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EFFECT OF INITIAL CONDITIONS ON THE DEVELOPMENT OF TWO-PHASE JETS

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APRIL 1990

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13. ABSTRACT *(Maximum 200 words)*
The results of an experimental investigation into the behavior of an unconfined, steady, fully turbulent, two-phase jet of diameter of 12.7 mm at the exit, with an exit flow velocity of 50 m/s and containing particles with a mass density of loading of 1.5% is described. The second phase consisted of glass beads 80 μm in diameter. Velocity profiles in a plane parallel to the exit of the jet at several downstream stations, as well as the rms values, turbulent intensity and velocity cross correlations were measured for both phases. The radial rms velocities of the particles, although similar to those of the fluid, were found to be surprisingly higher than for a jet of 25.4 mm in diameter with a lower exit velocity. Measurements of the particle velocities were extremely sensitive to changes in the upstream boundary conditions.

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LIST OF ILLUSTRATIONS

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NOMENCLATURE

D	jet pipe diameter
d_p	particle diameter
L	upstream pipe length
l_e	integral length scale
Re_p	particle Reynolds number
r	radial coordinate
S_e	mean Stokes number at jet exit
S_m	mean Stokes number
t_m	time scale of mean flow
t_p	particle time constant
U	streamwise fluid mean velocity
U_0	bulk velocity of fluid at exit
U_{om}	peak streamwise mean velocity of fluid at exit
U_p	streamwise mean velocity of particles
u	streamwise rms velocity of fluid
u_p	streamwise rms velocity of particles
z	streamwise coordinate
ν_f	kinematic viscosity of fluid
ρ_p	particle density
ρ	fluid density

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I. INTRODUCTION

Experimental verification of the predictions of advanced models of the ballistic cycle, Reference 1, lags far behind the results of parametric studies which increased computer power has made available to modelers. Until recently, beside wall temperature surveys and pressure measurements, little of the emerging non-intrusive technologies have been applied to the hostile environment of the flow in a gun tube.

Erosion in gun tubes, where the presence of propellant particles is thought to play a role, is a case in point. Neither the trajectories nor the distribution of the particulates in a fast convecting flow are known with any degree of certainty. The role of the particles in the generation and/or damping of turbulence is also an open issue. In view of the importance of turbulence on the level of heat transfer, this too is a vital, but as yet unresolved question.

Laser Doppler Velocimetry, Particle Image Velocimetry, holographic flow surveys, just to mention a few of the newer technologies have, as yet, found few practicioners in the ballistic diagnostic field. These approaches promise to add considerable information to our understanding of the basic physics of the ballistic cycle. It is with this in mind that the experiments described in this report were undertaken.

The earlier measurements obtained in a two-phase, unconfined jet of 25.4 mm diameter and peak exit velocity of 20 m/s with glass beads of mean diameter of 80 μm at a mass loading of 1.5% are reported in References 2 and 3. This study was undertaken in a similar arrangement comprising a smaller jet of 12.7 mm diameter and a peak exit velocity of 25 m/s laden with the same particles at two mass loadings of 1% and 5%. The results are compared with those of References 2 and 3 to quantify the effect of upstream boundary conditions, more specifically the L/D ratio, on the development of the two-phase jet.

The experimental system and the flow conditions considered are described in the following section. Section 3 presents and discusses the results and the report ends with a summary of the main findings in Section 4.

II. EXPERIMENTAL SYSTEM AND FLOW CONDITIONS

A detailed description of the experimental system is given in Reference 2. Briefly, the jet issued vertically downward from a pipe of 12.7 mm in diameter and 0.56 m in length giving an L/D ratio of 44. The air to the jet was supplied from a blower, controlled by means of a set of valves and monitored by a rotameter. The peak jet velocity at the exit was 25 m/s and the corresponding Reynolds number was around 17,500 based on the exit bulk velocity of about 21.5 m/s. The time scale of the flow at the exit, equation 1, was around 0.6 ms compared to that of the 80 μm glass bead particles of around 50 ms, equation 2.

$$t_m = D/U_0 , \quad (1)$$

$$t_p = d_p^2(1 + 2\rho_p/\rho)/36\nu_f . \quad (2)$$

The resulting mean Stokes number at the exit, Eq. 3, and those at downstream locations defined by Eq. 4 (Reference 4), were always less than unity so that the particles were considered to be unresponsive to the mean flow and a slip between the two phases was expected.

