Numerical simulation of gas-particle flows over an in-line tube bank

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Abstract

We present a numerical investigation of particle-wall collision phenomenon and its contribution to particle phase flows in an in-line tube bank. Particles with diameters of $30\,\mu$m and $93\,\mu$m were simulated using a Lagrangian particle tracking model, which included a particle-wall collision model and a stochastic wall roughness model. The predicted mean velocity and fluctuation profiles for both gas and $93\,\mu$m particles were validated against experimental data. The numerical predictions reveal that the wall roughness has a considerable effect by altering the rebounding behaviours of large particles, and consequently affecting particle trajectories downstream.

Contents

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1 Introduction

Gas-particle flows are commonly found in a wide variety of engineering applications. Typical examples include the flue gas and flue ash flow over heat exchanger tubes in coal fired boilers [12]. Here, erosion caused by particle collisions presents a major problem in these coal fired boilers, especially in reheaters and economizers [3]. Therefore, detailed information on the gas-particle flows and particle-wall interaction is crucial to fundamentally understand and hence to predict tube erosion.

With the rapid progress of computational power, Lagrangian particle tracking models have become attractive investigative tools to predict and analyse gas-particle flows. Lagrangian models can fundamentally describe the particle-wall collision process and provide detailed description of particle motion required by erosion models, such as particle incidence and rebounding velocities, particle incident angle, particle collision frequency, and so on.

Currently, three basic categories of particle-wall collision models are used in Lagrangian particle tracking models.

- The first type of collision model takes the normal and tangential restitution coefficients as constants, that is, $e_n = v_n^p/u_n^p = \text{constant}_1$. Vari-

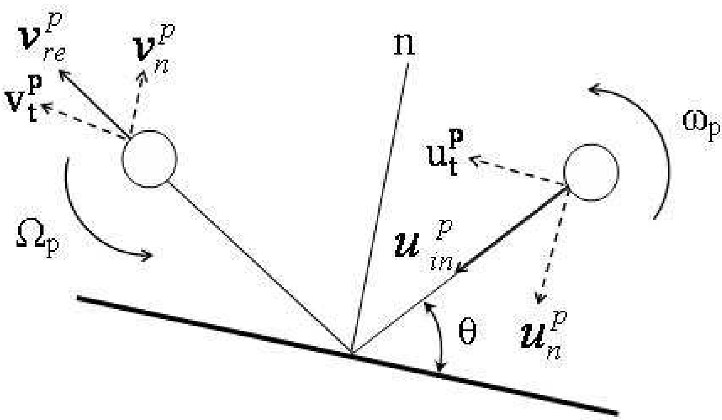


Figure 1: Particle-wall collision configuration

ables are illustrated in Figure 1.

- The second type of collision model treats the values of normal and tangential restitution coefficients as a function of particle incident angle, that is, $e_n = f_n(\theta)$ and $e_t = f_t(\theta)$ [2] where the parameters in these functions were determined through experiments.

- The third type comprises a set of equations that are based on the particle impulse and momentum equations [6]. In this model, the normal restitution coefficient and the dynamic friction coefficient were obtained from experiments.

Some Lagrangian simulations using different particle-wall collision models towards the investigation of gas-particle flows in tube banks are reviewed. Schuh et al. [5] studied the particle trajectories and tube erosion in a gas-particle flow over an in-line tube bank via the first type of collision model, assuming $e_n = e_t = 0.3$. They found that particles with large inertia tended to strike many tubes due to rebounding particles from the tube surfaces, while particles with low inertia tended to follow streamlines closely and were entrained in the bulk flow between tubes. In their simulation of a gas-particle flow in a tube bank, Jun & Tabakoff [3] took the second type of collision model to account for particle-wall collisions. The empirical equations of quartz and aluminium particles impacting on aluminium surfaces [2] were used to calculate restitution coefficients. Nevertheless, to the best of our knowledge, no in-depth investigation has been performed on gas-particle flows and tube erosion in a tube bank using the third type of collision model.

