MASTER

THE EFFECT OF SOLID PARTICLES
ON THE TURBULENT FLOW OF A ROUND
GASEOUS JET

A MATHEMATICAL AND EXPERIMENTAL STUDY

QUARTERLY TECHNICAL PROGRESS REPORT
FOR THE PERIOD
OCTOBER 1 TO DECEMBER 31, 1980

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TABLE OF CONTENTS

	Page
I. SCOPE	1
II. PROGRESS TO DATE	2
III. DETAILED DESCRIPTION OF PROGRESS	3
A. Mathematical Study	3-10
B. Experimental Study	11-16
IV. WORK IN PROGRESS	17
V. REFERENCES	18

I. SCOPE

Combustion of pulverised coal involves chemical reaction in turbulent two phase flow. This combustion process depends, among other factors, on the structure of turbulence in the combustion chamber. Turbulent fluctuations of temperature and concentration strongly influence the local rates of chemical reaction and heat transfer and the rate of evolution of volatiles.

Also the turbulent fluctuations of the relative (slip) velocity between the particle and the surrounding gas influence the turbulent shear stress at the particle surface and hence affect the flame point symmetry. This in turn changes the rates of reaction and heat transfer.

Experiments (1, 2, 3, 4) on inert, two-phase flows show the turbulence structure is altered as a result of the presence of particles or droplets in the flow.

It is therefore essential to understand the mechanism of turbulence modulation due to the dispersed phase. This is the main objective of this project which addresses the problem with a combined mathematical/experimental effort.

The mathematical study aims at developing a numerical prediction procedure which embodies a new turbulence model that accounts for the two-phase interaction. The experiment will provide non-intrusive optical local measurements of the time-mean and the fluctuating velocities of the particle and gas, the solid-phase volume fraction throughout the flow field of a vertical, round, turbulent isothermal jet seeded with solid particles of uniform size. The influence of the particle size and injection velocity will also be studied.

The predictions will be compared with the experimental data and refinements of the mathematical model will be made to minimize the discrepancy between them.

II. PROGRESS TO DATE

During this first quarter of the project the following tasks have been completed:

A. Mathematical Study:

Derivation of the complete time-averaged conservation equations of the two-phase turbulent flow. These are the conservation equations of:

- continuity of the solid phase
- momentum of the solid phase in the axial and radial directions
- momentum of the gaseous phase in the axial and radial directions
- turbulence kinetic energy
- dissipation rate of the turbulence kinetic energy

B. Experimental Study:

- . A review of the proposed design
- . Design of the apparatus
- . Hardware fabrication

III. DETAILED DESCRIPTION OF PROGRESS

A. Mathematical Study

This section describes the flow studied and lists the time averaged equations.

A.-1

THE FLOW: ● A TURBULENT ROUND JET ISSUES FROM A PIPE.

- THE JET FLUID CONSISTS OF A CONTINUOUS LIGHT PHASE (AIR) AND A PARTICULATE PHASE OF UNIFORM SIZE AND SPHERICAL.

- NO PHASE CHANGE TAKES PLACE.

REQUIRED: CALCULATE THE VELOCITY COMPONENTS (u_1, v_1), (u_2, v_2), THE PRESSURE, AND THE VOLUME FRACTIONS ϕ_1, ϕ_2 , TURBULENCE PROPERTIES (ENERGY AND LENGTH SCALE) AS FUNCTIONS OF (x, r).

ASSUMPTIONS: ● DRAG IS THE ONLY MECHANISM OF INTERACTION.

- COLLISION BETWEEN PARTICLES IS NEGLIGIBLE (LOW LOADING).

A.-2 Continuity

INSTANTANEOUS, SOLID PHASE:

$$\frac{\partial}{\partial t} (\rho_2 \phi_2) + \frac{\partial}{\partial x} (\rho_2 \phi_2 u_2) + \frac{1}{r} \frac{\partial}{\partial r} (\rho_2 \phi_2 r v_2) = 0$$

GLOBAL

$$\phi_1 + \phi_2 = 1$$

TIME AVERAGED, STEADY STATE, SOLID PHASE

$$\frac{\partial}{\partial x} (\rho_2 \bar{\phi}_2 \bar{u}_2) + \frac{1}{r} \frac{\partial}{\partial r} (\rho_2 \bar{\phi}_2 r \bar{v}_2) = - \frac{\partial}{\partial x} (\rho_2 \bar{\phi}_2' u_2') - \frac{1}{r} \frac{\partial}{\partial r} (\rho_2 r \bar{\phi}_2' v_2')$$

A.-3 Momentum

GASEOUS PHASE

x - MOMENTUM

$$\frac{\partial}{\partial t} (\rho_1 \phi_1 u_1) + \frac{\partial}{\partial x} (\rho_1 \phi_1 u_1 u_1) + \frac{1}{r} \frac{\partial}{\partial r} (\rho_1 \phi_1 r v_1 u_1) = -(1 - K \phi_2) \frac{\partial P_{av}}{\partial x} + \frac{1}{r} \frac{\partial}{\partial r} (\phi_1 \mu_1 r \frac{\partial u_1}{\partial r}) - K F (u_1 - u_2)$$

r - MOMENTUM

$$\frac{\partial}{\partial t} (\rho_1 \phi_1 v_1) + \frac{\partial}{\partial x} (\rho_1 \phi_1 u_1 v_1) + \frac{1}{r} \frac{\partial}{\partial r} (\rho_1 \phi_1 r v_1 v_1) = -(1 - K \phi_2) \frac{\partial P}{\partial r} - K F (v_1 - v_2)$$