$$S_e = (D/U_0) / t_\rho . \qquad (3)$$

$$S_m = S_e(1/6.57)(z/D)^2 . \qquad (4)$$

The glass beads of 80 μm mean diameter and 2950 kg/m^3 density were introduced in a plenum upstream of the jet pipe by means of a rotating brush/piston assembly at mass loadings of 1% and 5%; the 5% loading represented the maximum limit achievable with this arrangement under present flow conditions. The particle loading was controlled by the speed of the piston driven by a variable speed motor. The size distribution of the glass beads is shown in Figure 1. The majority of the particles had a diameter in the range of 65-90 μm so that the effect associated with polydispersed particles was minimized. For single phase flow measurements the particle disperser was used to seed the flow with titanium dioxide particles of micron size. Velocity measurements obtained with these particles in the absence of glass beads are assumed to approximated those of the carrier phase.

The velocity of the fluid and particle flow was measured by a dual-beam laser Doppler velocimeter operated in back-scatter mode. The detailed characteristics of the optical arrangement are given in Reference 2. When measuring particle velocity, in order to reduce the probability of "cross-talk" due to small particles, both the laser power and the amplifier gain were turned down to reduce the amplitude of the signal from the micron particles by at least a factor of ten. In this way the trigger level of the signal processor was effectively increased by the same factor, thereby reducing the possibility of measuring the amplitude signals which were mainly due to micron size particles.

The effect of the trigger level on the "cross-talk" phenomenon is demonstrated in Figure 2. It shows three velocity pdf's obtained with different trigger-level settings at a downstream location of $z/D = 17$ where the particles were expected to lead the fluid. Increasing the trigger level reduces the probability of lower velocities associated with the carrier phase. For the measurements of particle velocity, therefore, a high trigger-level setting was employed. In addition the test rig was thoroughly cleaned prior to measurements to minimize the residue of titanium dioxide particles.

The major sources of error associated with velocity measurements were due to finite-size statistics and velocity gradient broadening effects; see for example Reference 5. The overall error in the mean velocity is estimated to be of the order of 3% and around 10% for the rms velocity.

III. RESULTS AND DISCUSSION

The velocity results are presented in Figures 3 - 6 in the form of centerline and radial distributions and are all normalized by the peak mean velocity of fluid at the exit, U_{om}. This allows a clear description of the jet velocity decay and also gives a better comparison between the particles and fluid flow velocities.

It was assumed that for the relatively dilute concentrations considered, the single-phase flow results closely approximate those of the carrier phase. The degree of influence of the particles on the carrier phase flow depends on the size and concentration of particles and the slip velocity between the two phases. Reference 6, for example, indicates that for particle diameter to turbulent length scale ratios, d_p/l_e, of 0.001 to 0.1, the change in fluid turbulent intensity caused by the presence of particles is generally small and the results of Reference 4 show almost identical velocity characteristics for the fluid flow with and without the particles at mass loadings up to 20%. It is also expected that for particle Reynolds numbers (see Eq. 5) less than 110 as in the present case ($Re_p < 40$) no vortex shedding downstream of the particle would occur, Reference 7, to enhance the turbulence of the carrier phase.

$$Re_p = (U_p - U)d_p/\nu_f. \qquad (5)$$

Figure 3 shows the centerline distributions of the streamwise mean and rms velocity for the fluid and particle flow mass loadings of 1% and 5%. The glass beads lagged the fluid near the exit. The lag decreased from around 25% at the exit to zero at about z/D = 7. At locations downstream of z/D =7 the particles led the fluid and the lead increased to around 40% at z/D = 19. Increasing particle loading from 1% to 5% had no significant effect on velocity characteristics. With mass loading of 5%, the momentum flow rate of particles is not high enough to cause a significant change in the flow and the particle-to-particle interaction is still negligible at this loading. In parallel with the results of References 3 and 4 the particles rms velocities were higher at the exit, up to 3 times, than the corresponding fluid values mainly due to the "fan-spreading" effect described in those references. Downstream of the exit and as the "fan-spreading" effect diminished, for z/D > 5, the particle rms velocities became lower than those of the fluid since they were unresponsive to both the mean flow and the turbulence. At z/D > 14, however, the two rms values were surprisingly comparable. This may probably be due to the bouncing of the glass beads off the bottom panel of the jet enclosure. This phenomenon needs to be checked, and the use of a PIV technique may provide insight in this respect.

