# Experimental Investigation of Confined Turbulent Jets Part II: Particle-Laden Flow Data

C. J. Park* and L.-D. Chen†
*University of Iowa, Iowa City, Iowa*

**A particle-laden coaxial jet in a sudden expansion flow environment was studied. Spherical glass beads (40 μm in diameter) were added to the central jet of the injector. Two flow conditions at two particle mass loadings (mass loading ratios of 0.065 and 0.13) were studied. Mean and fluctuation velocities were measured for the gas phase and particles employing a laser Doppler anemometry technique. The results were compared to the single-phase flow data at comparable conditions. The presence of particles was found to reduce the rate of velocity decay and to increase the recirculation zone length. The velocity fluctuation of particle-laden jets was higher in the near-injector region but lower at downstream locations. The slip velocity between particles and the gas phase existed over the flow domain examined. The gas phase had a higher mean velocity in the near-injector region but a lower mean velocity at downstream locations. The effects of particles on the flow were more pronounced as the particle mass loading was increased.**

## Nomenclature

| | |
|---|---|
| $d$ | = annular jet outer diameter, 25.6 mm |
| $D$ | = chamber diameter, 101.6 mm |
| $L$ | = chamber length, 1016 mm |
| MLR | = particle mass loading ratio at injector exit |
| $p$ | = static pressure |
| $r$ | = distance along radial direction |
| $Re$ | = Reynolds number |
| $u$ | = axial component of fluctuation velocity |
| $U$ | = axial component of mean velocity |
| $x$ | = distance along axial direction |

*Subscripts*

| | |
|---|---|
| $c$ | = centerline |
| $g$ | = gas phase data of particle-laden flow |
| $m$ | = volumetric mean value at injector exit |
| $p$ | = particle phase data of particle-laden flow |
| 0 | = injector exit |

## Introduction

FLOW measurements of particle-laden jets in a sudden expansion flow environment are reported. The objective of the research was to study the effects of particles on the single-phase flow reported in a companion paper.[1] In the present study, spherical glass beads were added to the central jet of a coaxial jet nozzle. The particles had a nearly uniform size and a mean diameter of 40 μm. Two particle mass loadings were considered. The gas- and particle-phase velocities were measured employing a laser Doppler anemometry (LDA) technique. The results were compared with the baseline data,[1] and the effects of particles on the flow were discussed.

Particle-laden flows are common in many engineering systems. Some examples are gas-turbine combustors, rocket exhaust plumes, and pulverized coal furnaces. Data on particle-laden jets were reported—see Refs. 2–4 for free jets and Refs. 5 and 6 for ducted jets and the references cited therein. Earlier studies showed that there exists a velocity lag between particles and the gas phase near the nozzle exit. The spread of the gas phase was faster than particles; as a result, the particle velocity was higher than the gas-phase velocity at downstream locations. The radial velocity profile of the gas phase was found to be narrower than a single-phase jet at comparable conditions. The profiles became narrower when the initial particle mass loading was increased. Particles were also found to increase as well as to decrease the velocity fluctuation, depending on the particle size as compared to turbulence length scales. Small particles tend to suppress the velocity fluctuation, whereas large particles tend to increase the fluctuation.

Studies of particle-laden pipe flows were reported. For example, Tsuji and co-workers conducted LDA measurements of particle-laden flows in horizontal[7] and vertical[8] pipes. The studies[7,8] were concerned with pneumatic conveying of large particles. Solid particles having a mean diameter ranging from 0.2 to 3.4 mm were added to the pipe flow. Detailed measurements of the flow structure were made. The results showed that the gas-phase velocity fluctuation was decreased when small particles were added to the flow, but the fluctuation was increased when large particles were used.

The present work differed from earlier studies[2-8] in that flow recirculation was present in the gas phase. The flow condition was similar to that reported by Stock et al.[9] Their work, however, was concentrated on the development of an LDA technique for gas- and particle-phase velocity measurements; particle mass loading was not specified. The lack of particle mass loading excludes the possibility of using the data for model evaluation. The present work was intended to provide a database for particle-laden jets in recirculation flow and to serve as a database for model evaluation.

## Experimental Methods

The experimental setup was modified from that described in Ref. 1. The modification provided an access for large particles to the central jet of the coaxial jet injector. A brief description of the apparatus is provided here. The apparatus consisted of a coaxial jet injector, a Plexiglas chamber, and particle feeders. The coaxial jet injector was mounted vertically downward at the top of the Plexiglas chamber. The injector has an inside diameter of 12.7 mm, an outer diameter of 25.4 mm, and a wall thickness of 3.1 mm between the inner and outer jets. The Plexiglas chamber has an inside diameter of 101.6 mm and a length of 1016 mm. The apparatus provided satisfactory inlet conditions for the present study, i.e., uniform mean velocity and low turbulent intensity at the injector exit.[1]

Nearly spherical glass beads (Plotter Industries Inc.) having a specified mean diameter of 45 μm were used. Prior to each

Received May 15, 1987; revision received Nov. 15, 1988. 

