Structure of Ducted Particle-Laden Turbulent Jets

Q-F. Zhang,* J-S. Shuen,† A.S.P. Solomon,†
and G. M. Faeth‡
The Pennsylvania State University
University Park, Pennsylvania

Introduction

BOTH new and existing measurements were recently used in this laboratory to develop and evaluate models of particle-laden jets and sprays, yielding encouraging results for a stochastic separated flow (SSF) model which treats effects of interphase slip and turbulence using random-walk computations of particle (drop) motion.[1-4] At the same time, Modarress et al.[5,6] also reported new measurements within ducted particle-laden jets which were used to evaluate a different model proposed by Elghobashi and Abou-Arab[7] with some success. The purpose of this Note is to describe evaluation of the SSF model of Refs. 1-4 using the data of Modarress et al.[5,6] so that both methods of analysis can be compared on a common basis.

Data Base

Modarress et al.[5,6] considered a 20-mm-diam particle-laden jet directed vertically downward in a coflowing airstream within a 600-mm-diam cylinder. The initial air velocity of the jet was 12.6 m/s with coflow velocities of 0.05 and 0.10 m/s. Outflow from the cylinder was discharged through an exhaust duct.

The experiments considered a pure air jet as well as particle-laden jets with particle diameters d_p of 50 and 200 μm and initial particle loading ratios ϕ_0 (the mass flow rate of particles per unit mass flow rate of air) in the range 0.32-0.85. Mean and fluctuating velocities of both phases were measured at the jet exit and within the cylinder using laser Doppler anemometry (LDA). Some information concerning particle concentration profiles was also reported.

Theoretical Methods

Three models of particle-laden jets were considered in Refs. 1-4: 1) a locally homogeneous flow (LHF) model, where slip between the phases is neglected; 2) a deterministic separated flow (DSF) model, where slip is considered but particles only interact with the mean motion, neglecting effects of turbulent fluctuations and dispersion; and 3) the SSF model, where effects of interphase slip and turbulent fluctuations are considered using random sampling for turbulence properties in conjunction with random-walk computations for particle motion. All three models use a k-ϵ turbulence model which was evaluated extensively for constant- and variable-density jets in this laboratory over the past 10 years, cf., Refs. 1-4 and 8 and references cited therein. The present study concentrated on the SSF model, since the LHF and DSF models were relatively unsuccessful over the original data base.[1-4] The SSF model considered here follows a proposal by Gosman and Ioannides,[9] but differs in some details.[1-4] Versions both ignoring (SSF model) and considering (SSFM model) effects of particle source terms in the k and ϵ equations were examined, since the latter feature was treated by the Elghobashi and Abou-Arab model. The source term in the ϵ equation is modeled in a way consistent with conventional k-ϵ models, but this introduces one new empirical constant, $C_{\epsilon 3}$, which is not known accurately. For the flows considered here, however, the computations were relatively insensitive to $C_{\epsilon 3}$ (values between 0 and 5 giving essentially the same result to the scale of the following figures), since the effect of turbulence modulation was dominated by the source term in the k equation. A full description of the models and the numerical computations can be found in Ref. 3.

Results and Discussion

Air Jet

The test configuration of Modarress et al.[5,6] requires extreme care in the operation of the exhaust and coflow systems to avoid the development of a pressure gradient in the cylinder and to avoid recirculation zones near the jet boundary due to inadequate supply of coflow air to meet jet entrainment requirements. Since static pressure measurements along the duct were not available, computations using the present model were made for the pure air jet conditions, while imposing a range of axial pressure gradients. Predictions and measurements of mean centerline velocities are summarized in Table 1. It is evident that without imposition of a small negative pressure gradient, the model significantly overestimates the rate of centerline velocity decay; therefore, a range of pressure