Figures 4 - 6 show the radial profiles of the streamwise mean and rms velocity of the single-phase flow and the particles with 1% mass loading at z/D = 1, 9 and 18 respectively. Consistent with Figure 3, the particle mean velocities near the jet core at z/D = 1 were lower, the rms velocities higher and the profiles flatter than those of the fluid. The particle lag of 25% on the centerline compares with that of 8% with the 25.4

mm jet and a peak exit velocity of 20 m/s of Reference 3. This is partly due to the difference between the two exit Stokes numbers. The exit Stokes number here was 0.01 compared to 0.03 in Reference 3; with lower Stokes number more slip between the phases is expected. The main reason, however, is associated with differences in the two upstream boundary conditions. The L/D ratio in Reference 3 was around 22 as opposed to 44 here and the flow was consequently not fully developed pipe flow observed here.

Figures 5 and 6 are also consistent with Figure 3 and show that the particles led the fluid, the lead was more pronounced at $z/D = 18$ and the particle rms levels were lower at $z/D = 9$ but comparable at $z/D = 18$ to those of the fluid.

IV. CONCLUSIONS

Measurements in an unconfined, axisymmetric jet with 1% and 5% mass loadings of 80 μm particles were carried out by laser Doppler velocimetry and the results compared to those of References 2 and 3 to quantify the effect of upstream boundary conditions on velocity characteristics. The most important findings were as follows:

The particles lagged the fluid by 25% near the exit but later led it by about 40% at 18 jet diameters downstream. The particle rms velocities near the exit were higher by a factor of three than the fluid values due to the "fan-spreading" effect.

The particle lag at the exit was three times more than that of Reference 3 mainly due to the difference between the two upstream L/D ratios. In the present case the L/D ratio was 44 compared to 22 of Reference 3 and consequently the flow in the upstream pipe was more fully developed.

Increasing the particle loading from 1% to 5%, the upper limit achievable with the present system, did not cause any significant effect on the development of two-phase jet.

There are several implications of these results for ballistic submodels. Early on, in their passage down the tube, the particles will be lagging the carrier phase. This trend will reverse as time progresses. This suggests that the particle drag models may need to be reexamined. The particle rms velocities, i.e. turbulence, will be considerably higher than that of the fluid during the initial phase. Clearly, the turbulence of the second phase can not be neglected. The "fan-spreading" effect will influence the migration of the particles, with effect on the boundary layer development and thus the heat transfer to the tube walls. As yet, none of these observations can be deduced from current ballistic models. Their modification is a task which need to be addressed soon.

REFERENCES

1. Horst, A.W., Keller, G.E., Gough, P.S., "New Directions in Multiphase Flow Interior Ballistic Modeling," to appear in Proc. 11th International Symposium on Ballistics.

2. Zoltani, C.K., Bicen, A.F., "Velocity Characteristics of Single-Phase and Particle-Laden Jet Flows," BRL TR-3005, June 1989.

3. Zoltani, C.K., Bicen, A.F. "Velocity Measurements in a Turbulent, Dilute, Two-Phase Jet," to appear in Experiments in Fluids, 1990.

4. Hardalupas, Y., Taylor, A.M.K.D., Whitelaw, J.H., "Velocity and Particle-Flux Characteristics of Particle-Laden Jets," Imperial College, Mech. Eng. Dept. Report FS/87/14, 1987.

5. Durst, F., Melling, A., Whitelaw, J.H., "Principles and Practice of Laser-Doppler Anemometry," 2nd Ed., Academic Press, New York, 1981.

6. Gore, R.A., Crowe, C.T., "Effect of Particle Sizing on Modulating Turbulent Intensity," Int. J. Multiphase Flow, Vol. 15, No. 2, 1989.

