

Validation of a Model of Dilute Two-Phase, Gas-Solid Turbulent Flows

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Abstract

Due to the frequent occurrence of particulate flows within processes of importance to the chemical and process industries it is important to have robust and reliable means of predicting these flows. A paper presented previously at ESCAPE-14 described a new two-phase model capable of simulating dilute, gas-solid turbulent flows. This model is based on solutions of the Reynolds-averaged Navier-Stokes transport equations for the fluid phase, with these equations closed using a full Reynolds stress turbulence modelling approach. This is combined with a Lagrangian formulation for the solid phase which allows the inclusion of poly-dispersed particles and the use of complex particle equations of motion. The particles are tracked through the turbulent flow field and act as a source or sink of momentum for the fluid phase, this in turn modifying the fluid phase solution which further impacts on the trajectories of the particles. The present paper extends that given previously and employs this model to simulate a number of different flows involving dispersed particles. The model is applied to three dilute, gas-solid, turbulent round jets where data is available in the literature. Comparisons between predictions and data for all three jets show reasonable agreement, and provide much needed validation of the two-phase model.

Keywords: turbulent, dilute solid particles, Lagrangian model, jets.

1. Introduction

One of the most frequently identified shortcomings of existing computational fluid dynamic (CFD) models is their inability to accurately predict two-phase flows (Fairweather, 2001). As these types of flow occur regularly in a wide range of manufacturing processes it is important to develop robust two-phase CFD models which have been rigorously validated against a range of reliable data (Fairweather, 2001; Fairweather and Hurn, 2004). This will increase user confidence, allowing the use of CFD models in the optimisation and performance improvement of existing equipment and processes, as well as the evaluation of retrofit options and the design of new equipment, systems and plant, including process scale-up. The present work concerns the validation of a new model (Fairweather and Hurn, 2004) designed for the prediction of turbulent flows containing dilute solid particles. Comprehensive reviews of CFD models of such flows are available (Shirolkar et al., 1996; Loth, 2000).

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2. Mathematical Model

The model employed in this paper is based on solutions of the Reynolds-averaged Navier-Stokes equations expressing conservation of fluid phase properties, and incorporates the full anisotropic, Reynolds stress turbulence closure of Jones and Musonge (1988). Unlike more conventionally used eddy viscosity-based turbulence models, this closure does not assume isotropy of the fluid stresses which can be important when simulating particle dispersion. The particle phase is modelled using a Lagrangian formulation. This involves simulating a large number of particles which are tracked through the flow domain by solving their equations of motion. Statistics are then collected on the particles to produce results for time-averaged properties such as mean velocities and turbulence stresses. Two variants of the equation of motion are employed: a ‘complex’ version as described by Vojir and Michaelides (1994); and a ‘simple’ equation involving only the drag term of the particle. The complex equation further incorporates terms such as the Basset history and added mass of the particle. Momentum transfer between the fluid and particle phases is calculated and used as a source term in the fluid phase momentum equations. This change in momentum alters the fluid flow structure, which in turn alters the particle trajectories and thus an iterative procedure is followed until both phases have converged. To incorporate particle dispersion the continuous random walk model of Burry and Bergeles (1993) was used to predict fluid velocity fluctuations in the turbulent flow. Solutions of the gas phase conservation equations were derived using a modified version of the GENMIX code (Spalding, 1977) which was coupled to the Lagrangian particle model as described above. Full details of the model have been given previously (Fairweather and Hurn, 2004).

3. Results and Discussion

The three jets examined were those studied experimentally by Modarress et al. (1983), Shuen et al. (1985) and Fleckhaus et al. (1987). Simulations used available experimental data to specify initial conditions, including cases where the source flow contained poly-dispersed particles (Shuen et al., 1985; Fleckhaus et al., 1987). Fairweather and Hurn (2004) have demonstrated the benefit of using a full Reynolds stress closure over the more commonly employed $k-\epsilon$ approach when predicting this type of flow. In this work, good agreement with experimental data for gas phase properties across all of the three jets noted above was achieved with $C_{\epsilon 1}=1.45$ in the Reynolds stress equations, with all other constants set to those given by Jones and Musonge (1988).