*Graduate Assistant, Department of Mechanical Engineering; currently Senior Research Engineer, Advanced Engineering and Research Institute, Hyundae Motor Co., South Korea.

†Associate Professor, Department of Mechanical Engineering. Member AIAA.

experiment, the glass beads were sieved carefully using a Ro-Tab Shaker for narrow size distribution, and the particles were then characterized by a particle sizer (Micrometrics Sedigraph Model 5000 ET). The results showed that the sieving yielded a mean diameter of 40 $\mu$m and a tight size distribution. A densitometer (Autopsycomometer Model 1320) was used to measure the density of the glass beads, and a density of 2470 kg/m$^3$ was obtained. The glass beads were spherical in shape, as seen from scanning electron microscope (SEM) micrographs. The SEM micrographs and the particle size distribution can be found in Ref. 10. To introduce the glass beads to the flow, an auger screw particle feeder was designed and installed above the injector section of the test apparatus. The particle feeder was driven by a dc motor, and the rotational speed was monitored by an optical system. The particle mass loading was obtained from the weight measurements using a load cell (Statham Model UC2).

A dual-beam forward-scattering LDA system was used for velocity measurements. The system components and data acquisition were described in Ref. 1. A Bragg cell frequency shifter was used and operated in the 2–10 MHz range. Typical sampling rates were 10–20 kHz for gas-phase measurements and about 5 kHz for particle velocity measurements. Eight thousand data points were taken at a 50 Hz rate for all of the data reported in this paper. Due to particle deposition on the chamber wall, the signal quality deteriorated after 1 h of operation. At this point, experiments were discontinued and the enclosure wall was cleaned.

Compressed air was used in the experiments, and special care was taken to ensure a stable air supply and the same injector exit conditions, e.g., see Ref. 1. Two flow conditions were studied. One condition had an equal velocity at the injector exit of the central and annular jets (flow I), and the other had a higher velocity (twice that of the annular jet) at the central jet exit (flow II). Flow I had a Reynolds number of 9400 at the central jet exit (based on the air viscosity, mean velocity of 11.4 m/s, and a diameter of 12.7 mm) and a Reynolds number of 6900 at the annular jet exit (mean velocity of 11.4 m/s and hydraulic diameter of 9.6 mm). The corresponding Reynolds numbers for flow II were 18,800 and 6,900 for the central and annular jets, respectively. Two particle mass loadings—mass loading ratio (MLR) = 0.065 and 0.13—were considered. The particle MLR was defined as the ratio of particle mass flow rate to air flow rate.

When measuring air flow velocity, submicron alumina particles were seeded to the flow. When particle velocities were desired, only glass beads were added to the flow. At this condition, the burst counter and photomultiplier were set at low gain settings to remove signals from residual and dust particles in the air supply. When the gas-phase velocity was desired, both LDA seeding particles and glass beads were present in the flow. As a result, a measure was needed to reject signals from large particles. The LDA system was operated at high gains of the burst counter and photomultiplier. The amplitude limit of the burst counter was adjusted to reject signals from large particles while validated signals from alumina seeding particles were recorded. To reduce the uncertainty in gas-phase measurements, different combinations of gain setting and amplitude limit were tested. Combinations were determined to be successful when no LDA signals were realized by the counter at the termination of the alumina seeding, although glass beads were still present in the flow.

It is recognized that the cross-talk error in the present study cannot be eliminated completely, and a better scheme was described in Refs. 5 and 6. The dilute mass loading (MLR = 0.065 and 0.13) and high alumina seeding levels provided a less stringent condition for the present study. The worst cross-talk ratio was estimated at 30% at the injector exit for flow II at MLR = 0.13 by following the method described by Modarress and Tan.[5] The uncertainty in gas-phase measurements resulting from the 30% cross-talk ratio was 15% for the mean velocity, assuming a 50% slip velocity based on measured gas-phase quantities. The 30% cross-talk ratio was the worst condition studied in this paper, i.e., flow II at the injector exit. The cross-talk error was reduced at downstream locations, where the local MLR was lower. The cross-talk error was also lower for flow I due to lower central jet velocity. The worst repeatability of the measurements was found to be within ±10% of the data reported in this paper.

## Results

Gas- and particle-phase velocities were measured for two flow conditions (flows I and II) at two particle mass loadings (MLR = 0.065 and 0.13). The single-phase data and prediction at comparable flow conditions were also included in the figures presented here. The single-phase results were taken from Ref. 1 for comparison purposes. In the discussion herein, the gas- and particle-phase data are referred to the gas- and particle-phase measurements of particle-laden flows, respectively.