7. Hetsroni, G., "Particles-Turbulence Interaction," Int. J. Multiphase Flow, Vol. 15, No. 5, 1989.

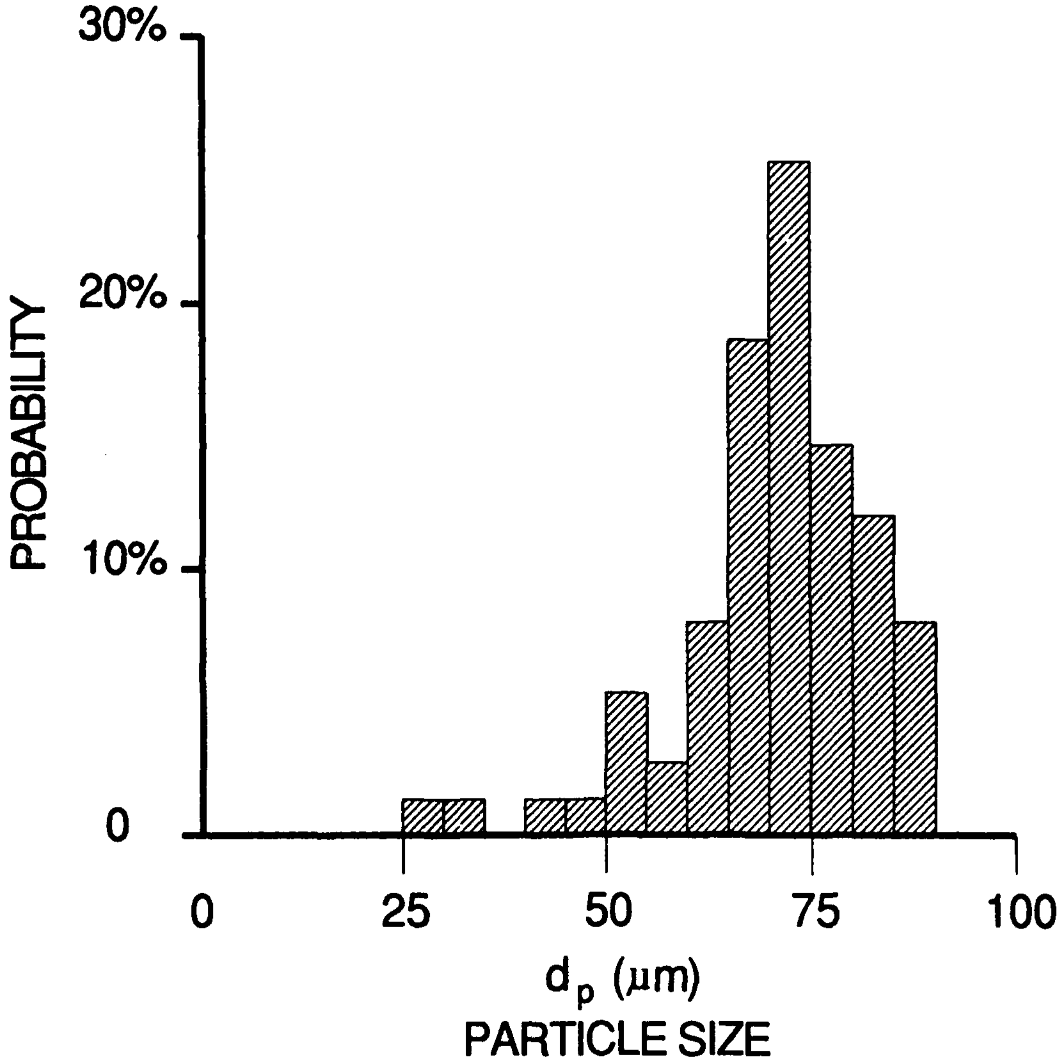

Figure 1. Size distribution of glass beads