SOLID PHASE

x - MOMENTUM

$$\frac{\partial}{\partial t} (\rho_2 \phi_2 u_2) + \frac{\partial}{\partial x} (\rho_2 \phi_2 u_2 u_2) + \frac{1}{r} \frac{\partial}{\partial r} (\rho_2 \phi_2 v_2 u_2) = - \phi_2 \frac{\partial P_{av}}{\partial x} + \frac{1}{r} \frac{\partial}{\partial r} (\phi_2 \mu_2 r \frac{\partial u_2}{\partial r}) + F (u_1 - u_2) + g \phi_2 (\rho_2 - \rho_1)$$

r - MOMENTUM

$$\frac{\partial}{\partial t} (\rho_2 \phi_2 v_2) + \frac{\partial}{\partial x} (\rho_2 \phi_2 u_2 v_2) + \frac{1}{r} \frac{\partial}{\partial r} (\rho_2 \phi_2 v_2 v_2) = - \phi_2 \frac{\partial P}{\partial r} + F (v_1 - v_2)$$

GASEOUS PHASE

x - MOMENTUM

$$\begin{aligned} \frac{\partial}{\partial x} (\rho_1 \bar{\phi}_1 \bar{u}_1 \bar{u}_1) + \frac{1}{r} \frac{\partial}{\partial r} (\rho_1 \bar{\phi}_1 r \bar{v}_1 \bar{u}_1) = & -(1 - K \bar{\phi}_2) \frac{\partial \bar{P}_{\lambda v}}{\partial x} + \frac{1}{r} \frac{\partial}{\partial r} (\bar{\phi}_1 \mu_1 r \frac{\partial \bar{u}_1}{\partial r}) \\ & - \frac{\partial}{\partial x} (\rho_1 \bar{\phi}_1 \bar{u}_1' \bar{u}_1') - \frac{1}{r} \frac{\partial}{\partial r} (\rho_1 r \bar{\phi}_1 \bar{u}_1' \bar{v}_1') \\ & - K F \bar{\phi}_2 (\bar{u}_1 - \bar{u}_2) - K F \bar{\phi}_2' (\bar{u}_1' - \bar{u}_2') \\ & + \frac{1}{r} \frac{\partial}{\partial r} (\mu_1 r \bar{\phi}_1' \frac{\partial \bar{u}_1'}{\partial r}) + K \bar{\phi}_2' \frac{\partial \bar{P}_{\lambda v}}{\partial x} \\ & - \frac{\partial}{\partial x} (\rho_1 \bar{\phi}_1' \bar{u}_1' \bar{u}_1') - \frac{1}{r} \frac{\partial}{\partial r} (\rho_1 r \bar{\phi}_1' \bar{u}_1' \bar{v}_1') \end{aligned}$$

r - MOMENTUM

$$\begin{aligned} \frac{\partial}{\partial x} (\rho_1 \bar{\phi}_1 \bar{u}_1 \bar{v}_1) + \frac{1}{r} \frac{\partial}{\partial r} (\rho_1 \bar{\phi}_1 r \bar{v}_1 \bar{v}_1) = & -(1 - K \bar{\phi}_2) \frac{\partial \bar{P}}{\partial r} - \frac{\partial}{\partial x} (\rho_1 \bar{\phi}_1 \bar{u}_1' \bar{v}_1') \\ & - \frac{1}{r} \frac{\partial}{\partial r} (\rho_1 \bar{\phi}_1 \bar{v}_1' \bar{v}_1') - K F \bar{\phi}_2 (\bar{v}_1 - \bar{v}_2) \\ & - K F \bar{\phi}_2' (\bar{v}_1' - \bar{v}_2') + K \bar{\phi}_2' \frac{\partial \bar{P}}{\partial r} \\ & - \frac{\partial}{\partial x} (\rho_1 \bar{\phi}_1' \bar{u}_1' \bar{v}_1') - \frac{1}{r} \frac{\partial}{\partial r} (\rho_1 r \bar{\phi}_1' \bar{v}_1' \bar{v}_1') \end{aligned}$$

