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
May 1 to October 30, 1981

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MASTER

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MASTER

I. PURPOSE OF REPORT

This report summarizes the work performed during the period May 1 to October 30, 1981.

The mathematical part of the work is described in Section IIA, and the experimental in IIB.

II. PROGRESS TO DATE

IIA. Mathematical Study

Introduction. The mathematical study aims at developing a numerical solution procedure which predicts turbulent two-phase flows. The procedure embodies a new two-equation turbulence model which accounts for the interaction between the two phases.

Exact transport equations of mass and momentum for the two phases, the carrier fluid's kinetic energy of turbulence and its dissipation rate have been derived for incompressible two-phase flows.

The modeling of the various turbulence correlations has been completed. The finite-difference formulation of the equations is in progress at present. An outline of the work completed so far is described in the next section.

Work Completed. During the third and fourth quarters of the project, the following tasks have been completed.

- (1) Modeling the turbulent correlations in the transport equations up to third order.

The exact transport equations contain more than one hundred terms involving second, third and fourth order correlations. An order of magnitude study of each term allowed us to drop all fourth order correlations and some third order ones for high Reynolds number flows. All remaining terms have been modeled following the methods used in single-phase turbulent flows.

- (2) Derivation of the finite-difference form of the modeled momentum equations for both phases.

The modeled momentum equations, which now contain additional correlations involving the fluctuations of the slip velocity and the volume fraction, have been written in a finite-difference form. The independent variables are the axial and radial coordinates in the parabolic flow of a free round jet.

- (3) Testing the model of the correlation $\overline{u_\ell v_\ell}$.

One of the important interactions between the two phases is the correlation between the fluctuating velocities of the two phases, $\overline{u_\ell v_\ell}$, where u_ℓ is the velocity fluctuation of the carrier fluid in the ℓ direction and v_ℓ is the velocity fluctuation of the dispersed phase in the same direction. This correlation appears in the turbulence kinetic energy equation and represents additional dissipation. The modeled form of this correlation involves the ratio of densities of the two phases, particle diameter and the Lagrangian frequency function. Existing experimental data of turbulent two-phase flows in pipes provide excellent means of testing the proposed model. Comparison between the model predictions and the data showed very good agreement.

- (4) Derivation of a relation between the coefficient of momentum transfer and the Reynolds number.

Experiments show that under certain conditions, momentum cannot be transferred from the particle to the surrounding fluid. For example if the particle velocity is higher than the fluid, the particle decelerates and its mean kinetic energy is dissipated in the resulting wake. Other parameters that control this transfer of momentum include the spacing between the particles relative to the boundary layer thickness on the particle surface before separation occurs, the Reynolds number based on the slip velocity and particle diameter. No criterion exists so far for the transfer of momentum from particles to a turbulent fluid. In order to establish such a criterion a numerical study has been completed to examine the turbulent flow over a single sphere. A criterion has been developed for the momentum transfer from the particle to the fluid; validation testing is in progress.

IIB. Experimental Study

The following summarizes the work completed to date on the experimental part of the project which is being performed by Spectron Development, Inc. (under subcontract).

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1.0 INTRODUCTION

The progress of the project in the area of clear air jet measurements (TASK VIIa) and data reduction and analysis (Task VIII) are included in this report.

Using a two-color, bragg cell shifted laser velocimeter, attempts were made to obtain two-dimensional measurements of clear air jet. A complete data set for the streamwise component of mean velocity and turbulence intensity were recorded and are included in this report. Some data for tangential velocity components were also recorded. These data were obtained using a recently modified software package for two-component data acquisition. In the process of the experiment, some software/hardware problems evolved which resulted in incorrect values for shear stress data as well as the tangential velocity samples. The hardware and the software for the coincidence requirement of the two components were modified and the work is presently in progress.

The data for streamwise flow were compared with the available data for circular jet flow. The agreement was good in the inner half of the jet while some scatter were observed in the outer region of the jet.

2.0 CLEAR AIR JET MEASUREMENT (TASK VIIa)

A two-color, bragg cell shifted laser velocimeter using a 0.5 watt Argon-ion laser was used in this experiment. The collection angle was chosen to be about 30° . This reduced the effective size of the probe volume while still allowed a reasonable signal strength and an acceptable level on signal to noise ratio. The transmitting lense had a focal length of 711 mm and the spacing of the beams were 36 mm for a streamwise component (U) and 35 mm for tangential component (W). These resulted in fringe spacing of 10.3 and 10.0 microns respectively. A frequency shift of 1 MHz was used for both components. The probable volume was essentially of cylindrical shape with a length of about 400 microns and a diameter of about 200 microns.