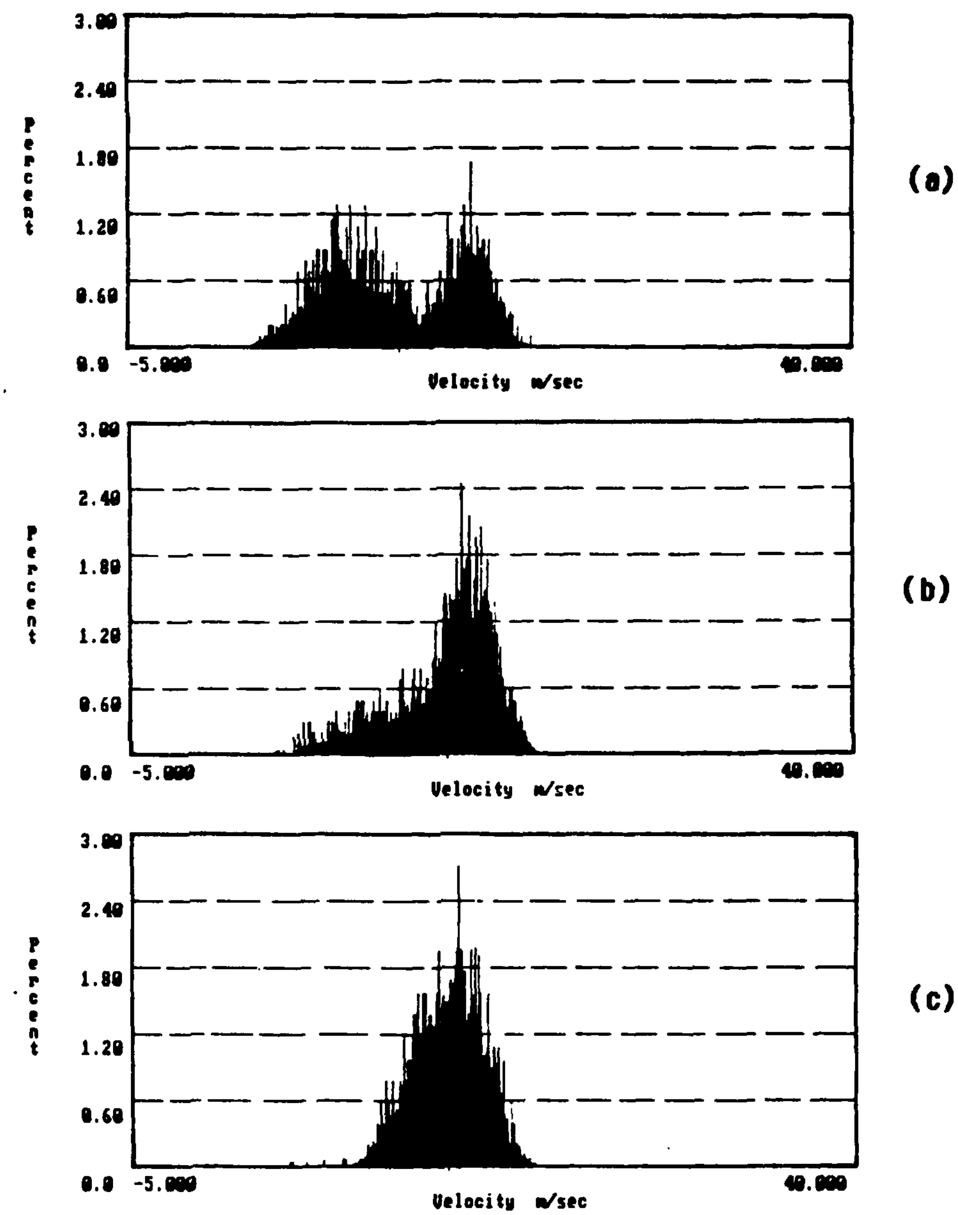

Figure 2. Effect of trigger level on "cross-talk"
(a) low trigger level
(b) medium trigger level
(c) high trigger level

