Predictions of the Structure of Turbulent, Particle-Laden Round Jets

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Abstract

MODELS of dilute, particle-laden flows were evaluated using existing measurements in round jets. Three models were considered: 1) a locally homogeneous flow (LHF) model where velocity differences (slip) between the phases are neglected, 2) a deterministic separated flow (DSF) model where slip is considered but the effects of turbulent fluctuations on particle motion are ignored, and 3) a stochastic separated flow (SSF) model where random sampling is used to treat both slip and the effects of turbulent fluctuations. The LHF and DSF models over- and underestimated flow development rates. In contrast, the SSF model generally yielded good agreement with measurements—except at high particle loadings where the effects of turbulence modulation were observed. Data with full specification of initial conditions are needed, however, for more definitive model evaluation.

Contents

As a step in developing models of sprays, models of turbulent particle-laden gas jets in a still environment were evaluated using measurements of Yuu et al.[1] McComb and Salih,[2,3] Laats and Frishman,[4,5] and Levy and Lockwood.[6] The present study extends an earlier evaluation,[7] which was limited to a smaller data base.

Three models of the process were considered—all using a k-ϵ turbulence model for the gas phase that provided good predictions of mean and turbulent properties of constant and variable density single-phase jets.[8] The simplest model used the common locally homogeneous flow (LHF) approximation, where the particles are assumed to act like tracer particles that instantly adopt the local gas velocity.

Next in complexity was a deterministic separated flow (DSF) model, typical of recent spray models, where velocity differences between phases (slip) are considered but particles are assumed to interact only with mean gas motion. With the DSF formulation, particles follow deterministic trajectories found by solving their Lagrangian equations of motion. Void fractions exceeded 99.8% and density ratios exeeded 200 for the data base; therefore, the computations employed the standard drag coefficient for spheres and virtual mass and Bassett forces were ignored with little error. Effects of particle drag were considered in the mean gas momentum equation; however, similar terms were ignored in the governing equations for turbulence quantities due to the high void fractions of the data base.

The most complex model was a stochastic separated flow (SSF) model, where both slip and turbulent fluctuations are considered similar to a proposal by Gosman and Ioannides.[9] Particles are assumed to interact with a succession of turbulent eddies using random-walk calculations. The properties of each eddy (assuming isotropic turbulence and uniform eddies) were found at the start of particle/eddy interaction by random sampling. The time of particle interaction with an eddy was assumed to be either the eddy lifetime or the transit time required for a particle to cross the eddy, whichever was smaller. The characteristic eddy size L_e, taken to be the dissipation length scale and the eddy lifetime, $t_e = L_e/(2k/3)^{1/2}$, were found from the k-ϵ turbulence model. Earlier work[7] used a linearized method (LSSF model) for determining transit times from L_e and t_e. A nonlinear method (NSSF model), where particles interact with an eddy as long as their residence times and displacements are less than t_e and L_e, was also examined here. Other aspects of the SSF model are identical to the DSF model.

Comparison of predictions and measurements for the data of Yuu et al.[1] and McComb and Salih[2,3] indicated that the LHF model generally overestimated the rates of flow development and particle spread. The DSF model generally underestimated particle spread rates for the entire data base and these results will not be presented here.

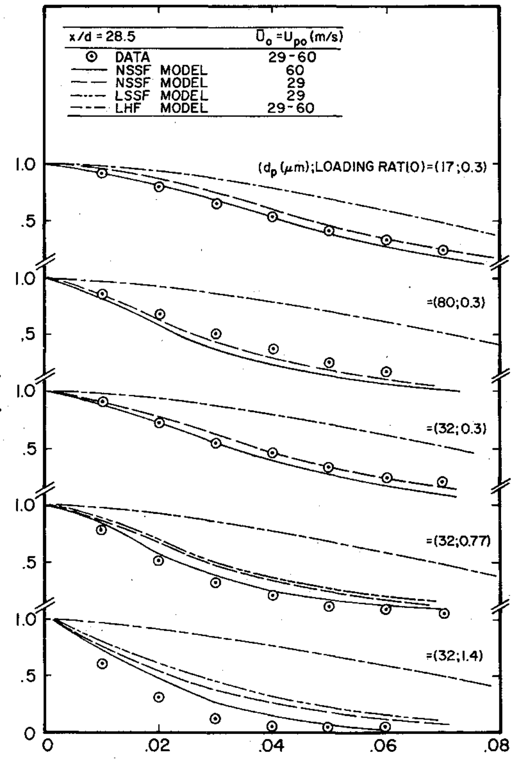

Fig. 1 Predicted and measured mean particle mass fluxes in particle-laden jets (data of Laats and Frishman[4,5]).