### Axial Profile

The axial velocity profiles are summarized in Figs. 1–4. The presence of large particles had an immediate effect on the gas phase at the injector exit, i.e., the chamber inlet. At that location, the gas phase velocity ($U_{gc}$) was found to be lower than that of the single-phase flow ($U_c$). This was due to particles entering the injector at a velocity lower than the local gas flow. While particles were accelerated through the injector section, the gas phase was decelerated, resulting in a lower velocity at the injector exit. However, kinematic equilibrium was not reached at the injector exit. The particle-phase velocity ($U_{pc}$) was found to be lower than the gas-phase velocity. The nonequilibrium between the two phases was confirmed by integrating the equations of motion for 40-$\mu$m spherical particles passing through the injector section. The results showed that particles entered the chamber at 8.2 and 13.0 m/s for flow I and flow II conditions, respectively. The preceding calculation assumed a zero particle velocity at the injector inlet and stand-

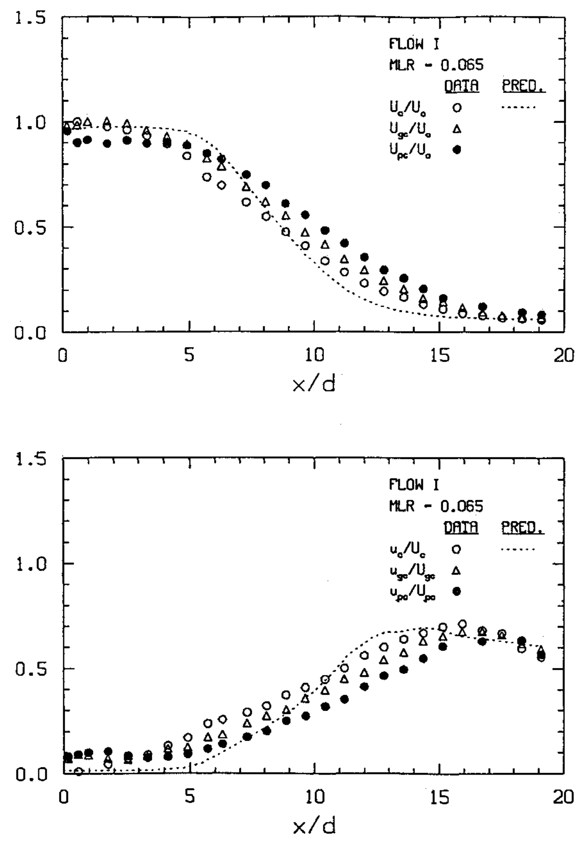


Fig. 1 Axial profiles of flow I with a solid mass loading ratio of 0.065.

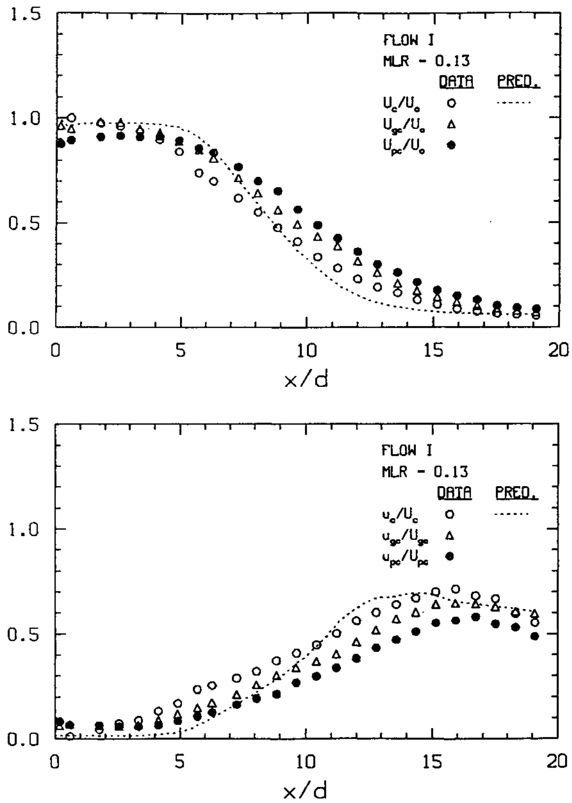


Fig. 2 Axial profiles of flow I with a solid mass loading ratio of 0.13.

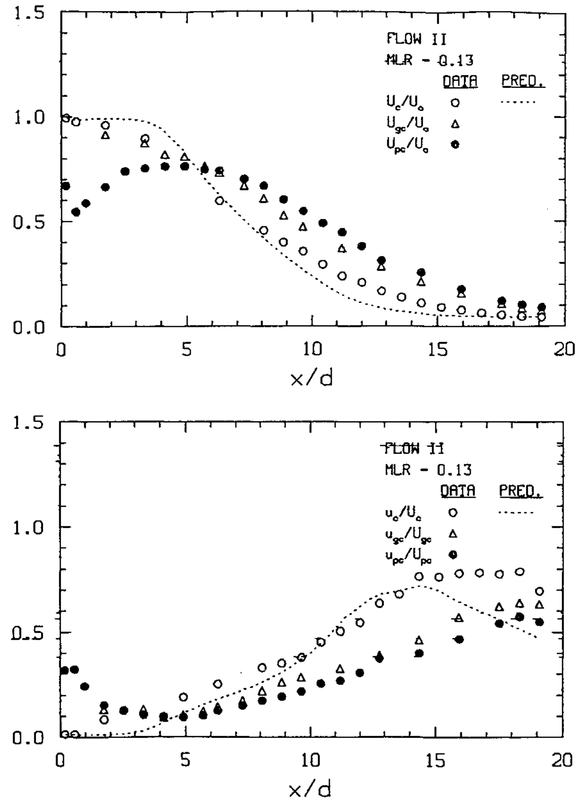


Fig. 4 Axial profiles of flow II with a solid mass loading ratio of 0.13.