This article therefore reports a preliminary study of gas-particle flows over an in-line tube bank using a particle-wall collision model that is in the framework of the third type of collision model [6, 7]. Based on the momentum equations together with Coulombs law of friction, this model is capable of taking into consideration the influence of particle incident angle, wall surface roughness and particle initial angular velocity on the particle-wall collision process, thus overcoming the problems associated with applying a single empirical constant for both normal and tangential restitution coefficients as found in the first type collision model. In this study, the normal restitution coefficient and the dynamic friction coefficient of glass particles colliding on a steel surface measured by Sommerfeld and Huber [7] were used. Also, a stochastic approach developed by Sommerfeld [6] was adopted to model the wall roughness effect. The particle-wall collision model and the wall roughness model were implemented into FLUENT via User Defined Functions. This allowed flexibility in extending these models to handle complex engineering flows. The predicted velocity and fluctuation profiles of both gas phase and 93 μm particles were validated against experimental data of Tu et al. [13].

2 Computational method

2.1 Gas phase and particle phase models

The generic CFD code, FLUENT, was utilised to predict the velocity profiles of gas phase under steady-state conditions through solutions of the conservation equations of mass and momentum. The air phase turbulence was handled by the Renormalization Group theory (RNG) based k-ϵ model [14]. For the particle phase, Lagrangian particle tracking method is used to trace the dispersion of particles about the trajectory. Here, the Eulerian equations for the gas phase were initially solved and then particles were individually tracked by integrating the equations of particle motion throughout the flow field [9]. An 'eddy lifetime' model was used to account for the effect from the gas-phase turbulence to the particle phase. More details regarding RNG k-ϵ model and the 'eddy lifetime' model are given by Tian et al. [10].

A non-equilibrium wall function was employed for the gas phase flow. All governing transport equations were discretised using the finite-volume approach and the QUICK scheme was used to approximate convective terms while the second order accurate central differencing scheme was adopted for diffusion terms. The pressure-velocity coupling was realized through the SIMPLE method while the convergence criteria for gas phase properties were 10^{-5}. All numerical exercises were performed in a two dimensional (2D) environment because only 2D representative measurements were available.

2.2 Particle-wall collision model and wall roughness model

Figure 1 illustrates the impact of a spherical particle on a plane wall in 2D form. At the end of contact with a wall, a particle is considered to be rolling when the following condition is satisfied:

$$\left| u_t^p - \frac{d_p}{2}\omega_p \right| \leq \frac{7}{2}\mu_d \left(1 + e_n\right) u_n^p \, . \tag{1}$$

The subscripts n and t represent the normal and tangential velocity components, respectively while μ_d is the particle dynamic friction coefficient. Under the condition of rolling collision, rebound velocity components are calculated as follows:

$$\begin{aligned} v_t^p &= \frac{1}{7}\left(5u_t^p + d_p\omega_p\right) \, , \\ v_n^p &= -e_n u_n^p \, , \\ \Omega_p &= 2\frac{v_t^p}{d_p} \, . \end{aligned} \tag{2}$$

If the particle is not rolling during the collision, it is then considered to be sliding and the rebound velocity components are defined as

$$\begin{aligned} v_t^p &= u_t^p - \mu_d \left(1 + e_n\right) \varepsilon_0 u_n^p \, , \\ v_n^p &= -e_n u_n^p \, , \\ \Omega_p &= \omega_p + 5\mu_d \left(1 + e_n\right) \varepsilon_0 \frac{u_n^p}{d_p} \, . \end{aligned} \tag{3}$$

Here, ω_p denotes the angular velocity before the collision, Ω_p is the angular velocity after the collision, and the direction of the relative velocity between particle surface is

$$\varepsilon_0 = \operatorname{sign}\left(u_t^p - \frac{d_p}{2}\omega_p \right) \tag{4}$$

A stochastic approach has been developed by Sommerfeld [6] to model the wall roughness effect. Here, the incident angle θ' comprises of the particle incident angle θ and a stochastic contribution due to the wall roughness (Figure 2),