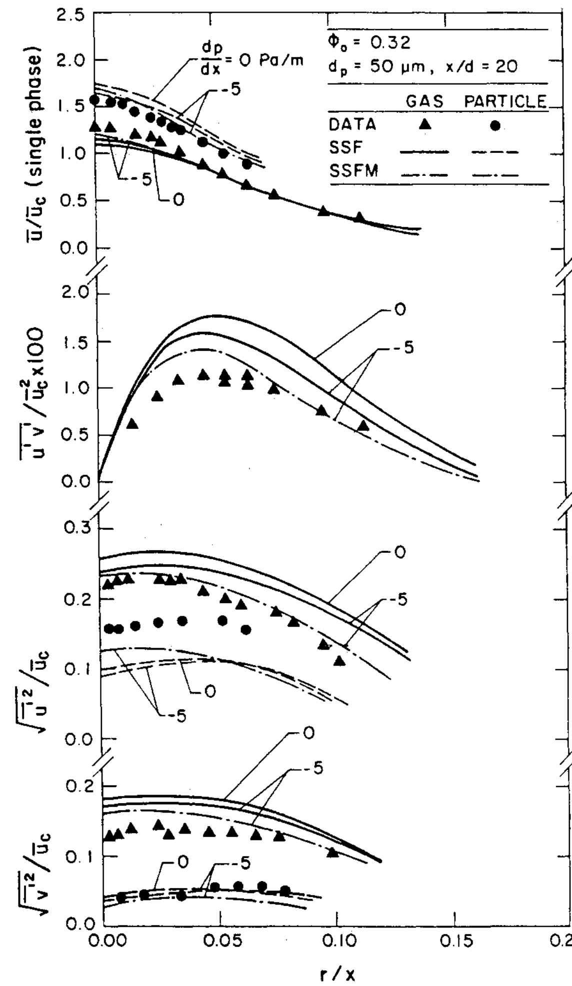

Fig. 1 Flow properties at $x/d = 20$, $d_p = 50$ μm, and $\phi_0 = 0.32$. Data of Modarress et al.[5,6]

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*Adjunct Lecturer, on leave from Department of Aero-Engine, Nanjing Aeronautical Institute, Nanjing, China.
†Research Assistant, Department of Mechanical Engineering.
‡Professor, Department of Mechanical Engineering. Member AIAA.

gradients was considered, parametrically, during the particle-laden jet calculations.

The potential presence of recirculation zones was also investigated. It is known that when the coflow is exceeded by the entrainment requirements of a jet in a confined duct, the balance is satisfied by recirculated fluid. Entrainment calculations based on the empirical expressions of Abramovich[10] showed that all of the coflow air was entrained at $x/d = 14$ and 26 for coflow velocities of 0.05 and 0.10 m/s, where x is the distance from the jet exit and d the initial jet diameter. These results were checked using the results of Becker et al.[11] which located the front edge of the recirculation zone at $x/d = 15$ and 24 for the same coflow conditions. Specific locations may have been different for the tests of Refs. 5 and 6, due to effects of multiphase flow and pressure gradients, but it appears to be prudent to limit model evaluation to the measuring station nearest to the injector, $x/d = 20$, while ignoring effects of recirculation zones since the data presented by the authors did not show flow reversal near the jet boundary at this station.

Particle-Laden Jets

Predicted and measured flow properties at $x/d = 20$ are illustrated in Fig. 1 for a jet having a particle diameter of 50 μm and a loading ratio of 0.32. Mean and fluctuating streamwise velocities $\bar{u}$ and $(\overline{u'^2})^{1/2}$ and the fluctuating radial velocity $(\overline{v'^2})^{1/2}$ of both phases, as well as the gas phase Reynolds stress, are shown as a function of radial distance r with $\bar{u}_c$ denoting mean centerline velocity. Predictions of fluctuating velocities were obtained assuming $\overline{u'^2} = 2\overline{v'^2} = k$, which is approximately observed in the fully developed region of single-phase round jets. Mean velocity profiles are normalized by the centerline velocity of the single-phase jet to illustrate the effects of particles on the gas-phase velocity field. The effect of a small axial pressure gradient, -5 Pa/m, is significant, improving predictions for both the SSF and SSFM models. Differences in the predictions of the two models suggest significant influence of turbulence modulation for this flow. It should be noted that the limit of -5 Pa/m was chosen to show the potential effects of the pressure gradient, i.e., it was not used to fit the multiphase predictions. It should also be noted that the recirculation calculations for the single-phase flow by the original authors[12] of Refs. 5 and 6 yielded pressure gradients (0-1 Pa/m) that fell within the limit.