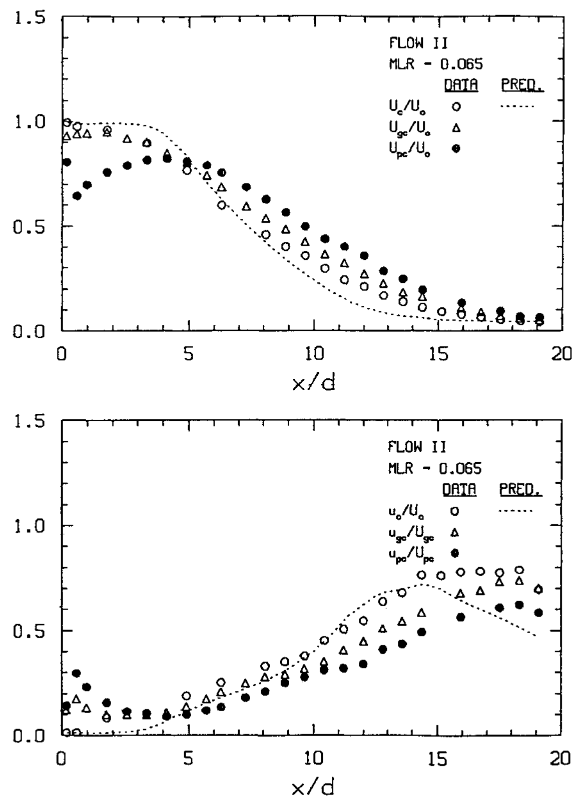


Fig. 3 Axial profiles of flow II with a solid mass loading ratio of 0.065.

ard drag coefficients for spherical particles.[10] The calculated slip velocity ($U_{gc} - U_{pc}$) agreed with the experimental data. The slip velocity increased when the central jet velocity or particle mass loading was increased, e.g., see Figs. 1–4.

Leaving the injector, particles were accelerated by the gas flow until the end of the potential core was reached. The slip velocity was reduced gradually and reached a minimum near the end of the potential core, e.g., $x/d \approx 5$. Beyond the potential core, the gas-phase velocity was decreased due to the spread of the central jet and entrainment of the lower velocity annular air. Large particles, however, cannot follow the flow; thus, the rate of the velocity decay was slower than the gas phase. In the region $3 < x \times d < 15$, the gas-phase velocity at the centerline became higher than that of the single-phase flow at comparable conditions. This was due to the reduced spread of the central jet and momentum transfer from particles. In this region, the particle phase has a higher velocity than the gas phase. Further downstream, e.g., $x/d > 15$, the velocities of the particle phase and the gas phase approached that of a single-phase flow. The particles, however, still had a higher velocity than the gas phase.

The presence of particles appeared to suppress the flow turbulence, except at locations immediately downstream of the injector. In the near-injector region, the particle-laden flow showed a higher turbulence intensity for both the particle phase and the gas phase, compared to single-phase flow data. At downstream locations, e.g., $x/d > 2$, the particle-laden flow had a lower gas-phase fluctuation velocity than the single-phase flow. The effects of particles on flow turbulence can be explained as follows. The large slip velocity and the nonlinear interaction between particles and the flow probably were responsible for the high gas-phase turbulence intensity in the near-injector region. The nonlinear interaction can be quantified following the model developed by Shuen et al.[2] The turbulence length scale in the near-injector region may be smaller than the particle size since the length scale was limited by the thin shear layer from the nozzle. The interaction between particles and the flow thus favored the production of flow turbulence in the near-injector region. At downstream locations, the growth of the shear layer resulted in a length scale approaching the radius of the injector. As a result, turbulence modulation was seen.