SOLID PHASE

x - MOMENTUM

$$\begin{aligned}
\frac{\partial}{\partial x} (\rho_2 \bar{\phi}_2 \bar{u}_2 \bar{u}_2) + \frac{1}{r} \frac{\partial}{\partial r} (\rho_2 \bar{\phi}_2 r \bar{v}_2 \bar{u}_2) = & - \bar{\phi}_2 \frac{\partial \bar{P}_{av.}}{\partial x} + \frac{1}{r} \frac{\partial}{\partial r} (\bar{\phi}_2 \mu_2 r \frac{\partial \bar{u}_2}{\partial r}) \\
& - \frac{\partial}{\partial x} (\rho_2 \bar{\phi}_2 \overline{u'_2 u'_2}) - \frac{1}{r} \frac{\partial}{\partial r} (\rho_2 \bar{\phi}_2 \overline{u'_2 v'_2}) \\
& + F \bar{\phi}_2 (\bar{u}_1 - \bar{u}_2) + F \bar{\phi}'_2 (\bar{u}'_1 - \bar{u}'_2) \\
& + \frac{1}{r} \frac{\partial}{\partial r} (\mu_2 r \bar{\phi}'_2 \frac{\partial \bar{u}'_2}{\partial r}) - \bar{\phi}'_2 \frac{\partial \bar{P}'_{av.}}{\partial x} \\
& - \frac{\partial}{\partial x} (\rho_2 \bar{\phi}'_2 \overline{u'_2 u'_2}) - \frac{1}{r} \frac{\partial}{\partial r} (\rho_2 r \bar{\phi}'_2 \overline{u'_2 v'_2}) \\
& + g \bar{\phi}_2 (\rho_2 - \rho_1)
\end{aligned}$$

z - MOMENTUM

$$\begin{aligned}
\frac{\partial}{\partial x} (\rho_2 \bar{\phi}_2 \bar{u}_2 \bar{v}_2) + \frac{1}{r} \frac{\partial}{\partial r} (\rho_2 \bar{\phi}_2 r \bar{v}_2 \bar{v}_2) = & - \bar{\phi}_2 \frac{\partial \bar{P}}{\partial r} - \frac{\partial}{\partial x} (\rho_2 \bar{\phi}_2 \overline{u'_2 v'_2}) - \frac{1}{r} \frac{\partial}{\partial r} (\rho_2 \bar{\phi}_2 \overline{v'_2 v'_2}) \\
& + F \bar{\phi}_2 (\bar{v}_1 - \bar{v}_2) + F \bar{\phi}'_2 (\bar{v}'_1 - \bar{v}'_2) \\
& + \frac{\partial}{\partial x} (\rho_2 \bar{\phi}'_2 \overline{u'_2 v'_2}) - \frac{1}{r} \frac{\partial}{\partial r} (\rho_2 \bar{\phi}'_2 \overline{v'_2 v'_2})
\end{aligned}$$

A.-4 Kinetic Energy of Turbulence $[k \equiv \frac{\overline{u_i'^2}}{2}]$

$$\begin{aligned}
 & \frac{\partial}{\partial x_l} \left(\rho \bar{\phi}_i \bar{u}_l \frac{\overline{u_i'^2}}{2} \right) + \frac{\overline{u_i'^2}}{2} \frac{\partial (\rho \bar{\phi}_i \bar{u}_l)}{\partial x_l} = - \overline{u_i' u_l'} \frac{\partial \rho \bar{\phi}_i \bar{u}_i}{\partial x_l} - \left\{ \begin{aligned} & \bar{\phi}_i' u_i' u_l' \frac{\partial \rho \bar{u}_i}{\partial x_l} \\ & - \bar{\phi}_i' u_i' u_i' \frac{\partial \rho \bar{u}_l}{\partial x_l} \end{aligned} \right\} \\
 & + (1 - K \bar{\phi}_2) \overline{u_i' \frac{\partial \rho'}{\partial x_i}} - K \bar{\phi}_i' u_i' \frac{\partial \bar{\rho}}{\partial x_i} - K \bar{\phi}_i' u_i' \frac{\partial \rho'}{\partial x_i} \\
 & - \overline{u_i'^2 \frac{\partial \rho \bar{\phi}_i u_l'}{\partial x_l}} - \rho \bar{\phi}_i \overline{u_i' u_l' \frac{\partial u_i'}{\partial x_l}} + (1 - K \bar{\phi}_2) \overline{\frac{\partial u_i' \rho'}{\partial x_i}} \left\{ \right. \\
 & - \rho \bar{\phi}_i \bar{u}_i \overline{u_i' \frac{\partial u_i'}{\partial x_l}} - \rho \bar{u}_i \overline{u_i' \frac{\partial \phi_i'}{\partial x_l}} \\
 & - \rho \bar{u}_l \overline{u_i' \frac{\partial \phi_i'}{\partial x_l}} - \rho \bar{\phi}_i' u_i' \overline{\frac{\partial \bar{u}_i \bar{u}_l}{\partial x_l}} - \bar{u}_i \bar{u}_l \overline{u_i' \frac{\partial \rho \phi_i'}{\partial x_l}} \\
 & - \rho \overline{u_i' \phi_i' \frac{\partial \bar{u}_i u_l'}{\partial x_l}} - \overline{u_i' u_i' u_l' \frac{\partial \rho \phi_i'}{\partial x_l}} \left. \right\} \\
 & + K F_2 \bar{\phi}_2 \overline{u_l' (u_{2,l}' - u_l')} + K F_2 \bar{\phi}_2' u_l' (\bar{u}_{2,l} - \bar{u}_l) \left\{ \right. \\
 & + K F_2 \bar{\phi}_2' u_l' (\overline{u_{2,l}' - u_l'}) \left. \right\} \\
 & + \rho \bar{\phi}_i \nu \overline{u_i' \left(\frac{\partial u_i'}{\partial x_l} + \frac{\partial u_l'}{\partial x_i} \right)} + \nu \overline{u_i' \left(\frac{\partial u_i'}{\partial x_l} + \frac{\partial u_l'}{\partial x_i} \right) \frac{\partial \rho \bar{\phi}_i}{\partial x_l}} \\
 & + \rho \bar{\phi}_i' u_i' \overline{\frac{\partial}{\partial x_l} \nu \left(\frac{\partial \bar{u}_i}{\partial x_l} + \frac{\partial \bar{u}_l}{\partial x_i} \right)} + \nu \overline{u_i' \frac{\partial \rho \phi_i'}{\partial x_l} \left(\frac{\partial \bar{u}_i}{\partial x_l} + \frac{\partial \bar{u}_l}{\partial x_i} \right)} \left\{ \right. \\
 & + \rho \nu \bar{\phi}_i' u_i' \overline{\frac{\partial}{\partial x_l} \left(\frac{\partial u_i'}{\partial x_l} + \frac{\partial u_l'}{\partial x_i} \right)} + \nu \overline{u_i' \frac{\partial \rho \phi_i'}{\partial x_l} \left(\frac{\partial u_i'}{\partial x_l} + \frac{\partial u_l'}{\partial x_i} \right)} \left. \right\}
 \end{aligned}$$