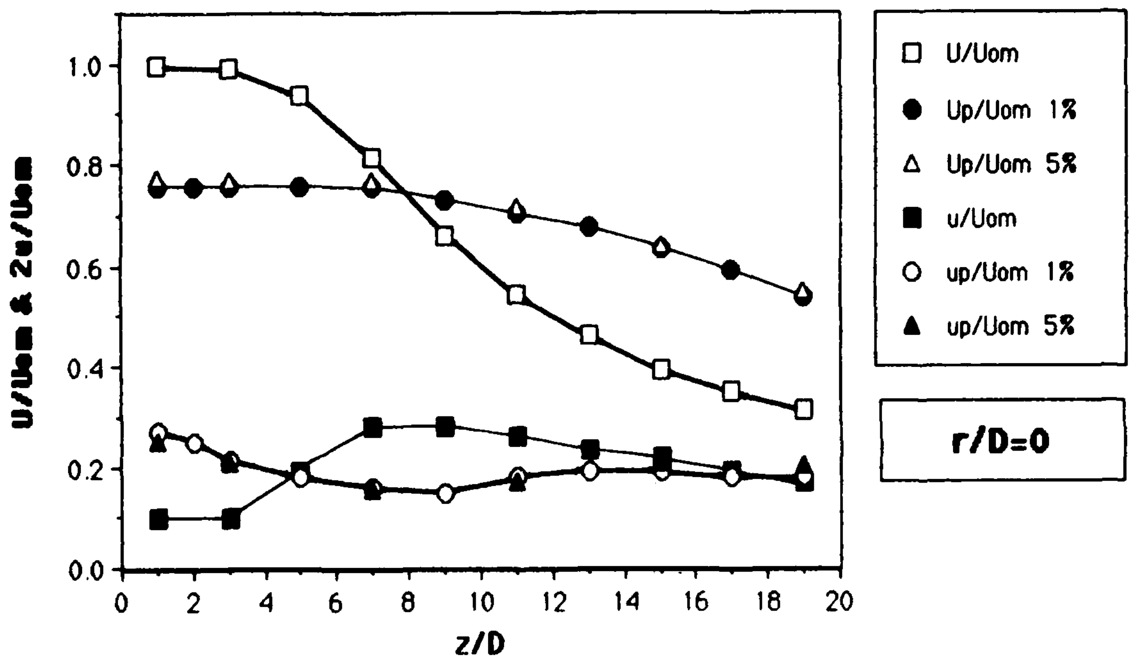

Figure 3. Centerline distributions of streamwise velocities of single-phase and particle flows

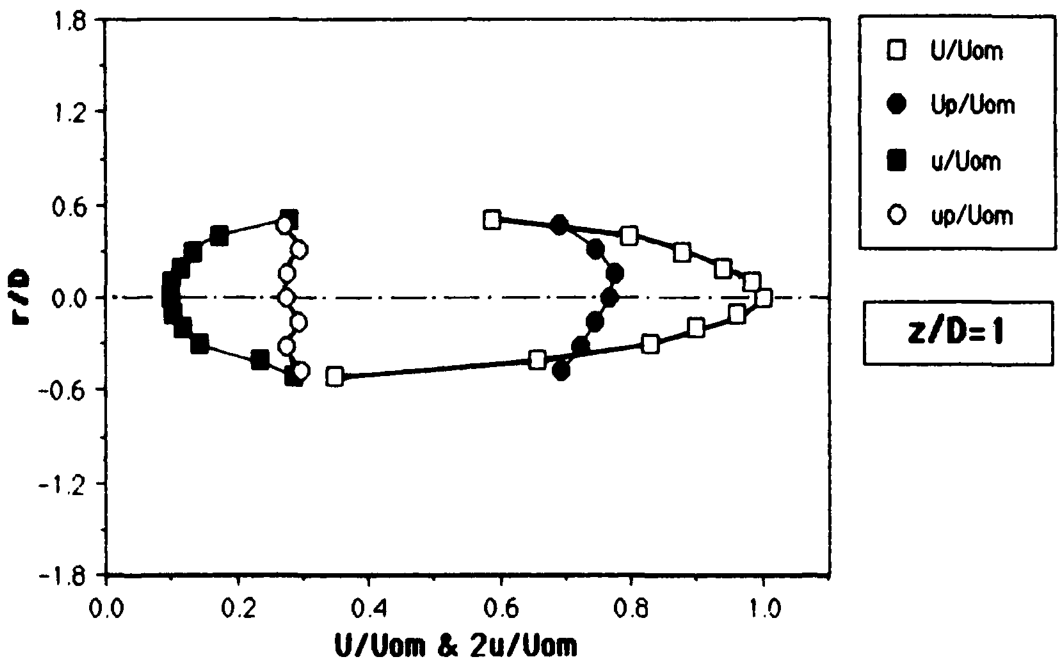

Figure 4. Radial distributions of streamwise velocities of single-phase and particle flows at z =1D