The data presented in Figs. 1–4 were rearranged and plotted in Figs. 5–8 to illustrate the effects of particle mass loading on the flow. The mean velocities ($U_{gc}$ or $U_{pc}$) were normalized by the single-phase axial velocity at the injector exit ($U_0$), and the fluctuation velocities ($u_{gc}$ and $u_{pc}$) were normalized by local centerline velocities ($U_{gc}$ or $U_{pc}$). The variation in particle mass loadings did not seem to qualitatively vary the gas-phase and particle-phase velocities for the conditions examined. Quantitative variations in velocities, however, were measured. In the near-injector region, $x/d<5$, the slip velocity between the two phases increased as the particle mass loading was increased. The normalized fluctuation velocities ($u_{gc}/U_{gc}$ and

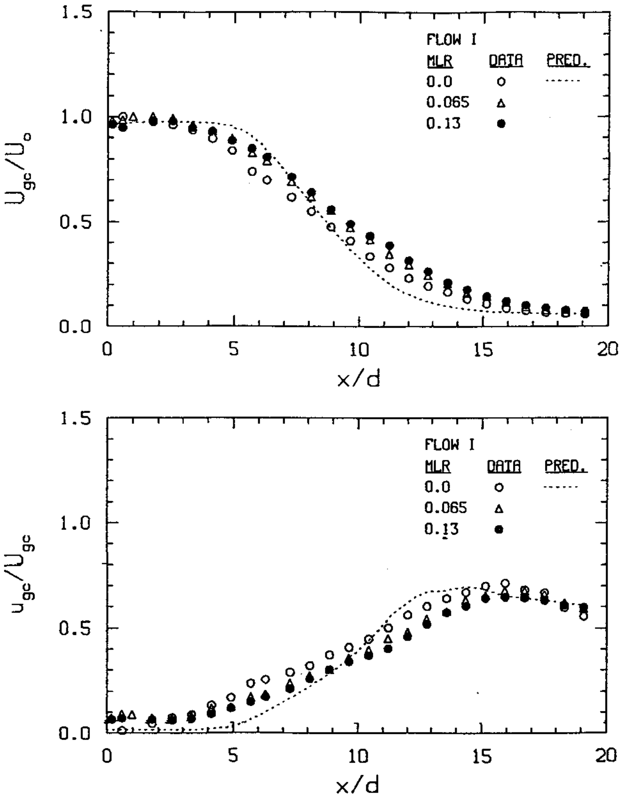


**Fig. 5 Effects of gas-phase mean and fluctuation velocities of flow I due to different mass loading ratios.**

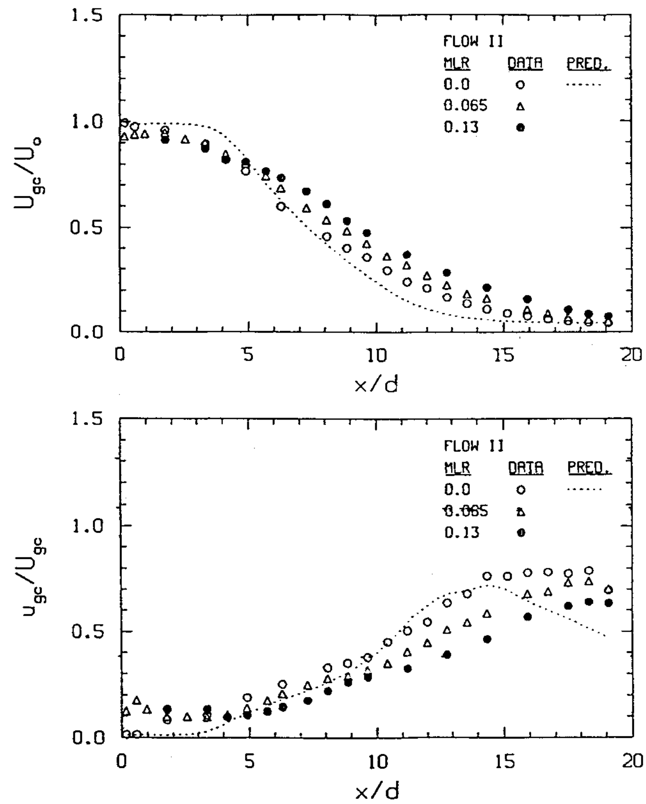