A.-5 Dissipation Rate of Turbulence Energy $[\epsilon \equiv \nu \overline{(\frac{\partial u'_i}{\partial x_l})^2}]$

$$\begin{aligned}
 \frac{\partial (\rho \bar{\phi}_i \bar{u}_l \bar{\epsilon})}{\partial x_l} + \bar{\epsilon} \frac{\partial \rho \bar{u}_l \bar{\phi}_i}{\partial x_l} &= -2\nu \frac{\partial \rho \bar{\phi}_i \bar{u}_l}{\partial x_l} \overline{\left(\frac{\partial u'_l}{\partial x_l} \frac{\partial u'_i}{\partial x_k} \right)} \\
 &\quad -2\nu \frac{\partial \rho \bar{\phi}_i \bar{u}_l}{\partial x_k} \overline{\left(\frac{\partial u'_l}{\partial x_l} \frac{\partial u'_i}{\partial x_l} \right)} -2\nu \frac{\partial (\rho \bar{\phi}_i \bar{u}_l)}{\partial x_l \partial x_k} \overline{u'_l \frac{\partial u'_i}{\partial x_k}} \\
 &\quad -2\rho \nu \left(\frac{\partial \bar{\phi}_i \bar{u}_l}{\partial x_k} \overline{\frac{\partial u'_i}{\partial x_l} \frac{\partial u'_i}{\partial x_k}} + \frac{\partial \bar{\phi}_i \bar{u}_l}{\partial x_l \partial x_k} \overline{u'_i \frac{\partial u'_i}{\partial x_k}} \right) \\
 &\quad -2\nu \bar{\phi}_i \bar{u}_l \overline{\frac{\partial u'_l}{\partial x_l} \frac{\partial u'_i}{\partial x_k}} -2\rho \nu \bar{\phi}_i \overline{\frac{\partial u'_i}{\partial x_k} \frac{\partial u'_i}{\partial x_k} \frac{\partial u'_l}{\partial x_l}} \\
 &\quad -2\rho \nu \bar{\phi}_i \frac{\partial}{\partial x_l} \overline{u'_i \frac{\partial u'_l}{\partial x_k} \frac{\partial u'_i}{\partial x_k}} -2\rho \nu \bar{\phi}_i \frac{\partial}{\partial x_l} \overline{u'_l \frac{\partial u'_i}{\partial x_k} \frac{\partial u'_i}{\partial x_k}} \\
 &\quad -2\nu \frac{\partial}{\partial x_k} \overline{\frac{\partial \rho}{\partial x_i} \frac{\partial u'_i}{\partial x_k}} \\
 &\quad +2\nu F_3 \left\{ \bar{\phi}_2 \overline{\frac{\partial u'_i}{\partial x_l} \frac{\partial u'_{i,2}}{\partial x_l}} + \overline{u'_{i,2} \frac{\partial u'_i}{\partial x_l} \frac{\partial \phi_2}{\partial x_l}} - \bar{\phi}_2 \overline{\frac{\partial u'_i}{\partial x_l} \frac{\partial u'_i}{\partial x_l}} \right. \\
 &\quad - \overline{u'_i \frac{\partial u'_i}{\partial x_l} \frac{\partial \phi_2}{\partial x_l}} + \bar{\phi}_2' \overline{\frac{\partial u'_{i,2}}{\partial x_l} \frac{\partial \bar{u}_{i,2}}{\partial x_l}} + \bar{u}_{i,2} \overline{\frac{\partial u'_i}{\partial x_l} \frac{\partial \phi_2'}{\partial x_l}} - \bar{\phi}_2' \overline{\frac{\partial u'_i}{\partial x_l} \frac{\partial \bar{u}_i}{\partial x_l}} \\
 &\quad - \overline{\frac{\partial u'_i}{\partial x_l} \frac{\partial \phi_2'}{\partial x_l}} \bar{u}_i + \bar{\phi}_2' \overline{\frac{\partial u'_{i,2}}{\partial x_l} \frac{\partial u'_i}{\partial x_l}} + \overline{u'_{i,2} \frac{\partial u'_i}{\partial x_l} \frac{\partial \phi_2'}{\partial x_l}} \\
 &\quad \left. - \bar{\phi}_2' \overline{\frac{\partial u'_i}{\partial x_l} \frac{\partial u'_i}{\partial x_l}} - \overline{u'_i \frac{\partial u'_i}{\partial x_l} \frac{\partial \phi_2'}{\partial x_l}} \right\}
 \end{aligned}$$

