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Original Research Paper

Prediction of acceleration length in turbulent gas–solid flows

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ABSTRACT

CFD investigation for gas–solid flows in a horizontal pipe was performed using Euler–Euler approach or two-fluid model and accounting for four-way coupling. Calibration of the numerical model is obtained by confirming the numerical predictions with published experimental data. Based upon the axial profiles of the pressure gradient, the authors investigated the acceleration length for different particle properties and loadings. It is found that acceleration length increases generally with increasing particulate loading and/or decreasing gas phase mean flow velocity. However, the variations of acceleration length with particle diameter are quite different under different operating conditions. Finally, an empirical correlation for acceleration length (L_a) is proposed, which contains two terms: the first-term matches with the entrance length for gas only flow; whereas the second term is regarded as the enhancement due to addition of solids to gas flow. The accuracy of the correlation is approximately ±11%.

1. Introduction

Dilute turbulent gas–solid flows prevail in many engineering applications like pneumatic conveying, pulverized coal combustion, spray drying, spray cooling, and particulate pollution control. A lot of work has been done to study the fully developed gas–solid flows and prediction of fully developed pressure drop [1–6]. After a certain distance from the entry, the shape of the velocity profile is no longer a function of the axial distance from the entrance. This state of fluid flow is called fully developed flow. The pressure profile across the axial direction remains linear and velocity profiles in the radial directions do not change in a fully developed state. The developing region or acceleration length cannot be neglected if the piping layout is of short span. Very little work has been done on the prediction of acceleration length in gas–solid flows. Enick and Klinzing [7] determined the acceleration length of fine particles in a vertical, two-phase, up-ward flow. The dimensionless acceleration length is correlated with the Froude number, the particle to pipe diameter ratio, the particle to fluid density ratio, the gas Reynolds number and particulate loading. Carpinlioglu and Gundogdu [8] conducted experiments to investigate the acceleration length in horizontal gas–solid flows. They found that acceleration length is a strong function of gas Reynolds number (Re_g) such that an increase in Re_g caused a decrease in the acceleration length while particulate loading seemed to be of secondary importance. The particle size was not found to be of much importance to the size range (200 μm to 1 mm) covered in the experiments. Lodes and Mierka [9] developed a correlation for the acceleration length (non-dimensionalized by the pipe diameter) in a vertical pipe based on the gas Reynolds number, the particulate loading and the particle size. Shimizu et al. [10] suggested from their experimental study of gas–solid suspension flow that the acceleration length for the upward flow can be well correlated to the suspension flow Reynolds number (Re_m) and is found to be an increasing function of Re_m. Stromgren et al. [11] performed two-fluid modeling to study the evolving gas–solid flows in a vertical pipe. It was shown that the acceleration length becomes shorter by increasing particle diameters (up to a particle diameter of 100 μm). Thereafter, the acceleration length becomes longer again for increasing particle diameters because larger particles need a longer time to adjust to the velocity of the gas phase.

Prediction of acceleration length in horizontal gas–solid flows has received less attention so far due to the complexities (i.e. gravity induced particle accumulation on the bottom wall and collisions) involved in the numerical simulation of a long horizontal pipe. Particle–wall collision along with particle–particle collision dominates the flow phenomena [12] in horizontal flows. In the present work, a numerical investigation using Euler–Euler approach was performed for the determination of acceleration length of two- phase particulate flows in a horizontal pipe. The gas used is air with density, $\rho_g = 1.225\ \mathrm{kg/m^3}$ and dynamics

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Nomenclature

C_D	drag coefficient
C_L	lift coefficient
d_p	diameter of solid particles (μm)
D	pipe diameter (mm)
e	restitution coefficient
f	friction factor
F_D	drag force
F_L	lift force
g	acceleration due to gravity (m^2/s)
g_0	radial distribution function
I	turbulent Intensity
k	turbulent kinetic energy
K_s	solid diffusion coefficient ($kg/m^3.s$)
L_a	acceleration length
p	mean pressure (Pa)
p_s	solid pressure (Pa)
R	radius
Re	Reynolds number
S	mean strain rate tensor
t	time unit (s)
T_s	granular temperature (m^2/s^2)
u	instantaneous velocity (m/s)
u'	fluctuating velocity (m/s)
U	mean Velocity (m/s)
V	volume
X, Y	distance along the radial directions
Z	distance along the axial direction