**Fig. 6 Effects on gas-phase mean and fluctuation velocities of flow II due to different mass loading ratios.**

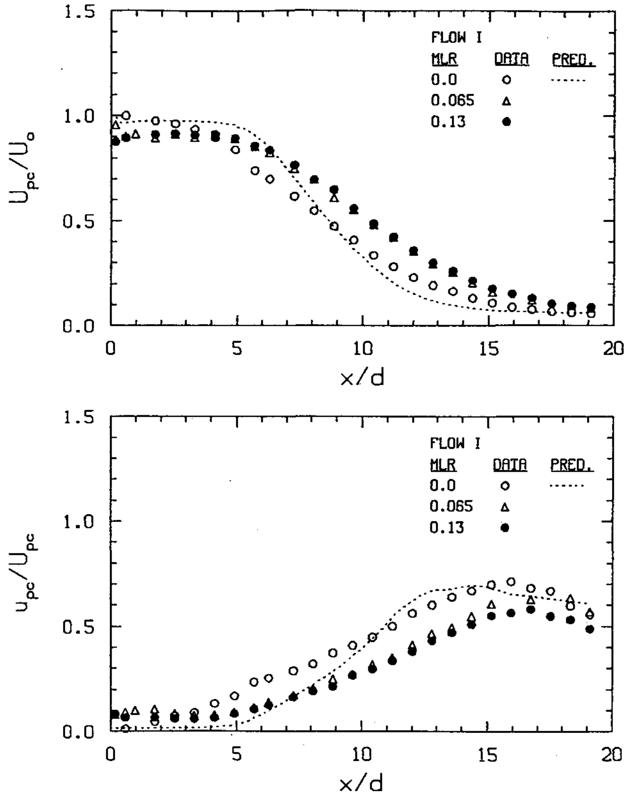


**Fig. 7 Effects on particle-phase mean and fluctuation velocities of flow I due to different mass loading ratios.**

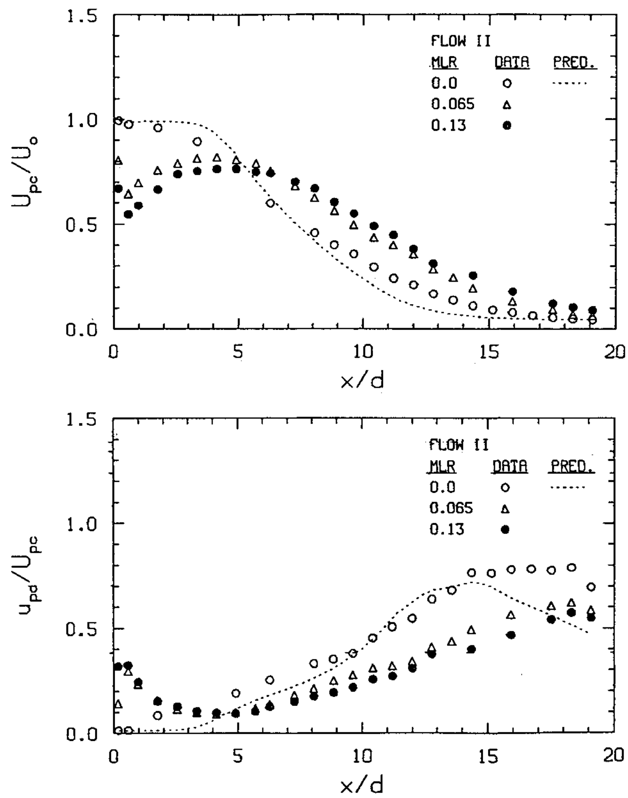


**Fig. 8 Effects on particle-phase mean and fluctuation velocities of flow II due to different mass loading ratios.**

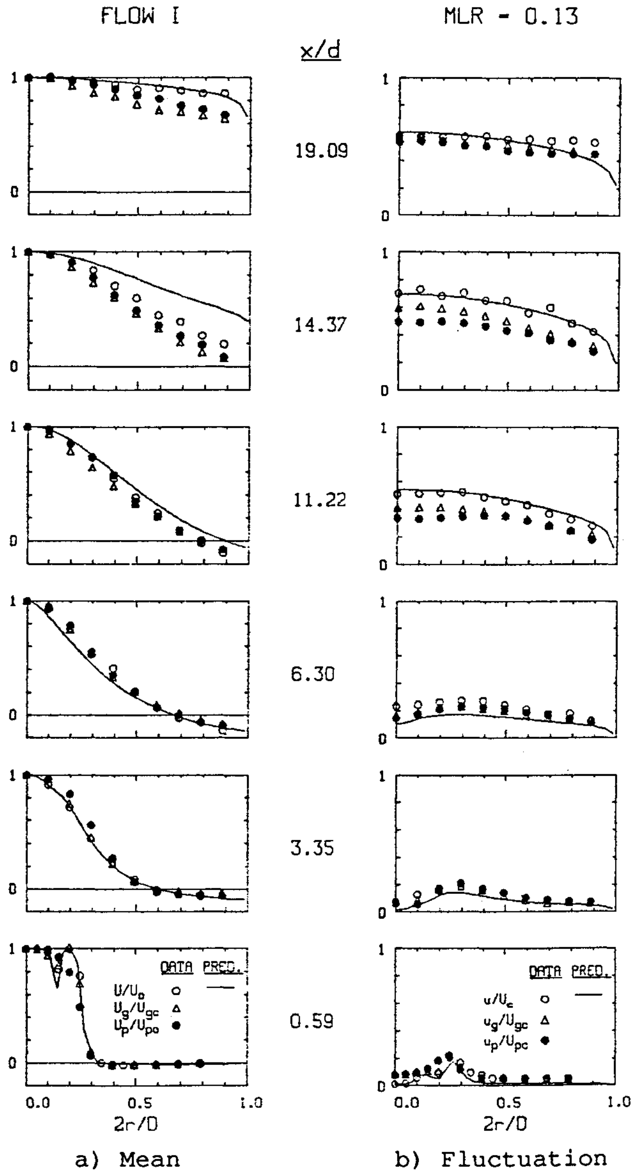


**Fig. 9 Radial profiles of mean and fluctuation velocities of flow I with a mass loading ratio of 0.13.**

$u_{pc}/U_{pc}$) were similar to, but higher than, the single-phase data. At downstream locations, $5 < x/d < 15$, both the gas phase and particle phase experienced a higher mean velocity but a lower normalized fluctuation velocity when the particle loading was increased. The reduced rate of the central jet spread and reduced turbulent diffusion probably were responsible for the measured higher mean velocities and lower velocity fluctuations.