The data examined below concerns particle phase properties, with comparison made between data and predictions derived using the complex and simple particle equations of motion. Figure 1 shows radial (r) profiles of the mean streamwise particle velocity ($U_{p,x}$) at two downstream locations, as well as similar profiles for streamwise ($u'_{p,x}$) and radial ($u'_{p,r}$) particle normal stresses at 20 pipe diameters (d) downstream of the jet exit, for the jet of Modarress et al. (1983) with a mass ratio (mass gas in/mass solid in) of $\phi=0.32$. It can be seen that there is reasonable agreement between experimental and simulation results, with similar results for the particle mean velocities given by both particle equations of motion. The particle stresses, however, tend to be over-predicted

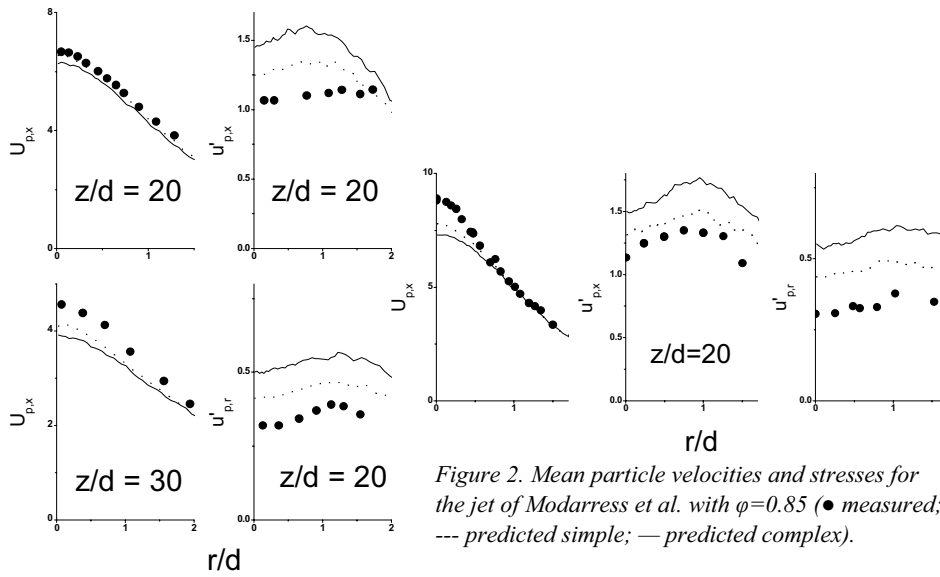


Figure 2. Mean particle velocities and stresses for the jet of Modarress et al. with $\phi=0.85$ (● measured; --- predicted simple; — predicted complex).

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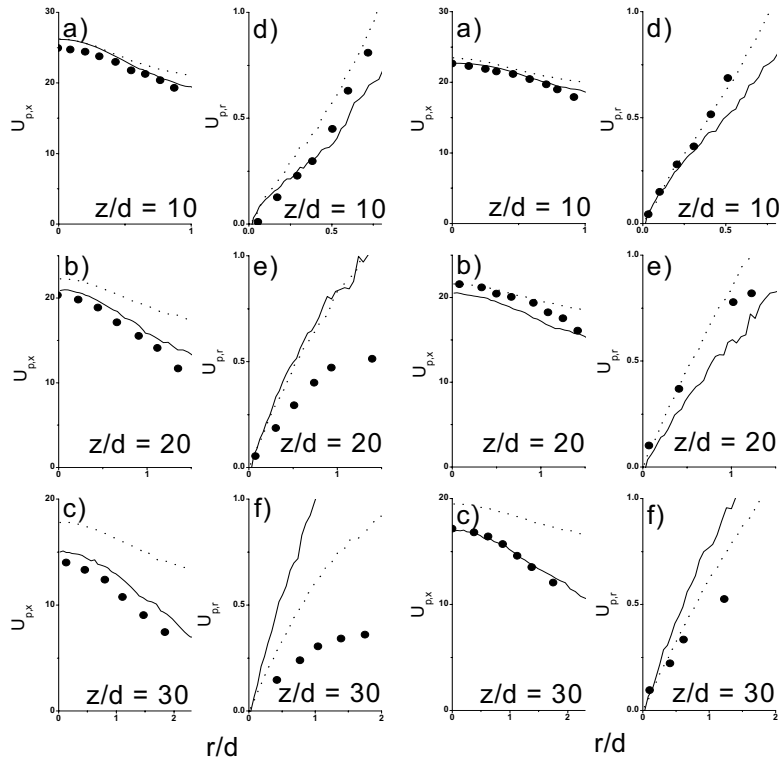