Predicted and measured flow properties for both phases at $x/d = 20$ are illustrated in Fig. 2 for a jet having the same particle size as Fig. 1 but with a higher loading ratio of 0.85. The agreement between predictions and measurements is similar to Fig. 1. As the particle loading ratio increases, the rate of decay of gas-phase centerline velocity is reduced. This trend is reproduced correctly by both models.

Results for larger particles, 200 μm in diameter, are illustrated in Fig. 3 for a loading ratio of 0.64. In this case, profiles of mean particle mass flux ϕ are also available for model evaluation. Differences between the SSF and SSFM models are smaller in Fig. 3 than in Figs. 1 and 2, since the larger-size particles interact less with turbulent fluctuations

Table 1 Mean velocity on the axis of a single-phase jet[a]

x/d	5	10	20	30
Measurements, m/s	11.50	8.44	4.03	2.90
Predictions, m/s				
$\dfrac{dp}{dx} = 0$, Pa/m	12.13	7.76	3.42	2.20
$= -5$, Pa/m	12.17	7.90	3.78	2.91

[a]Test conditions of Modarress et al.[5,6]

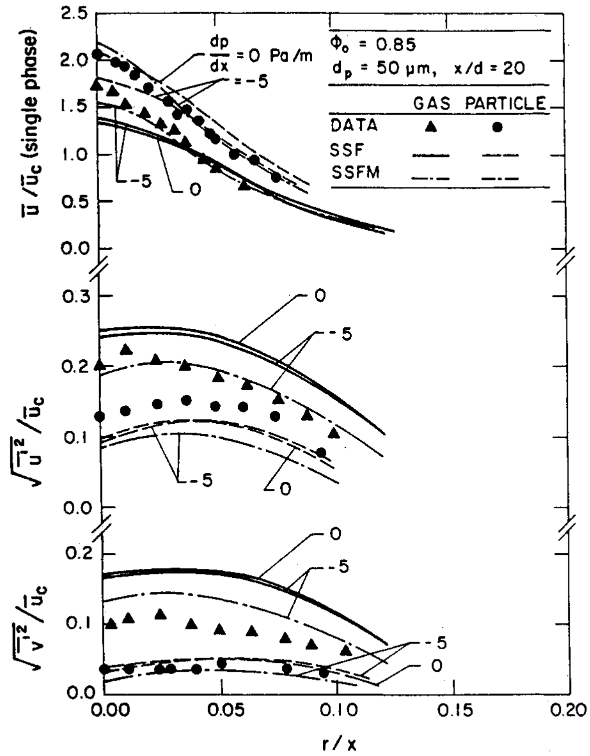

Fig. 2 Flow properties at $x/d = 20$, $d_p = 50$ μm, and $\phi_0 = 0.85$. Data of Modarress et al.[5,6]

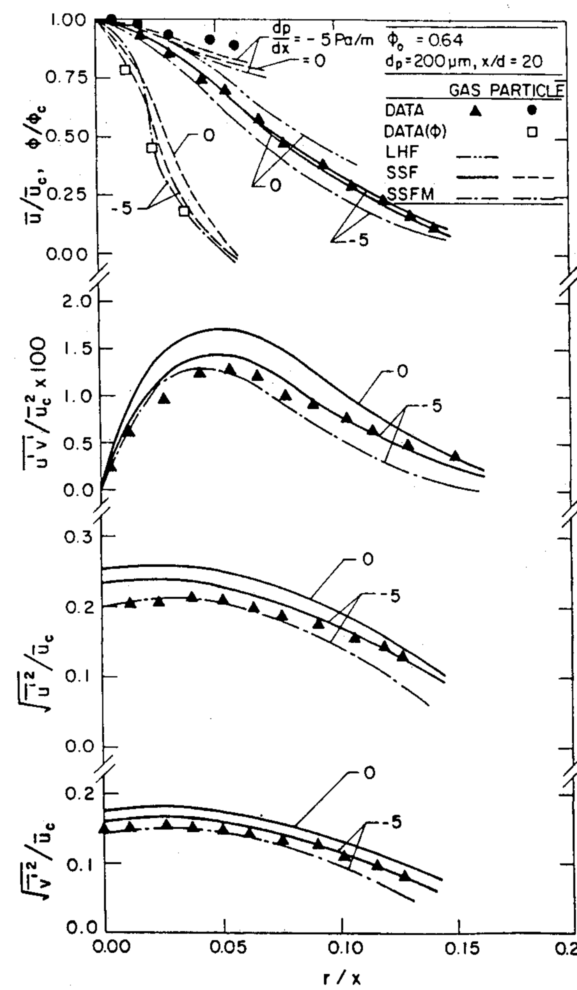

Fig. 3 Flow properties at $x/d = 20$, $d_p = 200$ μm, and $\phi_0 = 0.64$. Data of Modarress et al.[5,6]