$$\theta' = \theta + \Delta\gamma\xi \, , \tag{5}$$

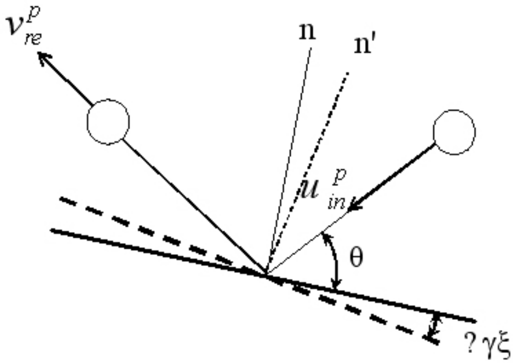


FIGURE 2: Virtual wall model for particle-wall collision

where ξ is a Gaussian random variable with mean of 0 and a standard deviation of 1. The value of $\Delta\gamma$ is determined through experiment. When the absolute value of $\Delta\gamma$ is larger than the incident angle, particles are less likely to impact on the *lee* side of a roughness structure. This is referred to as the shadow effect, which leads to a higher probability for particles to collide on the *luff* side, thus shifting the probability distribution function of $\Delta\gamma\xi$ towards positive values. A numerical procedure proposed by Sommerfeld and Huber [7] has been implemented to handle this shadow effect. This procedure shifts the distribution function of $\Delta\gamma\xi$ towards the positive side and avoids the unphysical situation that particles hit the roughness structure with a negative angle. In this study, the wall roughness $\Delta\gamma$ of 5.3° was used. This value was obtained for 100 μm glass particles impacting on a steel surface by Sommerfeld and Huber [7]. More details about the wall roughness model are given by Sommerfeld and Huber [7].

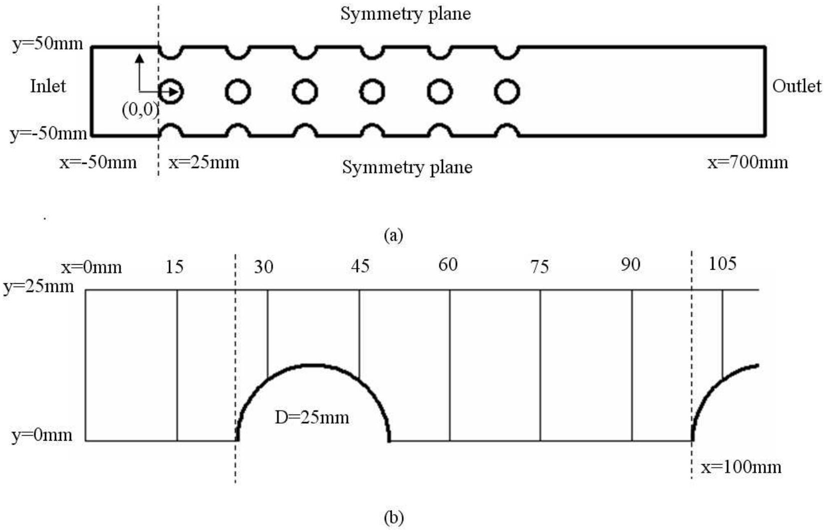
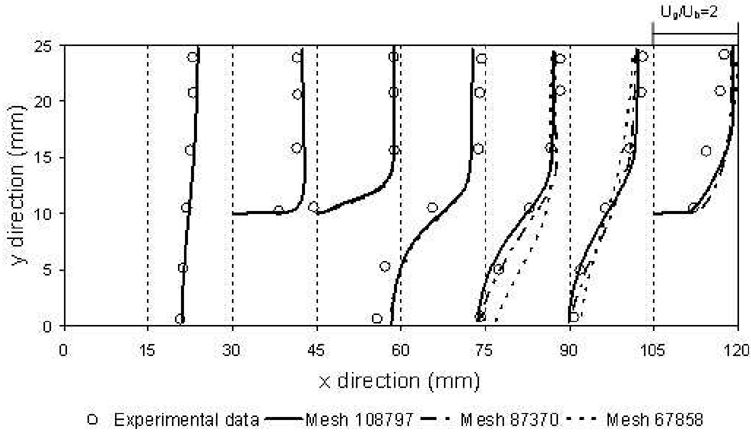


Figure 3: (a) Computational domain; (b) Region of comparison between prediction and measurement