Figure 3. Mean particle velocities for the jet of Fleckhaus et al. LHS $d_p=64\mu\text{m}$, RHS $d_p=132\mu\text{m}$ (● measured; --- predicted simple; — predicted complex).

by the complex equation of motion when compared to the simple one. The same trend is

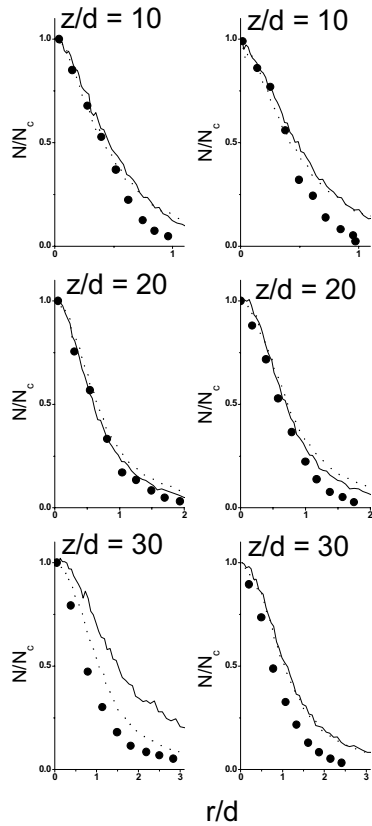


Figure 4. Mean particle number density for the jet of Fleckhaus et al. LHS $d_p=64\mu\text{m}$, RHS $d_p=132\mu\text{m}$ (\bullet measured; --- predicted simple; — predicted complex).

observed in Figure 2 which shows similar results for the same jet but with $\phi=0.85$.

The mean streamwise and radial ($U_{p,r}$) particle velocities for the jet of Fleckhaus et al. (1987) are given in Figure 3. The mean particle diameter in this case is $d_p=64\mu\text{m}$, with the jet having a higher Reynolds number than that of Modarress et al. It can be seen clearly that the particle profiles in the streamwise direction are in closer agreement with data when using the complex equation, with similar results observed for the (much smaller) radial velocities. The complex equation does, however, over-estimate the radial velocity at 30d downstream, a fact that is highlighted by the particle number densities (N) predicted by the complex model at this location, as shown in Figure 4. The same conclusions are reached when d_p is increased to $132\mu\text{m}$, with results also shown in Figures 3 and 4. In this case, however, the over-prediction of radial velocities by the complex model at 30d is not so severe, which leads to similar values to the simple model for N at this location (Figure 4).

Figure 5 shows centreline results for the jet of Shuen et al. (1985) with $d_p=79\mu\text{m}$ and an exit Reynolds number similar to that of Fleckhaus et al. Comparable results are given by both particle equations of motion, although the complex equation gives improved particle velocity predictions, whilst both equations perform relatively poorly for the particle kinetic energy (k_p). Radial profiles are shown at 20d in Figure 6, with superior mean particle velocity predictions again obtained when using the complex equation of motion. The particle stresses and particle mass flux (G) are predicted similarly by both equations, although the stress profiles tend to be too flat when compared with the data.

When the particle size is increased to $d_p=119\mu\text{m}$ the same conclusions are reached (Figures 5 and 6).