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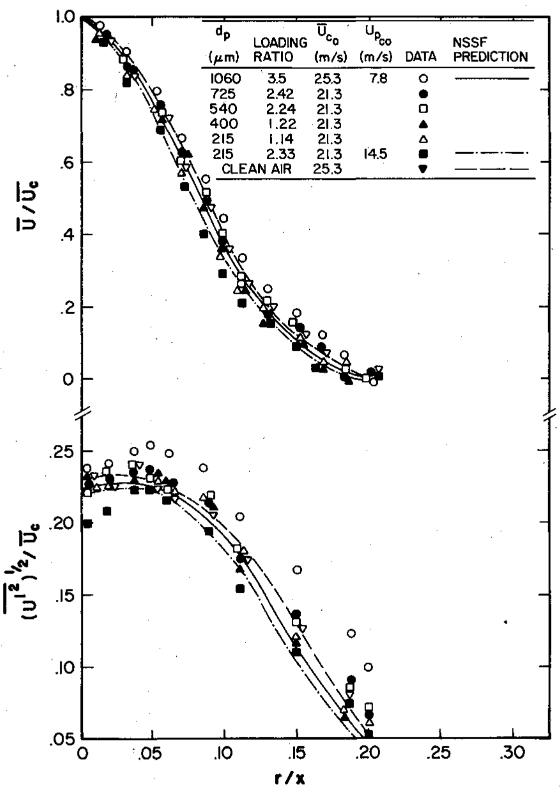

Fig. 2 Predicted and measured mean and fluctuating gas velocities in particle-laden jets (data of Levy and Lockwood[6]).

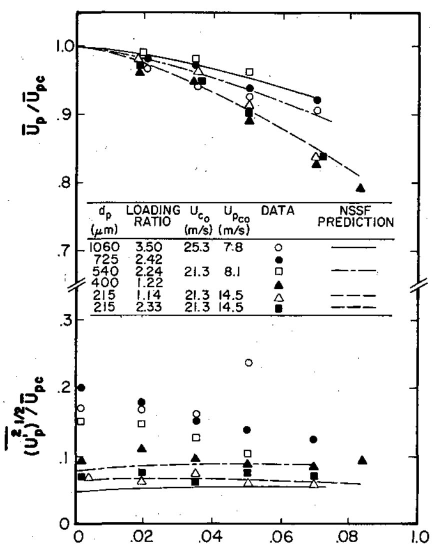

Fig. 3 Predicted and measured mean and fluctuating particle velocities in particle-laden jets (data of Levy and Lockwood[6]).

Predicted and measured mean particle mass fluxes $\bar{G}_p$ normalized by the centerline value $\bar{G}_{pc}$ are illustrated in Fig. 1 for the data of Laats and Frishman.[4,5] Results are plotted as a function of radial distance r divided by distance from the injector x in order to illustrate the estimation of flow widths. Other symbols appearing on the figure are: injector diameter d, particle diameter d_p, and initial gas and particle velocities $\bar{u}_0$ and u_{p0}. Only a range of initial velocities was provided for these measurements; therefore, predictions at the limits are shown. Since Laats and Frishman[4,5] used a long injector tube, the initial conditions for computations neglected slip and employed measured mass fluxes at the jet exit.

The LHF model overestimates rates of particle dispersion in all cases shown in Fig. 1. The SSF models, however, yield reasonably good predictions. Discrepancies for 80 μm particles may be due to initial slip, since these large particles are least likely to be equilibrated at the jet exit. Results for 32 μm particles indicate progressive overestimation of particle spread by the SSF models as the loading ratio increases, which could be due to overestimation of turbulence levels since damping of turbulent fluctuations by particle drag was ignored in the present computations.

Predictions and measurements of mean and fluctuating particle and gas velocities are illustrated in Figs. 2 and 3 for the data of Levy and Lockwood.[6] Fully developed pipe flow was assumed at the injector exit since the injector tube was long. Particle slip was estimated and particle concentrations were taken to be uniform of the jet exit, however, for lack of better information. Only predictions of the NSSF model are shown—LSSF predictions were nearly the same, while LHF predictions overestimated the particle spread rates as before. Isotropic turbulence was assumed for the predicted gas velocity fluctuations, i.e., $\overline{u'^2}=2k/3$, while particle velocity fluctuations were found directly from the SSF trajectory calculations.

The results in Fig. 2 show that particle size and loading have only a small effect on predicted and measured gas properties, since high loading corresponds to the large particles that exchange relatively little momentum with the gas between the jet exit and the measuring station for these data. In Fig. 3, predictions of mean particle velocities are reasonably good; however, predictions of velocity fluctuations of large particles are underestimated. This discrepancy can be explained as an artifact of the particle injection system, since the momentum exchange of large particles is too small for the flow to induce the large fluctuation levels shown in Fig. 3. In contrast, velocity fluctuation predictions for small particles are much improved, since they interact with the flow to a greater degree so that effects of the injector system are damped out.

Based on all the data, we conclude that the SSF model provides encouraging predictions of the structure of particle-laden jets. In contrast, the DSF model was unsatisfactory over the entire data base, while the LHF model was satisfactory only for the smallest particles considered (2.3 μm diam). Model evaluation was limited throughout by lack of complete specification of experimental jet exit conditions, emphasizing the need for more complete measurements.

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