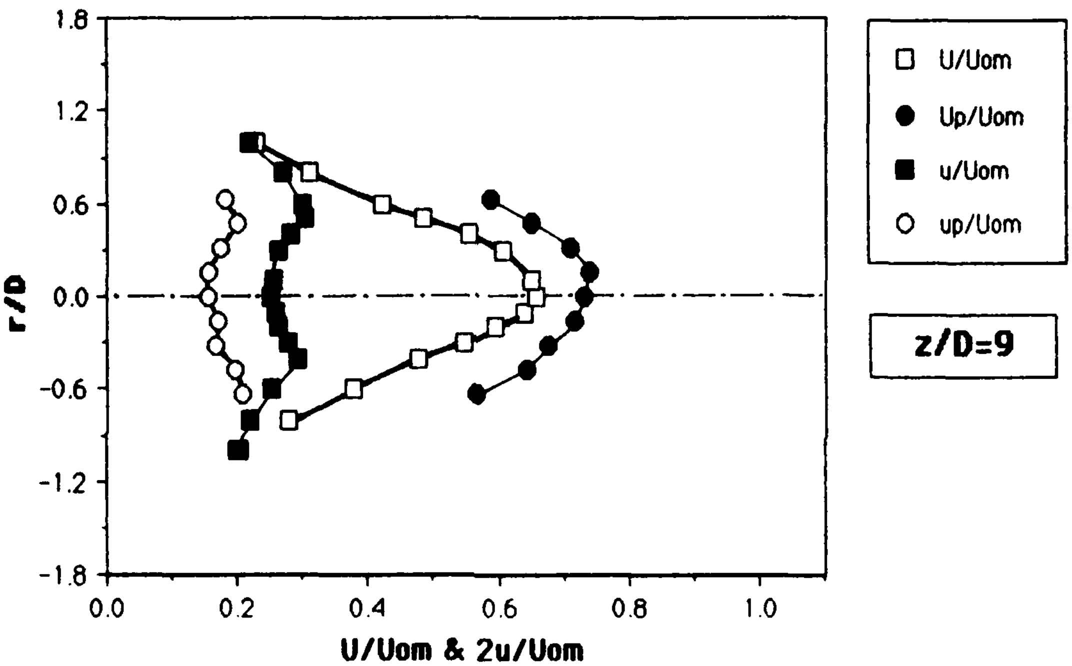

Figure 5. Radial distributions of streamwise velocities of single-phase and particle flows at $z/D = 9$

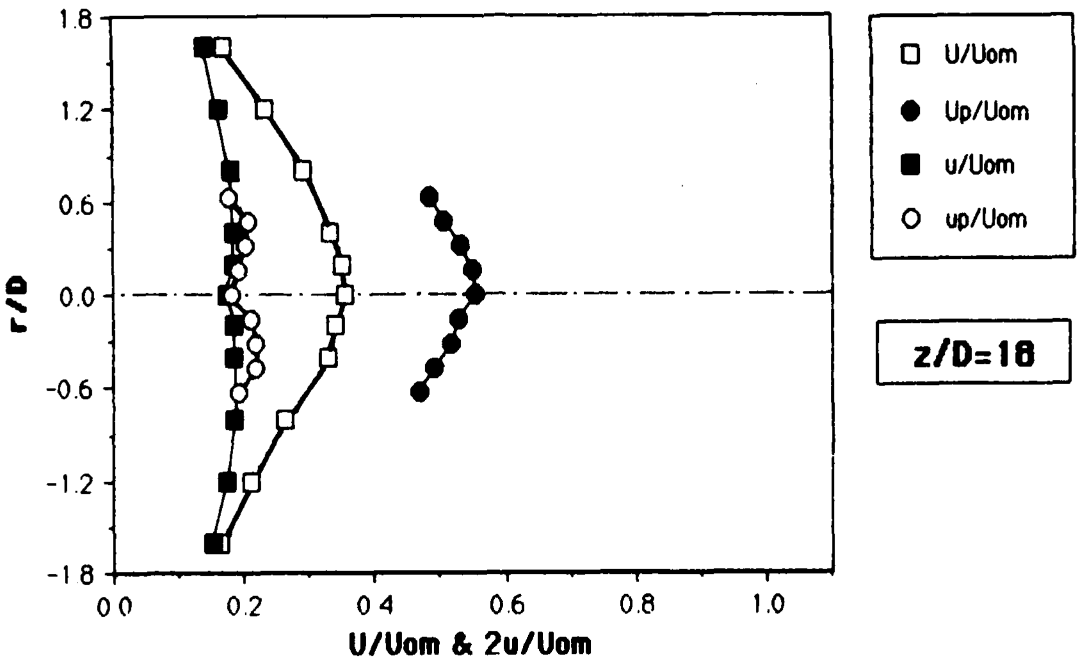

Figure 6. Radial distributions of streamwise velocities of single-phase and particle flows at $z/D = 18$

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