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Numerical modelling and validation of gas-particle flow in an in-line tube bank

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Abstract

This paper presents a numerical study of dilute gas-particle flows in an in-line tube bank. The physical characteristics of the particle–wall collisions and their contributions to particle phase flow field were investigated employing a Lagrangian particle-tracking model, which includes an algebraic particle–wall collision model and a stochastic wall roughness model. Particles with corresponding diameters of 1 μm, 15 μm and 93 μm were simulated under the gas flow condition of 11.2 m/s. The predicted mean velocities and fluctuations for both gas and 93 μm particles were validated against experimental data. The numerical predictions revealed that the wall roughness has a considerable effect by altering the rebounding behaviours of the large particles, and consequently affecting the particles motion downstream and shifting particle collision frequency distribution on the tubes. Also, the results demonstrated that the velocity fluctuations for large particles are predominantly determined by the particle–wall collisions.

Keywords: Gas-particle flow; In-line tube bank; CFD; Particle–wall collision; Wall roughness

1. Introduction

A great deal of research efforts and resources have been allocated to investigate the characteristics of particle–wall collisions in gas-particle flows. Through these probing investigations, significant improvements to prolong the operational longevity of industrial devices that are constantly subjected to the rigorous bombardment of solid particles can be achieved (Tu, Yeoh, Morsi, & Yang, 2004). Some typical examples of such devices are heat exchanger tubes in coal combustion equipments that are widely used in chemical plants (Tu, Fletcher, Behnia, Reizes, Owens, & Jones, 1997). The bombardment of coal ash particles on the heat exchanger tubes for considerable periods of time can cause significant erosion to the extent that may result in the catastrophic consequences because of continuing removal of materials from these tubes (Morsi, Tu, Yeoh, & Yang, 2004).

This paper presents one of the continuing series of efforts to better understand the particle–wall collision phenomenon and its contributions to the characteristics of particle phase flow field. Previously, Tu, Fletch, Morsi, Yang, and Behnia (1998) measured the gas-particle flow in an in-line tube bank using the Laser–Doppler anemometry (LDA) system and compared the measurements with predictions of an Eulerian model. Reasonable agreements were obtained between the predicted and measured mean flow field of both gas and particle phases. The inherent weakness of the Eulerian formulation was to correctly describe the aerodynamics drag force on the particle phase in the vicinity of a wall surface. Recently, Tian, Tu, and Yeoh (2005) demonstrated that the incident and reflected particles during the process of particle–wall collision were still far away from adequate resolution for the Eulerian model.

To overcome the difficulties associated with the application of the Eulerian approach for the particle phase, the Lagrangrian particle-tracking model is thereby revisited to study the gas-particle flows. The Lagrangian model considers the motion of individual particle and relevant variables along the particle trajectory. It can therefore provide rather detailed physical description of the particle behaviours in near-wall region before and after collision. The rebounding characteristic of glass particle (with diameters of 66 μm and 93 μm) impacting on the stainless steel tube bank had been investigated in Morsi et al. (2004)

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Nomenclature

a, b exponential constants in Eqs. (19) and (20)
a_1, a_2, a_3 empirical constants in Eq. (11)
A_i convective flux
B diffusion coefficient
C_D particle drag coefficient
C_μ, C_ν coefficients in the κ–ε turbulence model
$C_{\varepsilon 1}, C_{\varepsilon 2}$ model constants for standard and RNG κ–ε turbulence models
d_p particle diameter
D diameter of tube
e overall restitution coefficient
e_n, e_t mean normal and tangential restitution coefficients
g gravitational acceleration
k, l constants in Eqs. (19) and (20)
L_s characteristic length of the system
P gas phase pressure
P_A^R the normal impulse due to adhesion during rebound
P_D^A the normal impulse generated by deformation during approach
P_k generation of turbulence kinetic energy
R strain rate
R_1 restitution coefficient in the absence of adhesion
Re Reynolds number
Re_p relative Reynolds number
S source term
St Stokes number
S_{ij} strain rates
t_p particle relaxation time
t_S system response time
u_c particle capture velocity
u_i, u_j velocity
u_{in}^p, v_{re}^p particle incident and reflected velocities
u_n^p, v_n^p particle normal incident velocity and normal reflected velocity
U_b bulk velocity
V_s characteristic velocity of the system
x horizontal location along X-axis
x_i, x_j, x_k Cartesian coordinate system
y vertical location along Y-axis
$'$ fluctuation

Greek letters
α angular location of impact
ε dissipation rate of turbulent kinetic energy
ϕ governing variable
η function defined in Eq. (7)
η_0 model constant for RNG κ–ε turbulence model
κ turbulent kinetic energy
μ dynamic viscosity
μ_1 the ratio of tangential and normal impulse
θ, θ' the particle incident angle without and with roughness effect
ρ density
ρ_1 adhesion coefficient
σ turbulence Prandtl number
ω, Ω particle annular velocity before and after collision
ζ normally distributed random number

Subscripts
eff effective
g gas phase
ij 1, 2 (x, y)
n normal direction
t tangential direction
p particle phase
s system

Superscripts
g gas phase
p particle phase

by using both Lagrangian modelling method and LDA measurement. A simple collision model was employed in which the normal and tangential restitution coefficients were respectively assumed as $e_n = -v_n^p/u_n^p = 0.9$ and $e_t = v_t^p/u_t^p = 0.9$ (see Fig. 1). Tu et al. (2004) further carried out a study of particle rebounding characteristics in the gas-particle flow over a cylindrical body. The simple collision model for the Lagrangian modelling technique was also employed assuming the normal and tangential restitution coefficients set as $e_n = 0.3$ and $e_t = 0.9$. Because of the varying and arbitrary restitution coefficients that can be adopted or specified, there is a need to employ a more realistic particle–wall collision model in the context of computational fluid dynamics (CFD) modelling. It has been known that several physical parameters govern the particle–wall collision process. Among these parameters are the particle incident velocity, particle initial angular velocity, incident angle, diameter and shape of the particle as well as its material properties. Other parameters such as the surface characteristics and roughness can also contribute to significantly influence the particle impacting on and rebounding away from the wall surface (Li, Dunn, & Brach, 2000; Sommerfeld, 1992). Primarily, the absence of any

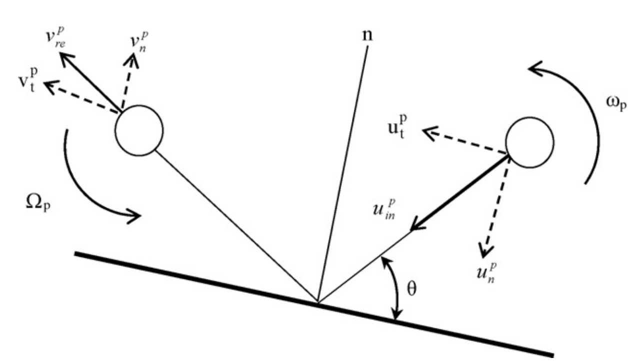

Fig. 1. Particle–wall collision configuration.