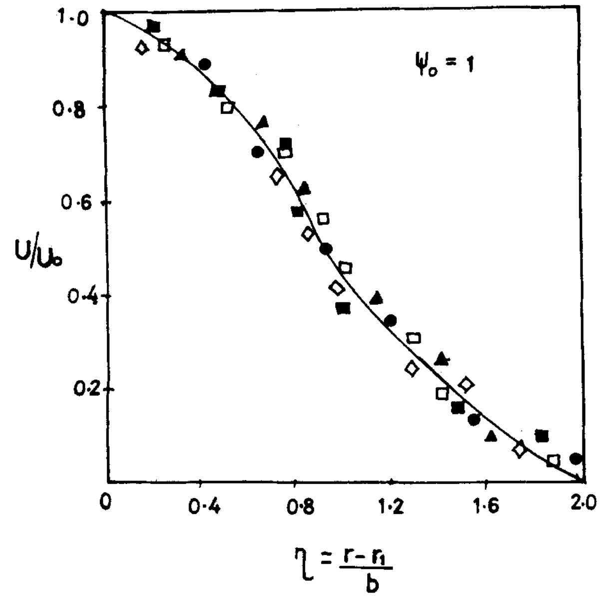

Figure 2. Velocity profile in the annular shear layer. The solid curve represents the cosine profile given by Eq. 6.

x/r_o

3 ●

5 □ Experimental

10 ◇ Data

15 ■

20 ▲

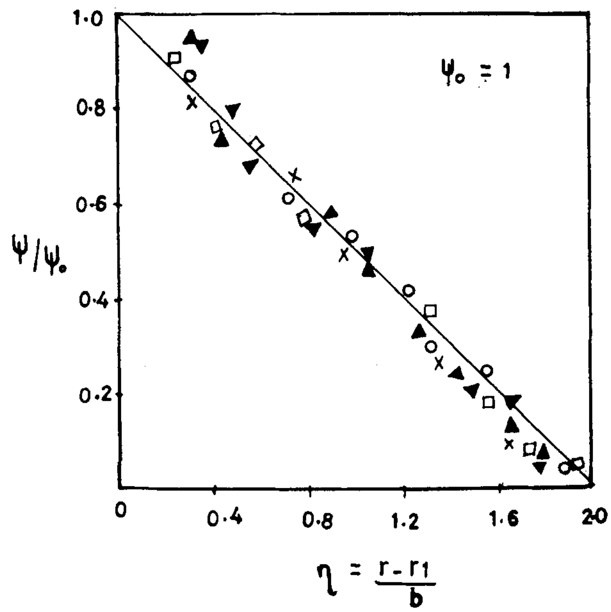

Figure 3. Concentration profile in the annular shear layer. The solid line represents the linear profile given by Eq. 7.

x/r_o

4 ○

5 □ Experimental

10 ▲ Data

15 ▼

20 ×

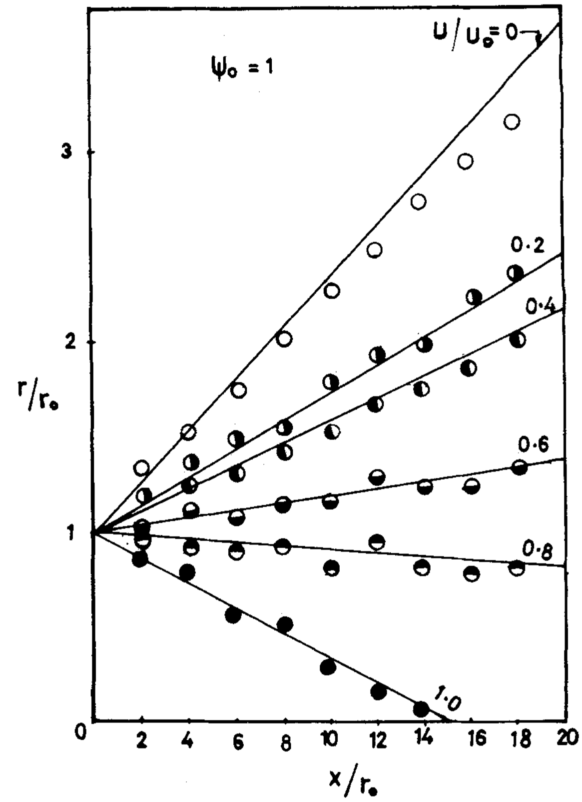

Figure 4. Equal dimensionless velocity lines for the initial region of a two-phase jet.

U/U_o

0 ○

0.2 ◑

0.4 ◐ Experimental

0.6 ◒ Data

0.8 ◓

1.0 ●

1978) and the particles were collected using eight filter tubes arranged symmetrically in a perspex chamber. Suction was applied using a vacuum pump. At any radial position, the suction was so adjusted that the pressure at the tip of the isokinetic tube equalled the atmospheric pressure. This adjustment was made when particles were not present in the system. The isokinetic tube was thereafter moved away from the jet periphery and particles were introduced into the systems. At the zero count, the suction tube was quickly moved into place and the collection time varied from 5 to 10 minutes. Adjustments of the probe position at any radial distance could be made within an accuracy of 0.025 mm using a vernier scale. A micromanometer capable of giving readings as small as 10 mPa was used in the measurements.