(CONTINUED)

$$- \left\{ 2\nu \int \bar{u}_i \bar{u}_l \frac{\partial \Phi_1}{\partial x_l \partial x_k} + 2\nu \int \frac{\partial \Phi_1}{\partial x_k} \left(\bar{u}_i \frac{\partial u_l}{\partial x_l} + \bar{u}_l \frac{\partial u_i}{\partial x_l} \right) \right\} \frac{\partial u_i}{\partial x_k}$$

$$- \left\{ 2\nu \int \Phi_1' \left(\frac{\partial \bar{u}_i}{\partial x_l} \frac{\partial \bar{u}_l}{\partial x_k} \right) + 2\nu \int \bar{u}_i \frac{\partial \bar{u}_l}{\partial x_k} \frac{\partial \Phi_1'}{\partial x_l} + 2\nu \int \Phi_1' \frac{\partial \bar{u}_i}{\partial x_l} \frac{\partial \bar{u}_l}{\partial x_k} \right\} \frac{\partial u_i}{\partial x_k}$$

$$- 2\nu \int \bar{u}_l \frac{\partial \bar{u}_i}{\partial x_k} \frac{\partial \Phi_1'}{\partial x_l} \frac{\partial u_i}{\partial x_k} - \left\{ 2\nu \int u_i' u_l' \frac{\partial^2 \Phi_1'}{\partial x_l \partial x_k} + 2\nu \int \frac{\partial \Phi_1'}{\partial x_k} \left(u_i' \frac{\partial u_l'}{\partial x_l} + u_l' \frac{\partial u_i'}{\partial x_l} \right) \right\} \frac{\partial u_i}{\partial x_k}$$

$$- \left\{ 2\nu \int \Phi_1' \frac{\partial}{\partial x_l} \left(u_i' \frac{\partial u_l'}{\partial x_k} \right) + 2\nu \int u_i' \frac{\partial u_l'}{\partial x_k} \frac{\partial \Phi_1'}{\partial x_l} + 2\nu \int \Phi_1' \left(\frac{\partial}{\partial x_l} u_l' \frac{\partial u_i'}{\partial x_k} \right) + 2\nu \int u_l' \frac{\partial u_i'}{\partial x_k} \frac{\partial \Phi_1'}{\partial x_l} \right\} \frac{\partial u_i}{\partial x_k}$$

$$+ 2\nu \int \frac{\partial u_i}{\partial x_k} \frac{\partial^2}{\partial x_k \partial x_l} \left\{ \bar{\Phi}_1 \left(\frac{\partial u_i}{\partial x_l} + \frac{\partial u_l}{\partial x_i} \right) \right\} + 2\nu \int \frac{\partial u_i}{\partial x_k} \frac{\partial^2 \Phi_1'}{\partial x_k \partial x_l} \left(\frac{\partial \bar{u}_i}{\partial x_l} + \frac{\partial \bar{u}_l}{\partial x_i} \right)$$

$$+ 2\nu \int \frac{\partial u_i}{\partial x_k} \frac{\partial^2 \Phi_1'}{\partial x_k \partial x_l} \left(\frac{\partial u_i}{\partial x_l} + \frac{\partial u_l}{\partial x_i} \right)$$

$$- 2\nu \int u_i' u_l' \frac{\partial u_i}{\partial x_k} \frac{\partial \bar{\Phi}_1}{\partial x_l \partial x_k} - 2\nu \int \frac{\partial \bar{\Phi}_1}{\partial x_k} \left(u_i' \frac{\partial u_l'}{\partial x_l} + u_l' \frac{\partial u_i'}{\partial x_l} \right) \frac{\partial u_i}{\partial x_k}$$

$$- 2\nu \int u_i' \frac{\partial u_l'}{\partial x_k} \frac{\partial u_i}{\partial x_k} \frac{\partial \bar{\Phi}_1}{\partial x_l} - 2\nu \int \bar{\Phi}_1 u_l' \frac{\partial u_i}{\partial x_k} \frac{\partial u_l'}{\partial x_l \partial x_k} - 2\nu \int u_l' \frac{\partial u_i}{\partial x_l} \frac{\partial u_i}{\partial x_k} \frac{\partial \bar{\Phi}_1}{\partial x_l}$$