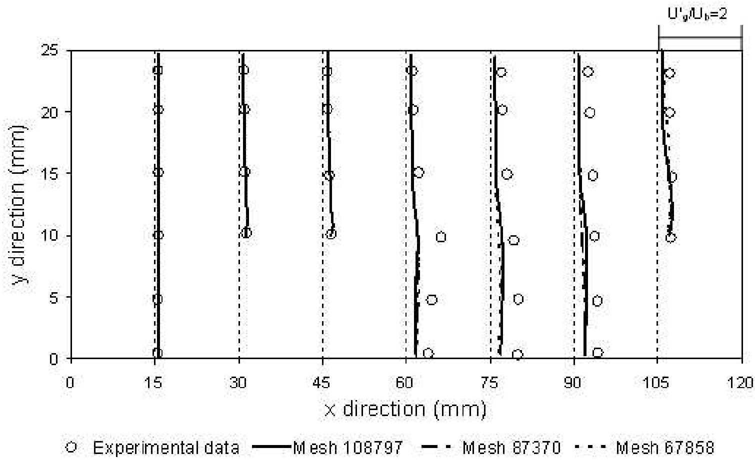
3 Results and discussion

Figure 3 illustrates the 2D computational domain which starts from $x = -50$ mm and extends up to $x = 700$ m, including six tubes and twelve half tubes. The height of the computational domain is 100 mm. In order to match the experimental conditions, uniform gas velocity of 11.2 m/s was imposed at the inlet, $x = -50$ mm. Symmetrical conditions were assumed at the top and bottom of the computational domain. These were slightly different from the experimental observation for the particle phase due to the gravity acting in the direction perpendicular to the flow.

Grid independence was checked by using three different mesh densities with 67858, 87370 and 108797 quadrilateral elements. Comparison and validation were carried out in the region shown in Figure 3 (from 0 mm to 105 mm in x direction and from 0 mm to 25 mm in y direction).



(a)



(b)

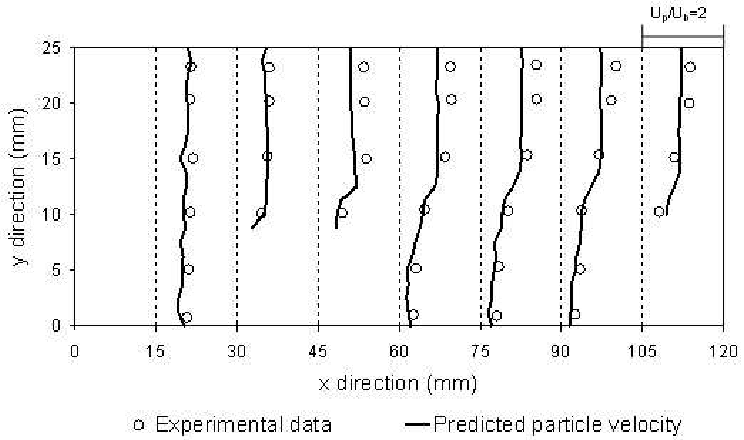
Figure 4: Grid independence test: (a) streamwise velocity; (b) turbulence intensity.

Figure 4(a) shows the comparison of both measured and predicted streamwise gas velocity profiles using three mesh densities at locations $x = 15$, 30, 45, 60, 75, 90 and 105 mm. The two finest grids yielded almost identical solutions that were in good agreement with the measurement except with a marginal over-prediction at $x = 105$ mm. Predicted turbulence intensity profiles of gas phase are presented in Figure 4(b). All three mesh densities predicted similar results that were in close agreement with the measurement up to $x = 45$ mm but deviated at $x = 60$, 75 and 90 mm. For accuracy considerations, simulation results presented hereafter were obtained using the finest mesh density.

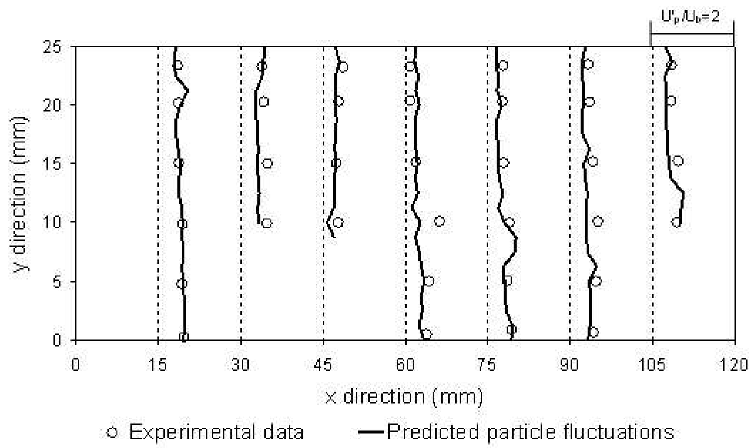
Particles (material density 2990 kg/m^3) with corresponding diameters of 30 μm and 93 μm were simulated. The normal restitution coefficient e_n, the dynamic friction coefficient μ_d and the wall roughness degree of 100 μm glass particles impacting on a steel surface measured by Sommerfeld & Huber [7] were used in the particle-wall collision model and the wall roughness model. Since their experiments were conducted in a narrow channel, the range of observed incident angle in experiment was relatively low—up to about 45°. So the restitution coefficients above 45° were assumed to have the same value as 45°, namely 0.52. The particle dynamic friction coefficient μ_d was 0.15.