### Radial Profile

Radial profiles of the axial mean and fluctuation velocities for flow I and flow II at MLR = 0.13 are shown in Figs. 9 and 10, respectively. In the figures, the gas-phase and particle-phase velocities were normalized by the mean velocities of each respective phase. Near the injector exit, $x/d = 0.59$, the gas-phase velocity ($U_g$) exhibited a velocity defect similar to that observed in single-phase flow.[1] The wake effect was a result of the finite wall thickness of the central jet injector. The wake effect, however, was not observed in particle-phase velocity, e.g., see Fig. 9. This was not surprising since particles were added only to the central jet of the flow, and the particles could not respond to the gas phase momentarily. In the near-injector region, $x/d \leq 3.35$, the normalized profiles for the gas phase and particle phase were similar (Figs. 9 and 10);

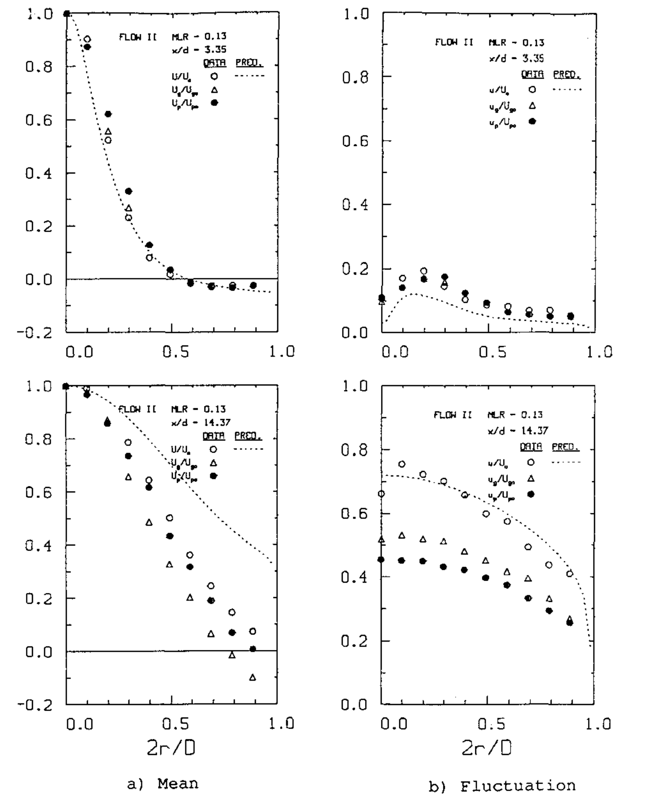


**Fig. 10 Radial profiles of mean and fluctuation velocities of flow II with a mass loading ratio of 0.13.**

the slip velocity between the two phases was quite large, however. Recall that the velocities were normalized by the centerline velocities of each respective phase. At the chamber centerline, substantial slip velocities were measured. The flow I radial profiles of normalized velocities $U_g/U_{gc}$ and $U_p/U_{pc}$ were qualitatively similar for $x/d$, up to 11.22, suggesting that the centerline mean axial velocity could be used as a scaling parameter even for flows with recirculation. This was also observed for flow II at $x/d = 3.35$, although less satisfactory results were obtained at radial locations where there existed a steep velocity gradient, e.g., $0.2 < 2r/D < 0.3$.

At locations near the flow reattachment, $x/d = 14.37$, the deviation in normalized mean velocities ($U_g/U_{gc}$ and $U_p/U_{pc}$) was larger than that at other locations, e.g., see Figs. 9 and 10. At $x/d = 14.37$, the single-phase flow had a flatter mean velocity profile than the particle-laden flow, suggesting the single-phase flow had a shorter reattachment length. At $x/d = 19.08$, a more uniform mean velocity profile was found in the single-phase flow. This is reasonable, since at centerline locations the particle-laden flow had higher velocities (both gas phase and particle phase) than the single-phase flow. As a result, only a narrower velocity profile can satisfy the conservation of momentum.