The velocity at the exit of the jet pipe was set at 20 m/s. The Reynold's number, based on the jet pipe diameter of 2 cm, was 26000. The velocity of the containment flow was set at 0.1 m/s. The level of turbulence in the containment flow was measured to be about 6% of the local velocity, which relative to the jet velocity, was less than 0.03%. The flow at the onset of the jet ($X/D = 0.1$) was verified to be that of fully turbulent pipe flow (1/7th power law). These results were reported in the previous quarterly report.

Figures 1a to 1e show additional streamwise mean velocity and turbulence intensity profiles for axial location $X/D = 5, 10, 15, 20,$ and 30. The mean velocity values are given in their dimensional

FIGURE 1a. RADIAL DISTRIBUTION OF STREAMWISE MEAN VELOCITY
AND TURBULENCE INTENSITY ($X/D = 5$)

FIGURE 1b. RADIAL DISTRIBUTION OF STREAMWISE MEAN VELOCITY AND TURBULENCE INTENSITY ($X/D = 10$)

FIGURE 1c. RADIAL DISTRIBUTION OF STREAMWISE MEAN VELOCITY AND TURBULENCE INTENSITY ($x/D = 15$)

FIGURE 1d. RADIAL DISTRIBUTION OF STREAMWISE MEAN VELOCITY AND TURBULENCE INTENSITY ($x/D = 20$)

FIGURE 1e. RADIAL DISTRIBUTION OF STREAMWISE MEAN VELOCITY
AND TURBULENCE INTENSITY ($\lambda/D = 30$)

forms and the turbulence data are non-dimensionalized with respect to $\bar{U}_m$, the mean velocity on the center line. The jet was verified to be axially symmetric and, hence, measurements were mainly made in one side of the jet. A few data points in the other side were also taken to verify the accuracy of the probe position in the radial direction. At the streamwise location close to the jet exit, probe positions were found to be correct. At $X/D \geq 10$, it was necessary to correct the radial position of each data point by 2 mm. This was consistently true for all profiles. There were no other corrections made to the data.

The above mentioned velocity profiles were replotted in a non-dimensional form in Figure 2. The mean velocity profile obtained by Wygnanski and Fiedler (Reference 1) are also included. The profile at $X/D = 5$ shows considerable deviation from the fully-developed profiles. The velocity profiles for $X/D \geq 10$ coincide with the similarity profile in the half-width range. The deviation (and possibly some scatter of data) in the outer half of the jet is more pronounced. Measurement in this region, where the shear layer produces regions of very high turbulence levels, were more difficult. The sudden deviation towards lower velocities at $r/x \approx .12$ may reflect the problem of multiple readings from a single particle. At this location, there are a number of particles with low speed and, therefore, high residence time. With bragg cell frequency shift, this will result in fringe crossings far in advance of the minimum 8-16 required for each sample. Therefore, it is possible to obtain multiple readings from a single particle resulting in a biased

FIGURE 2. MEAN VELOCITY PROFILE

sampling population towards lower moving particles. The problem is under investigation.

The variation of the mean velocity and turbulence intensities along the jet center line are given in Figures 3 and 4. In Figure 3, the inverse of the center line mean velocity, non-dimensionalized with respect to its original value $(\bar{U}_m)_0$, are plotted vs. X/D . The data of Reference 1 are also included. Good agreements in the data are apparent. The level of streamwise turbulence intensities remain relatively constant after $X/D \geq 10$. Figure 4 gives the jet's half-width location for various streamwise stations. After $X/D \geq 10$, these locations follow a straight line whose slope represents the rate of expansion of the half-width location. The slope of this line calculated to be 0.080.

FIGURE 3. VARIATION OF STREAMWISE COMPONENT OF MEAN VELOCITY AND TURBULENT INTENSITY ALONG THE JET CENTER-LINE

FIGURE 4. CIRCULAR JET'S HALF-WIDTH EXPANSION

3.0 SOFTWARE ASSEMBLY (TASK VIIIe)

The software/hardware assembly for the modified two-component data acquisition was finished and tested with idealized doppler burst signals. These systems were fully operational, and the results of the bench tests were satisfactory. However, when the program was used in conjunction with real doppler signals, it was found that the presence of noise in the signal resulted in incorrect communication between the two data management systems (DMS). This, in turn, resulted in a crash of the data acquisition system when coincidence was required.

The debugging of both the hardware and the software is being carried out and should be finished in the near future.

4.0 REFERENCES

1. Wagnanski, I. and Fiedler, H., "Some Measurements in the Self-Preserving Jet," Journal of Fluid Mechanics, Vol. 38, Part 3, pp. 577-612 (1969).