$$+ 2\nu \int \frac{\partial}{\partial x_k} \left(K \bar{\Phi}_2 \frac{\partial \Phi_1'}{\partial x_i} \right) \frac{\partial u_i}{\partial x_k} - 2\nu \int K \Phi_1' \frac{\partial u_i}{\partial x_k} \frac{\partial}{\partial x_k} \left(\frac{\partial \bar{\Phi}_1}{\partial x_i} \right)$$

$$- 2\nu \int \frac{\partial u_i}{\partial x_k} \frac{\partial K \Phi_1'}{\partial x_k} \frac{\partial \bar{\Phi}_1}{\partial x_i} - 2\nu \int \frac{\partial K \Phi_1'}{\partial x_k} \frac{\partial \Phi_1'}{\partial x_i} \frac{\partial u_i}{\partial x_k}$$

$$- 2\nu \int \frac{\partial u_l}{\partial x_k} \frac{\partial u_i}{\partial x_k} \left(\frac{\partial \Phi_1' \bar{u}_i}{\partial x_l} + \frac{\partial \Phi_1' \bar{u}_i}{\partial x_k} \right) - 2\nu \int \Phi_1' \bar{u}_i \frac{\partial^2 u_l}{\partial x_l \partial x_k} \frac{\partial u_i}{\partial x_k}$$

$$- 2\nu \int u_l' \left(\frac{\partial \Phi_1' \bar{u}_i}{\partial x_l \partial x_k} \right) \frac{\partial u_i}{\partial x_k} - 2\nu \int \Phi_1' \bar{u}_l \frac{\partial^2 u_i}{\partial x_l \partial x_k} \frac{\partial u_i}{\partial x_k}$$

$$- 2\nu \int u_i' \left(\frac{\partial^2 \Phi_1' \bar{u}_l}{\partial x_l \partial x_k} \right) \frac{\partial u_i}{\partial x_k} - 2\nu \int \frac{\partial \Phi_1' \bar{u}_l}{\partial x_l} \left[\left(\frac{\partial u_i}{\partial x_k} \right)^2 + \left(\frac{\partial u_i}{\partial x_l} \frac{\partial u_i}{\partial x_k} \right) \right]$$

A.-6 The Numerical Solution Procedure

MAIN FEATURES

- THE PROCEDURE IS A FINITE DIFFERENCE OF THE B.L. TYPE (MARCHING, BUT WITH ITERATION AT EACH STATION).
- ALTHOUGH THE FLOW IS OF THE B.L. TYPE, THE LATERAL MOMENTUM EQUATIONS OF BOTH PHASES MUST BE SOLVED TO COMPUTE THE EXCHANGE OF MOMENTUM (SLIP) IN THE r -DIRECTION.
- THE VARIATIONS OF PRESSURE IN THE RADIAL DIRECTION STILL DON'T INFLUENCE THE AXIAL MOMENTUM, BUT THEY DO CONTROL THE SLIP BETWEEN THE PHASES.

- THE CO-ORDINATES OF THE EXPANDING FINITE-DIFFERENCE GRID ARE x AND ψ , THE STREAM FUNCTION BASED ON THE GASEOUS-PHASE PROPERTIES, DEFINED AS:

$$\psi \equiv \int_0^r \rho_1 \bar{\phi}_1 \bar{u}_1 r dr$$

- THE STEPS FOLLOWED TO OBTAIN THE SOLUTION AT A GIVEN AXIAL LOCATION ARE:

- i) GUESS THE DOWNSTREAM $\bar{\phi}_1^*$, ϕ -DISTRIBUTION
- ii) SOLVE FOR $\bar{u}_1$ DOWNSTREAM: OBTAIN r 's AND $\bar{v}_1$'s.
- iii) OBTAIN $\bar{p}(r)$ FROM THE GASEOUS PHASE LATERAL MOMENTUM EQUATION
- iv) SOLVE FOR DOWNSTREAM $\bar{v}_2$, $\bar{u}_2$, $\bar{\phi}_2$ AND GET $\bar{\phi}_1$.
- v) SOLVE TURBULENCE EQUATIONS AND CALCULATE TRANSPORT COEFFICIENTS
- vi) COMPARE THE NEW $\bar{\phi}_1$ WITH THE GUESSED $\bar{\phi}_1^*$.
- vii) MAKE CORRECTIONS AND REPEAT STEPS i) TO v) UNTIL THE SOLUTION CONVERGES BEFORE MARCHING TO THE NEXT STATION.

B. Detailed Description of Technical Progress (Experiment)

B.-1 Review of the Proposed Design

One area of concern was a possible biasing in velocity data as caused by concentration gradient of seeding particles between the jet flow and containment flow. As described in the original proposal, the jet flow would discharge into a slow moving "containment" flow, so as to ensure the steadiness of the environment within which the jet is discharging and also to maintain a manageable boundary condition for the jet flow. The problem would arise if the two flows were seeded differently. This is due to the fact that the measurement of instantaneous velocity of the gas phase is done with Laser Anemometer which relies on the seeding particles within the flowfield. To ensure uniform seeding, and hence uniform particle concentration, both the jet flow and the containment flow were designed to have originated from a single source.