due to their greater inertia. Both separated flow models yield reasonably good predictions of flow properties, except for underestimation of mean particle velocities far from the jet axis. In contrast, predictions using the LHF model overestimate rates of flow development—similar to past experience with this approach.[1-4]

Conclusions

Evaluation of the SSFM model using the measurements of Modarress et al.[5,6] yielded results comparable to earlier work.[3,7] This is encouraging since all model constants (aside from $C_{\epsilon 3}$ whose value is not critical for these measurements) were unchanged from earlier work.[1-4] Present results suggest that data from coflowing jets in ducts should be accompanied by static pressure measurements, since even small pressure gradients appreciably influence jet properties. Furthermore, coflow sufficient for entrainment requirements should be supplied to avoid development of recirculation zones. Evaluation using the same measurements does not suggest any particular advantage of the method proposed by Elghobashi and Abou-Arab.[7] However, the stochastic model proposed by Gosman and Ioannides,[9] and further developed in Refs. 1-4, uses instantaneous flow properties to handle the interactions between turbulence and nonlinear interphase transport with less empiricism; therefore, it has greater potential for treating practical spray evaporation and combustion problems from first principles.[4,8] Development and evaluation of the method are being continued this laboratory.

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Laser Determination of Anisotropic Plasma Electron Density Profiles

Richard C. Warder Jr.*
University of Missouri—Columbia
Columbia, Missouri

In a recent series of papers, Self and colleagues[1-3] have measured the electron concentration in combustion MHD plasmas using submillimeter waves. These studies have utilized submillimeter laser interferometry supplemented by electric probes and more recently have been extended to include Faraday rotation measurements. The data analysis assumes that the plasma electron density is uniform. Annen[2] has investigated the electron density profile using an electric probe with a fixed bias to collect the ion current as the probe was swept to the plasma channel centerline. It is difficult to infer a density profile from the data, due to both the fluctuations in the probe current and the nonlinearity between probe current and electron density ($I \sim n^{3/4}$). This Note indicates how their Faraday rotation experimental arrangement can be used to infer the electron density distribution in the "line-of-sight" direction and also suggests a means for improved data acquisition.

If the plasma is assumed to be uniform over the propagation path, the determination of electron density is straightforward: one simply measures the interferometer fringe shift or the Faraday rotation angle and works backward. In general, the electron density in any physical situation is not uniform. The finite thickness of the plasma and the method by which it is generated will introduce boundary effects and consequently gradients of electron density in the direction of propagation (and possibly orthogonal to that direction as well). Thus, the sensitivity of the measurements to departures from the discrete interface assumption must be taken into consideration. It is this electron density distribution that we shall attempt to infer by an alternative analysis of Faraday rotation data.

Wharton et al.[4,5] devised a method for determining nonmagnetized plasma electron density profiles using an interferometer to measure the phase shift due to the plasma at several microwave probing frequencies. The frequencies are chosen so that, at the lowest one, the wave is just cut off, thereby determining the center or maximum electron density from the condition $\omega = \omega_p$. The phase shifts at the other frequencies are then appropriately normalized and compared with theoretical phase shift curves computed for various assumed electron density distributions. Thus, an estimate of the electron density profile can be obtained. However, the experimental arrangements can become quite complicated because a number of different simultaneous microwave setups are required in order to obtain data at widely separated microwave frequencies.

The results described here have a twofold usefulness. First, they will enable one to infer the electron density profile of a plasma in a magnetic field when the results of Wharton and Slager[4] cannot be used. Second, instead of determining the propagation phenomena as a function of microwave frequency, one can vary the magnetic field strength. Generally, this is more easily done and also allows a wider range of parameters to be covered than when only the laser frequency is changed.

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*Professor of Mechanical and Aerospace Engineering. Associate Fellow AIAA.