The normalized fluctuation velocities ($u/U_c$, $u_p/U_{pc}$) were qualitatively similar, as shown in Figs. 9 and 10. Near the injector exit, $x/d = 0.59$, the particle-phase velocity fluctuation was higher than the gas phase. At downstream locations, the presence of particles seemed to suppress the velocity fluctuation similar to that observed at centerline locations. Turbulent intensities, however, were quite high for particle-laden flows, especially near the flow reattachment, e.g., at $x/d = 14.37$. The velocity fluctuations at the centerline reached 0.6 ($u_g/U_{gc}$) and 0.5 ($u_p/U_{pc}$) for flow I (Fig. 9) and 0.5 ($u_g/U_{gc}$) and 0.45 ($u_p/U_{pc}$) for flow II (Fig. 10). This level of fluctuation was higher than that observed in free jets. It appeared that the centerline mean velocities of each respective phase can be used as the scaling velocities to yield similar radial profiles. The normalized gas-phase and particle-phase mean and fluctuation velocities were similar, although substantial slip velocities existed between the two phases and a less satisfactory result was seen near the flow attachment.

## Summary and Conclusions

A particle-laden coaxial jet in a sudden expansion flow environment was studied, and two flow conditions were considered. One condition had an equal velocity at the injector exit of the central and annular jets (flow I), and the other had a higher velocity (twice that of the annular jet) at the central jet exit (flow II). Nearly spherical glass beads having a mean diameter of 40 $\mu$m were added to the central jet of the flow. Two particle mass loadings were considered, MLR = 0.065 and 0.13. The mean and fluctuation velocities were measured for both the gas phase and particle phase. The results were compared with the single-phase data reported in a companion paper.[1]

Adding particles to the flow was found to reduce the rate of the velocity decay for the gas phase and to increase the recirculation zone length. Substantial slip velocities were observed between the gas phase and particles over the flow domain studied, especially at locations near the injector exit. When compared to the gas phase, particles had a lower mean velocity in the near-injector region but a higher velocity at downstream locations. The presence of particles was found to increase the velocity fluctuation of the gas phase in the near-injector region, $x/d < 5$, but the fluctuation was reduced at downstream locations. These effects became more pronounced when the particle mass loading was increased. The effects of particles on confined flows were similar to those observed in particle-laden free jets.

To advance the understanding of particle-laden flows in coaxial dump combustor environments, a higher particle mass loading is of interest, although the mass loading ratio considered in the present study corresponds to a typical stoichiometric condition for hydrocarbon fuels (in terms of fuel-to-air ratio) and also twice of that stoichiometric condition value. To advance our knowledge of spray combustion, the experiment can be extended to evaporating and combusting sprays. Further experiments are needed to quantify the mixing between the two streams, three-dimensionality of the turbulent structure, and evaporation and burning rates of fuel drops in high-temperature recirculation flows.

## Acknowledgments

This research was supported in part by the National Science Foundation under Grant CPE-8307141. Dr. R. E. Rostenbaugh was the program manager. The authors also acknowledge support from the College of Engineering in equipment.

## References

[1]Park, C. J. and Chen, L.-D., "An Experimental Investigation of Confined Turbulent Jets, Part I: Single-Phase Data," *AIAA Journal* (in press).

[2]Shuen, J.-S., Solomon, A. S., Zhang, Q.-F., and Faeth, G. M., "Structure of Particle-Laden Jets: Measurements and Predictions," *AIAA Journal,* Vol. 23, March 1985, pp. 396–404.

[3]Levy, Y. and Lockwood, F. C., "Velocity Measurements in a Particle Laden Turbulent Free Jet," *Combustion and Flame,* Vol. 40, No. 3, 1981, pp. 333–339.

[4]Fleckhaus, D., Hishida, K., and Maeda, M., "Effect of Laden Solid Particles on the Turbulent Flow Structure of a Round Free Jet," *Experiments in Fluids,* Vol. 5, No. 5, 1987, pp. 323–333.

[5]Modarress, D. and Tan, H., "LDA Signal Discrimination in Two-Phase Flows," *Experiments in Fluids,* Vol. 1, No. 3, 1983, pp. 129–134.

[6]Modarress, D., Tan, H., and Elghobashi, S., "Two-Component LDA Measurement in a Two-Phase Turbulent Jet," *AIAA Journal,* Vol. 22, May 1984, pp. 624–630.

[7]Tsuji, Y. and Morikawa, Y., "LDV Measurements of an Air-Solid Two-Phase Flow in a Horizontal Pipe," *Journal of Fluid Mechanics,* Vol. 120, July 1982, pp. 385–409.

[8]Tsuji, Y., Morikawa, Y., and Shiomi, H., "LDV Measurements of an Air-Solid Two-Phase Flow in a Vertical Pipe," *Journal of Fluid Mechanics,* Vol. 139, Feb. 1984, pp. 417–434.

[9]Stock, D. E., Jurewicz, J. T., Crowe, C. T., and Eschback, J. E., "Measurement of Both Gas and Particle Velocity in Turbulent Two Phase Flow," *Proceedings of the Fifth Symposium on Turbulence,* 1977, University of Missouri-Rolla, Science Press, pp. 91–102.

[10]Park, C. J., "An Investigation of Particle-Laden Flows in a Simulated Dump Combustor," Ph.D. Dissertation, Univ. of Iowa, Dept. of Mechanical Engineering, Iowa City, IA, 1987.