The velocity was measured with a total head tube of diameter 0.8 mm connected to the micromanometer. The tube was first calibrated in the potential core of the air jet for predetermined velocities and particle concentrations. Entrainment was determined by integration of the measured velocity profile.

RESULTS AND DISCUSSION

Figure 2 shows the velocity profile in the annular shear region obtained from impact probe measurements. The experimental data is seen to be approximated by the cosine profile of Eq. 6. The measurements were taken at equally spaced axial stations extending up to 20 nozzle radii. Up to $x/r_o = 2$, there was distortion of the

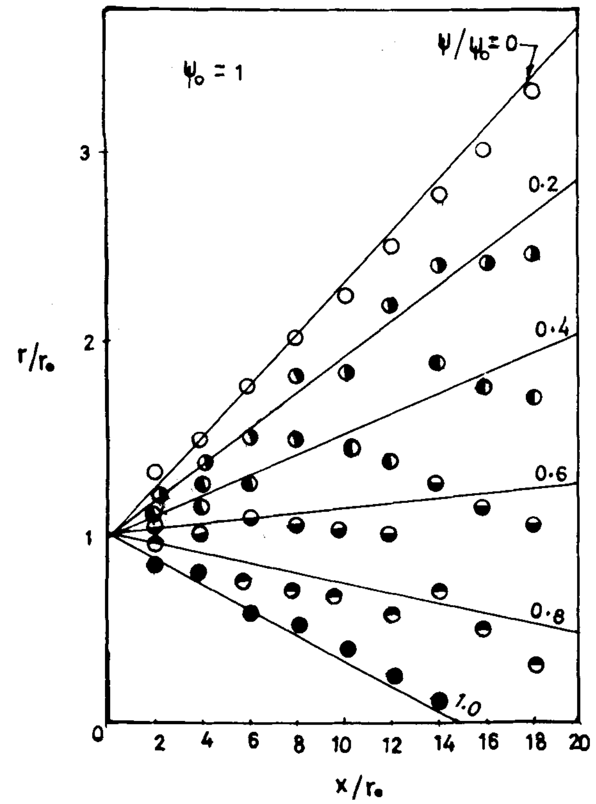

Figure 5. Equal dimensionless concentration lines for the initial region of a two-phase jet.

ψ/ψ_o

0 ○

0.2 ◑

0.4 ◐ Experimental

0.6 ◒ Data

0.8 ◓

1.0 ●

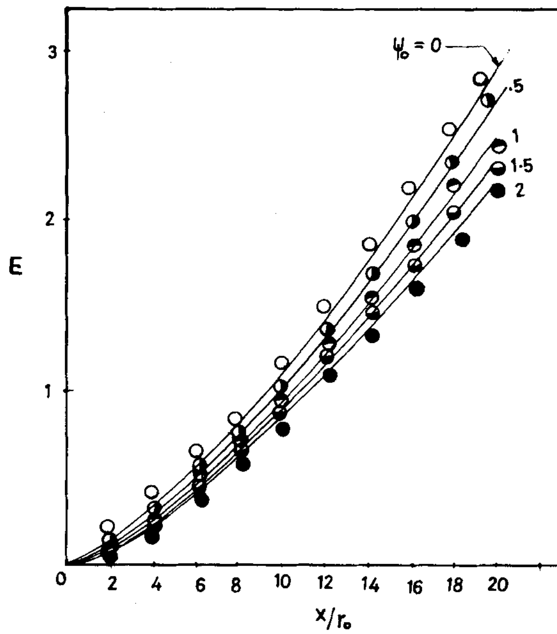

Figure 6. Entrainment vs. axial distance.

ψ_o

0 ○

0.5 ◑

1.0 ◓ Experimental

1.5 ◒ Data

2.0 ●

velocity profile and similarity was not achieved. The particle exit concentration was carefully checked every now and then to see if the initial conditions were responsible for this behavior. Beyond $x/r_o = 2$, it was possible to obtain almost similar conditions for velocity. The concentration profile measured using an isokinetic sampling device is plotted in Figure 3 and the experimental data is seen to fall close to the linear profile of Eq. 7. It is seen that similarity in the concentration profile occurs after $x/r_o = 3$. A probable explanation for this delayed similarity can be found in the transfer processes of momentum and mass. Particles are seen to lag behind the fluid phase (Memmot and Smoot, 1978). This behavior shows that the gas mixing rates are higher than the particle mixing rates for $\psi_o = 1$.

Figure 4 shows the equal dimensionless velocity lines for the initial region of the two-phase jet. These lines are drawn using Eqs. 1, 2, 6 and 12. The experimental data are also shown and are seen to lie close to the predictions. Similarly, the equal dimensionless lines for concentration drawn using Eqs. 1, 2, 7 and 12 are shown in Figure 5.