Figure 5 shows the validation of numerical results against the experimental data for velocity and turbulence intensity profiles of 93 μm glass particles. Fifty thousand particles were injected from 50 uniformly distributed points across the line $x = 0$ mm, which were individually tracked within the tube bank. In Figure 5(a), the Lagrangian model marginally under predicted the streamwise particle velocity from $x = 45$ mm to $x = 90$ mm. Figure 5(b) shows the comparison of particle fluctuations; there is a generally good agreement between the experimental and predicted data.

For gas-particle flows, the dimensionless Stokes Number, $\mathrm{St} = t_p/t_s$, represents an important criteria towards better understanding the state of particles whether they are in kinetic equilibrium with the surrounding gas. The system relaxation time t_s in the Stokes number definition has been deter-



(a)



(b)

FIGURE 5: Predictions of 93 μm particles: (a) streamwise velocity; (b) fluctuation.

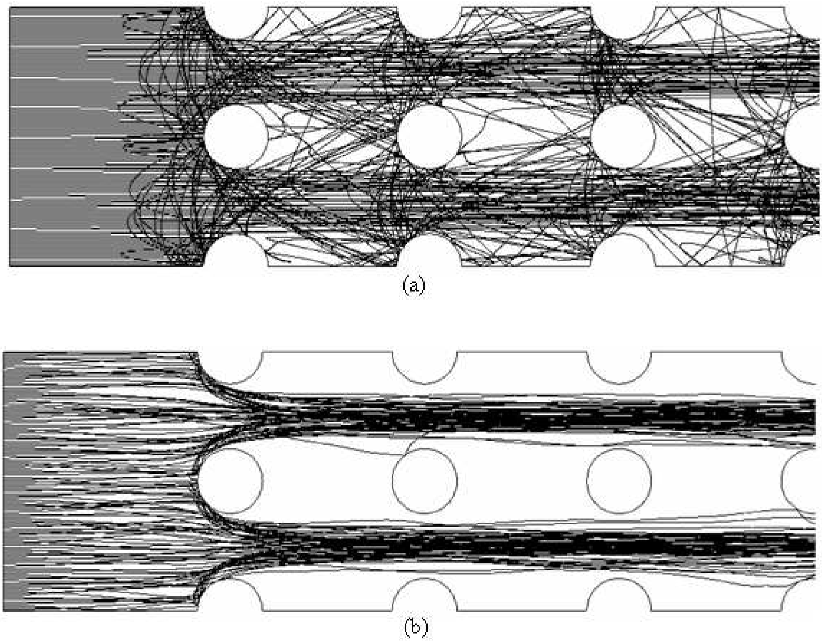


Figure 6: Computed trajectories: (a) 93μm particles; (b) 30μm particles.

mined from the characteristic length ($L_s = D = 25\,\text{mm}$) and the characteristic velocity ($V_s = 11.2\,\text{m/s}$) for the system under investigation, that is, $t_s = L_s/V_s$. For the case of 93 μm particles, the Stokes number was evaluated to be 31; a value much greater than unity. The influence from the gas phase turbulence onto the particles was found to be negligible. Rather, the particle phase velocity fluctuations were determined by particle-wall collisions. Figure 6(a) illustrates trajectories of 93 μm particles using the Lagrangian approach. Particles impacted on cylinders and rebounded to some considerable distance away from cylinders. As shown in Figure 6(b), 30 μm particles possessed lower inertia and gained less momentum to overcome the drag from the gas phase. This led to the significantly reduced distance traveled by the rebounded particle. Note that only a few particles impacted cylinders downstream the first line of cylinders.