Symbols

α	volume fraction
β	particulate loading
∇	gradient
δ	Kronecker delta
ε	dissipation rate of turbulence
η	diameter ratio (d_p/D)
ξ	inter-phase momentum exchange coefficient ($kg/m^3.s$)
γ_{T_s}	collisional energy dissipation ($kg/m.s^3$)
λ	bulk viscosity (kg/m.s)
μ	shear viscosity (kg/m.s)
ρ	density (kg/m^3)
φ	specularity coefficient
τ	stress–strain tensor ($kg/m.s^2$)
χ	energy exchange ($kg/m.s^3$)

Subscripts and Superscripts

a	acceleration
g	gas
p	particle
s	solid phase
t	turbulent
T	transpose of vector
w	wall

viscosity, $\mu_g = 1.79 \times 10^{-5}$ kg/m.s. The influence of gas phase mean flow velocity, particle properties and particle loading on the acceleration length are investigated.

1.1. Theoretical analysis of acceleration length

Consider a differential section, dL of the pipe containing solid particles of effective weight, Δm_s in a gas flow. The force balance on the particles may be represented by

$$\sum F = ma \tag{1}$$

$$dF_D - dF_g - dF_F = \Delta m_s \frac{dU_p}{dt} \tag{2}$$

The drag force [13],

$$dF_D = \frac{3}{4} C_D \frac{\alpha_g^{-4.7} \rho_g (U_g - U_s)^2}{(\rho_s - \rho_g) d_p} \Delta m_s \tag{3}$$

The solid friction loss, dF_F, may be represented by a friction factor similar to single phase gas only flow.

$$dF_F = \frac{f_s U_p^2}{2D} \Delta m_s \tag{4}$$

$$\frac{dU_p}{dt} = \frac{3}{4} C_D \frac{\alpha_g^{-4.7} \rho_g (U_g - U_p)^2}{(\rho_s - \rho_g) d_p} - g - \frac{f_s U_p^2}{2D} \tag{5}$$

$$dL = U_p dt$$

$$U_p \frac{dU_p}{dL} = \frac{3}{4} C_D \frac{\alpha_g^{-4.7} \rho_g (U_g - U_p)^2}{(\rho_s - \rho_g) d_p} - g - \frac{f_s U_p^2}{2D} \tag{6}$$

The solution of the above equation gives the acceleration length, L_a.

$$L_a = \int_{U_{s1}}^{U_{s2}} \frac{U_p dU_p}{\left(\frac{3}{4} C_D \frac{\alpha_g^{-4.7} \rho_g (U_g - U_p)^2}{(\rho_s - \rho_g) d_p} - g - \frac{f_s U_p^2}{2D} \right)} \tag{7}$$

f_s is calculated from the total pressure drop consideration in the gas–solid flow.

The usual approach in gas–solid flow pressure drop prediction is to consider the total pressure drop consisting of two components, i.e. pressure drop due to gas only and the additional pressure drop due to the presence of the solid particles. The overall pressure drop consists of acceleration, static (only for vertical flow) and frictional components.

$$\Delta p_T = \Delta p_a + \Delta p_{static} + \Delta p_F \tag{8}$$

The acceleration pressure drop (Δp_a) is calculated from the non-linear region of the axial pressure profile. This can be determined either from experiments or numerical simulations.

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$$\Delta p_{static} = (\rho_g \alpha_g + \rho_s \alpha_s) Lg$$

$$\Delta p_F = \Delta p_{Fg} + \Delta p_{Fs}$$

$$\Delta p_{Fg} = \frac{f_g \rho_g \alpha_g L U_g^2}{2D}$$

$$\Delta p_{Fs} = \frac{f_s \rho_s \alpha_s L U_s^2}{2D}$$

From the above equations, by rearranging,

$$f_s = \frac{2D}{\rho_s \alpha_s L U_s^2} \left(\Delta p_T - \Delta p_a - (\rho_g \alpha_g + \rho_s \alpha_s) Lg \right) - f_g \left(\frac{\rho_g}{\rho_s} \right) \left(\frac{\alpha_g}{\alpha_s} \right) \left(\frac{U_g}{U_s} \right)^2 \tag{9}$$

The gas friction factor can be calculated using Colebrook equation.