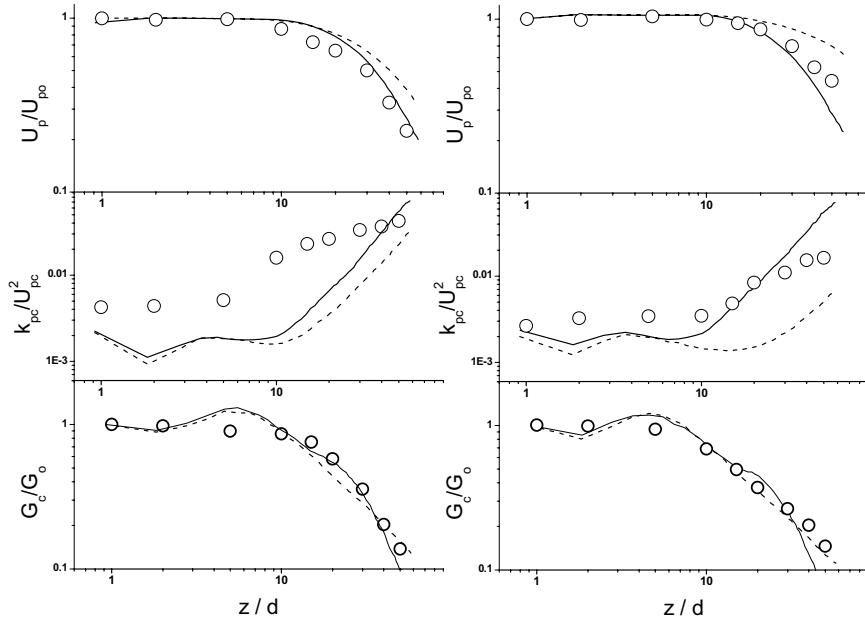


Figure 5. Axial particle profiles for the jet of Shuen et al. LHS $d_p=79\mu\text{m}$, RHS $d_p=119\mu\text{m}$ (● measured; --- predicted simple; — predicted complex).

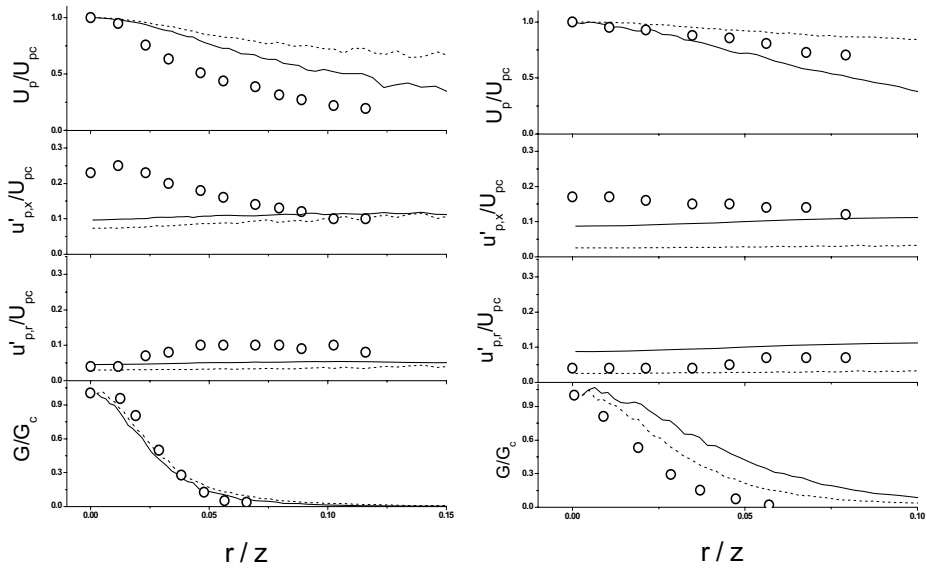


Figure 6. Radial particle profiles for the jet of Shuen et al. LHS $d_p=79\mu\text{m}$ at 20d downstream, RHS $d_p=119\mu\text{m}$ at 40d downstream (● measured; --- predicted simple; — predicted complex).

4. Conclusions

A model of dispersed solid-gas flows presented at ESCAPE-14 has been validated against a range of available experimental data obtained for round jets. The simulation results show good agreement with fluid data and, on the whole, the particle data is also reasonably well predicted. The complex particle equation of motion has been shown to improve results for mean particle velocities for higher Reynolds number jets. The particle stresses and kinetic energy are predicted with varying degrees of success, with results being similar for both equations of motion, and with the complex equation predicting higher values than the simple equation. The results shown here are similar to, but improve upon, predictions of the same jets that can be found elsewhere in the literature, e.g. Berlemont et al. (1990).

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Acknowledgements

The authors would like to thank BNFL and EPSRC for their financial support of the work described.