Another important criteria concerning the velocity measurement of the glass bead particles (solid phase) using Laser Anemometry is the light collection. The basis of Laser Anemometry measurement of the velocity of a particle is the frequency of the scattered light off such particle as it passes through the crossover point of laser beams (probe volume). The scattered light is then collected through a collection lens and a photomultiplier. The glass beads which are generally of spherical shape have a hollow irregular center. The concern was to determine if the internal refraction of the light beam through the glass beads would effect the results and also to find the optimum collection angle for the solid phase.

A bench test was set up using a fluidized bed containing a small 1/8" diameter jet carrying glass bead particles. A one-color forward scatter Laser Anemometer was set up and velocity measurement and particle sizing measurement using Droplet Sizing Interferometer (DSI) were carried out.

A study of the results revealed that the quality of the signal and the velocity data were independent of the collection angle (even through the intensity of the signal is a function of collection angle). On the other hand, the results regarding the size distribution of the particles showed more scatter when the collection angle was close to 0°. This was attributed to the irregular shape of the hollow center of the glass beads. A collection of 90° was found to be satisfactory as the light collected at this angle is mainly from surface reflection. Another advantage of having collection angle of 90° is the smaller probe volume and, hence, higher spatial resolution.

B.-2 Design of Apparatus

The features of the designed apparatus was mainly determined by the requirements of the theoretical analysis. As was given in the original proposal, the flow of interest was an unconfined vertical axisymmetric turbulent jet lightly loaded with uniform sized spherical solid particles. The designed flow parameters are basically those which are given in the original proposal.

Figure 1 illustrates the basic configuration of the apparatus. The jet air is connected to high pressure (40 psi) air and is discharged through a pipe 90 cm long. The airflow passes through a screen shaker system where particles are added to the flow. The flow of particles are controlled in two stages. A valve at the exit of the hopper controls the gravity feed of the glass bead particles. The particles are then accumulated over a laterally vibrating screen which will be discharged at a rate controlled by the amplitude of the vibration, frequency of the vibration, and the speed of airflow through the screen. The relative mesh size of the screen as compared to the size of the particle is also an important parameter controlling the particle flow rate.

The jet pipe and connected parts are designed to have a variable traversing capability. The jet port can be moved vertically through a distance of 24" (60 cm) and can be accurately positioned relative to pre-marked locations on one of the three stands. The parts which move with the jet pipe are marked in Figure 1.

Shown on the same figure is the containment flow arrangement. The entry port is a 6-inch diameter flexible tube attached to the Plexiglas. A set of stationary honeycomb flow straightener and screen plates moving with the jet pipe will be used to ensure the uniformity of the flow across the containment flow and also low turbulence levels outside the jet. Detailed drawings of various sections of the apparatus are given in Figures 2 - 6.

Figure 2 illustrates the arrangement for the jet and the containment flows. Supply air is 125 cfm at 100 psia which, with the use of flow meters and pressure regulators, are maintained at a constant steady state. The airflow will be seeded with 1 - 3 μ solid particles. This flow will then be divided into jet flow and containment flow. The seeding particle concentration will then be uniform across the jet.

EXPERIMENTAL CONFIGURATION

FIGURE 1. EXPERIMENTAL CONFIGURATION

The detailed design of the vibrating screen assembly is given in Figure 3. The motion of the screen is directly related to the rotation of an off-centered hub assembly attached to the motor shaft. The maximum amplitude of the screen vibration at the hinge is 2 cm and the frequency of vibration can be continuously changed from zero to 4000 rpm. Figure 4 shows a photograph of the assembled vibrator. Downstream of the vibrating assembly, an overflow port is located. This is to collect the excess particles originating from the perimeter of the screen. The diameter of the screen is 4 cm while the diameter of the jet pipe is 2 cm. The entrance of the pipe is located downstream of the screen, collecting the particles originating from the center portion of the screen, which would result in a more uniform particle concentration.

The design drawing of the containment device and the window ports for optical measurements are given in Figure 5. These measurement points at 0° , 90° and 180° are for transmitting optics, receiving optics for glass bead particles and for gas phase measurements, respectively. Vertical traverse will be done by moving the jet exit port and, therefore, measurement level will be held within a horizontal plane. Traversing in the horizontal plane will be achieved through the motion of collecting and receiving optics. Figure 6 shows the design of the base module. The flow field is contracted through a conical section and connected to a recovery system (for the glass beads) before being exhausted.

AIR SUPPLY CONFIGURATION

FIGURE 2. AIR SUPPLY CONFIGURATION

B.-3 Hardware Fabrication

Fabricating various parts are well underway. The vibrating screen mechanism which is a critical component of the particle phase of the experiment has been manufactured and assembled. The calibration of the particle flow rate with and without airflow is being done. These calibration curves will be used to specify the flow rate of the particles. The containment flow cylinder, measurement parts, base module and other components have all been ordered.