Particle-wall collision models should consider the effect of wall roughness and the resulting stochastic nature of the process, since experimental investigations [2, 1] found that the particle restitution coefficient was subject to some scatter due to wall roughness and nonspherical particles [6]. Several models have been proposed to account for the effect of wall roughness [4, 11, 6]. One notable finding in the numerical study of gas-particle flows in a horizontal channel by Tsuji [11] was that particles eventually deposited on the bottom of the channel when using a traditional particle-wall collision model without the wall roughness model. This was not consistent with experimental observations that showed particles continued to be suspended in the fluid due to continuous rebounding from the roughened walls. When they applied a 'virtual wall model' to account for the wall roughness, the particles suspended and constituted a steady flow.

The effect of wall roughness on the particle rebounding characteristics was investigated. Figure 7(a) illustrates trajectories of forty 93 μm particles released at the location of $(-0.04, 0.0)$ without the wall roughness model. Most of the particles rebounding from the first middle cylinder re-collided with the same cylinder for a second time before colliding with the second

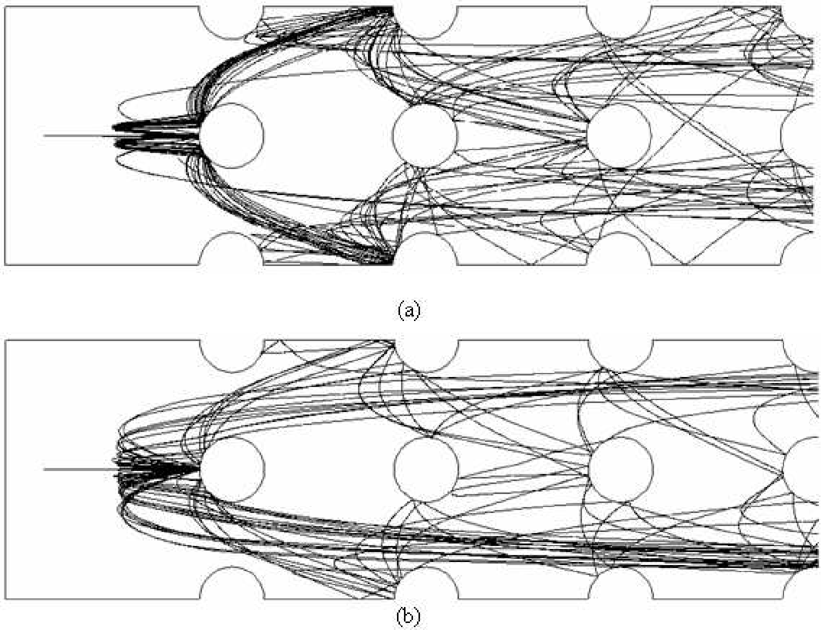


Figure 7: Computed trajectories for 93 μm particles: (a) without roughness model; (b) with roughness model.

upper and lower cylinders. When the wall roughness model was applied, in Figure 7(b), fewer particles were found re-colliding with the same first middle cylinder and consequently fewer particles impacted with the second upper and lower cylinders also.

4 Summary

This article is one of a continuing series of efforts to predict and analyse the particle rebounding characteristics of gas-particle flows and tube erosion in heat exchangers. The physical behaviours of particle rebounding flows in an in-line tube bank were numerically studied utilising a particle-wall collision model [6, 7] and a stochastic wall roughness model [6]. The performance of the particle-wall collision model was evaluated by validating the predictions of 93 μm particles against experimental data with good agreements.

The influence of particle-wall collisions on the particle fluctuation for different particle sizes was also investigated. The numerical results confirmed that the particle fluctuations were mainly determined through the particle-wall collisions for large particles, but not by the gas phase turbulence.

Through CFD simulations, it was established that the wall roughness considerably altered the rebounding behaviours of large particles, and consequently affected their motions downstream. This suggests that the particle-wall collision model should account for the effect of wall roughness in order to provide a more realistic description of the particle-wall collision phenomenon. Work is in progress to implement an empirical erosion model developed by Tabakoff et al. [8] into this wall collision model to predict tube erosion.

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