A comparison of Figure 4 with single-phase measurements of Albertson et al. (1948) shows that particles increase the length of the potential core. They obtained a length of potential core equal to 10. Introducing sand particles at an exit concentration of $\psi_o = 1$ is seen to increase the potential core length by 50%. The radius of the jet is also seen to decrease. Particles attenuate the turbulence and thereby reduce the lateral component of the fluctuating velocity which is responsible for the jet widening rate. It is seen from Figures 4 and 5 that the inner and outer boundaries of the jet for velocity and concentration are the same. The equal dimensionless concentration lines in the shear layer are, however, different from those for velocity. This kind of behavior has been predicted by Abramovich (1963) for a jet containing a passive contaminant. He has shown that mass and temperature profiles in the initial region of a jet exhibit a linear relationship. The same is not, however, true for the fully developed region where Reichardt (1942) has suggested a square root dependence of concentration on velocity.

Figure 6 shows the experimental values of entrainment obtained from $\psi_o = 0$–2. The curves have been plotted using Eq. 19 and the experimental data have been obtained from the actual measured velocity data using Eq. 15. In this paper entrainment has been determined by integration of the velocity profile and not by the direct measurement technique of Ricou and Spalding (1961) as in our previous paper (1982). Entrainment is seen to decrease with particles and higher concentration of particles leads to suppression of the mixing.

ACKNOWLEDGMENT

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NOTATION

A,B	= constants in the entrainment equation
b	= half width of the boundary layer (m)
E	= entrainment, defined by Eq. 15

F_1, F_2 = velocity integrals defined by Eqs. 17 and 18
f = velocity function, defined by Eq. 6
K, M, N = constants, defined by Eqs. 1 to 3 and 12 to 14
r_o = jet exit radius (m)
r_1 = radius of potential core (m)
r_2 = radius of jet edge (m)
U = velocity (m/s)
U_o = velocity at jet exit (m/s)
x = axial distance (m)
x_o = length of potential core (m)
y_1 = radial distance, Figure 1

Greek Letters

ρ = density (kg/m^3)
ρ_o = density at nozzle exit (kg/m^3)
ρ_a = density of air (kg/m^3)
η = dimensionless radial distance
ψ = particle concentration (kg particles/kg air)
ψ_o = initial particle concentration (kg particles/kg air)

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Measuring Temperature in a Flowing Gas-Solids Suspension with a Thermocouple

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Much research effort during the last two decades has been directed at understanding the heat-transfer characteristics of flowing gas-solids suspensions. This activity has been due to: (1) the usefulness of suspensions as heat-transfer media in situations of high temperature and/or high heat flux (e.g., nuclear reactors); and (2) a growing interest in entrained-flow reactors (e.g., coal pyrolysis).

When a gas-solids suspension flows through a heated tube, heat is transferred from the tube wall to the gas and from the gas to the particles. In addition, the particles gain heat directly from the wall by radiation and possibly by particle-wall collisions. Therefore, it is possible for the temperature of the solids to be either greater than or less than the temperature of the gas, depending on the rate of direct wall-to-particle heat transfer as compared with the rates of wall-to-gas heat transfer and gas-to-particle heat transfer.

In order to accurately analyze the kinetic and transport processes in gas-particle systems, it is necessary to know the temperatures of the gas and particle phases. The particle temperature in coal combustion and pyrolysis, for example, determines the rate of coal devolatilization and heterogeneous reaction as well as the rate of radiation heat transfer from the particles to the reactor wall. The gas temperature governs the rate of gas-phase reactions and wall-to-gas heat transfer. Due to the difficulty of measuring the temperature of the gas and solids independently, most investigators of heat transfer in gas-solids suspensions have assumed that the rate of gas-to-particle heat transfer is infinite, and that the particles and gas are in thermal equilibrium. However, this assumption is not practical for many systems of interest. Calculations by Bransford and Holden (1970), for 56-μm coal particles suspended in hydrogen gas flowing through a 0.0095-m-diameter tube 0.20 m long at typical reactor conditions (pressure 101.3 kPa, gas velocity 2.3 m/s, and tube wall temperature 1,750 K) show, for example that particle temperature lags gas temperature by approximately 550 K (1,000°R) at the tube outlet. Their conditions correspond to laminar flow (gas Reynolds number equals 120). Particle temperature probably does not lag that of the gas by as great an amount in turbulent flow. However, the need is evident for distinguishing between temperatures of gas and solid phases when analyzing the heat-transfer characteristics of many gas-solids suspensions of interest.

Particle temperature has been determined directly from radiation measurements using two-color pyrometry (Themelis and Gauvin, 1962), and this is probably the preferred method for high-temperature, reacting systems. Boothroyd (1971, p. 91) reports that "stout" thermocouples inserted directly into the flow have been found to register the gas temperature correctly. However, ther-

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