IV. WORK IN PROGRESS

A. Mathematical

An examination of the various terms in the time-averaged equations is being carried out with the objective of providing a mathematical model for each term. A set of density-weighted equations is also being derived for variable density flows.

B. Experimental

The assembly of the apparatus is in progress.

V. REFERENCES

1. Hetsroni, G. and Sokolov, M., "Distribution of Mass, Velocity, and Intensity of Turbulence in a Two-Phase Turbulent Jet", J. Applied Mech., Vol. 38, 2, pp. 315-327, 1971.
2. Abramovich, G. N., "The Effect of Admixture of Solid Particles, or Droplets on the Structure of a Turbulent Gas Jet", Soviet Physics - Doklady, Vol. 15, 2, pp. 101-104, 1970.
3. Goldschmidt, V. and Eskinazi, S., "Two-Phase Turbulent Flow in a Plane Jet", J. Applied Mech., Vol. 33, pp. 735-747, 1966.
4. Snyder, W. H. and Lumley, J. L., "Some Measurements of Particle Velocity Autocorrelation Functions in a Turbulent Flow", J. Fluid Mechanics, Vol. 48, Part 1, pp. 41-71, 1971.

Figure 3

ITEM	QTY	PART NO.	DESCRIPTION	DATE	NOTES
1	1	1056D001	VIBRATOR ASSEMBLY	10/1/70	
2	1	1056D002	SHAKER PLATE	10/1/70	
3	1	1056D003	SCREEN CHAMBER	10/1/70	
4	1	1056D004	SPHERICAL 1200 ENDS WITH SLEEVE BEARING INSERTS	10/1/70	
5	1	1056D005	TEE-SLOTTED HUB TO ADJUST SHAKER STROKE	10/1/70	
6	1	1056D006	VARIABLE-SPEED MOTOR 60-1800 RPM RANGE (CONTROL MODULE NOT SHOWN)	10/1/70	
7	1	1056D007	CLAMP-TYPE SHAFT COLLAR 3 EA.	10/1/70	
8	1	1056D008	PARTICLE BY-PASS TUBE WITH FLOW RATE CONTROL AND VACUUM CLEANER BAG FOR COLLECTION OF PARTICLES	10/1/70	
9	1	1056D009	FELT OR FOAM SEAL	10/1/70	
10	1	1056D010	ALUMINUM TOP PLATE	10/1/70	
11	1	1056D011	SCREEN AIR CHAMBER	10/1/70	
12	1	1056D012	FELT, FOAM, OR HORSE HAIR FLOW RESTRICTOR	10/1/70	
13	1	1056D013	PERFORATED PLATE	10/1/70	

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES TOLERANCES ARE: FRACTIONS DECIMALS ANGLES 1/16 0.015 0.10 1/32 0.005 0.10 1/64 0.003 0.10 1/128 0.002 0.10 1/256 0.001 0.10 1/512 0.0005 0.10 1/1024 0.0002 0.10 1/2048 0.0001 0.10 1/4096 0.00005 0.10 1/8192 0.00002 0.10 1/16384 0.00001 0.10 1/32768 0.000005 0.10 1/65536 0.000002 0.10 1/131072 0.000001 0.10 1/262144 0.0000005 0.10 1/524288 0.0000002 0.10 1/1048576 0.0000001 0.10 1/2097152 0.00000005 0.10 1/4194304 0.00000002 0.10 1/8388608 0.00000001 0.10 1/16777216 0.000000005 0.10 1/33554432 0.000000002 0.10 1/67108864 0.000000001 0.10 1/134217728 0.0000000005 0.10 1/268435456 0.0000000002 0.10 1/536870912 0.0000000001 0.10 1/1073741824 0.00000000005 0.10 1/2147483648 0.00000000002 0.10 1/4294967296 0.00000000001 0.10 1/8589934592 0.000000000005 0.10 1/17179869184 0.000000000002 0.10 1/34359738368 0.000000000001 0.10 1/68719476736 0.0000000000005 0.10 1/137438953472 0.0000000000002 0.10 1/274877906944 0.0000000000001 0.10 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FIGURE 4. ASSEMBLED VIBRATING SCREEN

NOTE -

1. MAKE 36" TALL CYLINDER FROM 20 GA. OR HEAVIER STOCK.
2. OUTFLOW DUCT + FUNNEL SECTION CAN BE 26 GA STOCK.

ITEM	QTY	PART NO.	DESCRIPTION	MFR	NOTES
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ARE FRACTIONS DECIMALS ANGLES ± 1/32 ± .01 ± .005 ± .1° ± .5° ± .005					
MATERIAL			GALVANIZED STEEL		
FINISH					
NEXT ASSEMBLY			USED ON		
APPLICATION			DO NOT SCALE DRAWING		
CONTRACT NO.			Spectron Development Labs		
APPROVALS			DATE 1-28-81		
DRAWN			CHECKED		
TITLE			BASE MODULE		
SIZE			CODE		
D			1056 D 112		
SCALE 1/4" X 1"			SHEET 1 OF 1		

Figure 6

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