Abstract

Numerical simulations of turbulent dilute phase, gas-solid flows in horizontal and vertical pipes are performed using a two-fluid model incorporating kinetic theory of granular flows (KTGF) and accounting for four-way coupling. Two-equation $k-\varepsilon$ model is used for gas phase turbulence while solid phase turbulence is calculated from granular energy balance equation. Numerical results for velocity profiles, turbulent intensity and pressure drop are compared with published experimental data (Tsuji et al., 1982 and 1984) and are found to be in good agreement with it. It is observed that particle-wall collision and particle-particle collision play important role in the prediction of fully developed velocity profiles and turbulent intensity.

In the next stage, efforts have been made to predict the fully developed pressure drop in horizontal and vertical flows. Sensitivity study of numerical parameters (such as restitution coefficients for particle-particle collision and particle-wall collision, and specularity coefficient) and uncertainty analysis of operating parameters (such as particle properties and particulate loading) are performed for the prediction of pressure drop. It is observed that pressure drop in gas-solid flows is very much sensitive to specularity coefficient (φ) value while the variation in other parameters show negligible change in the pressure drop. An extensive investigation has been done to study the effect of various flow parameters like particle properties, gas velocity and particulate loading on two-phase pressure drop. Pressure drop increases with increase in gas Reynolds number (Re_g), particulate loading (β) and particle density (ρ_s). However, with respect to particle diameter (d_p), pressure drop increases, reaches a peak and then starts decreasing. Pressure drop in vertical flows is always more than horizontal flows under similar flow conditions. Empirical correlations for pressure drop are proposed for horizontal and vertical gas-solid flows using a two-phase multiplier (ϕ), which when multiplied to single-phase pressure drop gives two-phase pressure drop. The correlations show that 95% of the data used to generate it falls within $\pm 17\%$ and $\pm 15\%$ error bands for horizontal flows and vertical flows, respectively. Thereafter, based upon the constant pressure gradient region of the axial static pressure profiles, entry length or acceleration length has been computed for different particle properties and loadings in a horizontal pipe. It is found that acceleration length increases generally with increasing particulate loading and decreasing gas velocity. Particle diameter affects acceleration length only at high particulate loading. An empirical correlation for acceleration length is also proposed with an accuracy of ± 11%.

Finally, numerical simulations using two-fluid model are performed for spatially developing, two-dimensional, axi-symmetric particulate free jet emanated from a circular nozzle and acting in downward direction. The circular nozzle has been simulated separately for various flow conditions to get fully developed velocity profiles at its exit under different flow conditions. The fully developed velocity profiles are expressed by power law, $U = U_c\left(1-(r/R)\right)^N$. The exponent, N is found to be 0.14 for gas phase irrespective of particle sizes and loadings. However, the solid phase velocity varies significantly with the particle diameter. For particle sizes up to $200\,\mu\text{m}$, the exponent is 0.12. For 1 mm and 2 mm size particles, the exponent is found to be 0.08 and 0.05, respectively. The center line velocity (U_c) of the solid phase decreases and hence, the slip velocity increases as the particle size increases. The free jet is simulated neglecting inter-particle collisions (two-way coupling). Drag force is the only term interacting between the phases and $k-\varepsilon$ turbulence model is used for the closure of the governing equations. The modulations on the flow structures and turbulent characteristics of gas flow due to the solid particles with different particle sizes and loadings are investigated. It is observed that jet spreading and decay of the center line velocity of the gas phase are reduced in two-phase flows. Additions of solid particles to the gas flow significantly modulate the gas turbulence in the nozzle as well as in the jet flows. Fine particles suppress the gas turbulence, and with increase in particle diameter, turbulence intensity of gas phase increases.

Keywords: Gas-solid flow, two-fluid model, pressure drop, two-phase multiplier, specularity coefficient, kinetic theory, particulate jet, turbulence modulation