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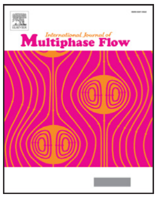

Analyzing the effect of wall roughness on gas–particle flow in confined channels based on a virtual-wall-group concept

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ABSTRACT

Present work aims to develop a particle history effect model for describing the effect of wall roughness on particle–wall collision in confined flow channels. To solve the real distribution function of roughness angle, the effective distribution function is scrutinized with a virtual testing method, and a further virtual-wall-group concept is proposed to investigate the effect of particle motion experience. It is found that roughness angle distribution should be described by a particle history effect–probability distribution function. Rebound angle is rebuilt according to the coordinate rotation operation. Multiple collisions are divided into two types, namely Type I induced by negative rebound and Type II led by positive rebound. Besides, a new probability function is derived to distinguish multiple collisions from a single collision. A set of modified algorithm for multi-collision is built and applied to simulate the particle–rough wall collision, and the predictions are evaluated by the measurements. It reveals that a typical peak can be seen in the probability distributions of both types of multiple collisions, and the effect of wall roughness decreases with the increase of impact angle. The simulated results of confined planar gas–particle flow are good in accordance with the measured data.

Introduction

The particulate two-phase flows within confined geometries where particle–wall interactions take an important role arise in many industrial applications (Lad and Issa, 2012). An example can be frequently encountered in the technology of bottom powder injection for ladle refining proposed by Cheng and Zhu (2014). In this new technique, particles are injected into molten bath through a device with a number of confined narrow slots to gain high kinetic energy. These injection devices are usually installed like a vertical riser, in which the confined particulate flows have two characteristics, namely, particles collide with the inner wall with a high frequency, and the collision angles are usually very small.

There are numerous parameters affecting the particle–wall inclination. Sommerfeld (1992) listed some important ones, of which wall roughness is known for its effects on not only the turbulent flow but also the particle–wall collision process (Sommerfeld and Huber, 1999; Tsuji et al., 1987), that produces a further impact on the dispersed phase according to the measurements of turbulent gas–particle flows in horizontal and vertical channels (Benson et al., 2005; Kussin and Sommerfeld, 2002). Napoli et al. (2008) showed that wall roughness causes a downward shift of the streamwise velocity in the log region and an increase of the drag coefficient for the turbulent flow. Laín and Sommerfeld (2008) pointed out that wall roughness makes a high collision frequency for inertial particles, but for particles with small-scale diameter it will give rise to a low collision frequency (Sommerfeld, 2003). From the measurements in horizontal turbulent two-phase channel flows of Kussin and Sommerfeld (2002), it was demonstrated that wall roughness enhances the transverse dispersion of particles and their fluctuation velocities. Thus the effects of wall roughness on the turbulent two-phase flows have to be taken into consideration.

The modeling of particle–rough wall interactions can be divided into two major categories: the deterministic modeling and the stochastic modeling, reviewed by Konan et al. (2009). Although the former gives more details of collision mechanism by constructing the rough wall structure, it is far too computationally expensive to effectively apply in numerical simulations. Nevertheless, some works have also been down based on this approach (Matsumoto and Saito, 1970a), e.g. Mando and Yin (2012) modeled the rough surface as a sine-shape with considering the shadow effect to simulate the gas–solid pipe flow. In contrast, the stochastic modeling is more practical, and it has been widely employed to analyze the effect of wall roughness on a colliding particle without describing the deterministic rough wall structure (Milici et al., 2014). Several stochastic approaches were proposed in literatures, and the virtual-wall concept gradually became one of the advanced methods. Tsuji et al. (1987) firstly introduced the virtual-wall modeling approach, and proposed

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an “Abnormal bouncing model”, while it could not reproduce the influence of the wall roughness for a larger incident angle. The measurements of wall roughness structure indicate that the physical roughness angle distribution could be approximated as a normal distribution function (Sommerfeld and Huber, 1999). However, the effective probability distribution function (EPDF) should shift toward positive due to the effect of particle incident perspective, namely, particles have more chances to hit the luff side (Schade and Hadrich, 1998). Considering this effect, Sommerfeld and Huber (1999) proposed a shadow effect model, in which the distribution function of wall roughness inclination seen by the given particle was modified by the EPDF, and they also gave a procedure to account for the shadow effect. The shadow effect model has been regarded as an advanced model for a long time, and widely adopted to model particle–rough wall collisions.

However, when the incident angle is small, the shadow effect model predicted many so-called grazing particles, namely, lots of rebound particles still remain in the near wall region, which causes closure problems in the derivation of rough wall boundary conditions (Konan et al., 2006). Konan et al. (2007) attributed the incapability of the model to the absence of mechanism permitting the grazing particles to return in the flow. According to the statistical analysis on the mechanism that particles rebound on two different rough wall geometries, Konan et al. (2009) proposed a so-called “rough wall multi-collision model” in which the random wall roughness angle was sampled from the EPDF, and the original procedure was further refined as a multiple rebound process. Through this new algorithm, the effect of incident angles on particle–rough wall collision could be reproduced. Mallouppas and van Wachem (2013) modified the multiple-collision model by introducing the repeated virtual wall, and particle–wall distance was used to judge the occurrence of one collision. While the multi-collision model, as well as the shadow effect model, adopted a single-virtual-wall concept, which ignored the effects of neighboring virtual walls and particle motion history, its probability distribution function (PDF) of roughness angle should be scrutinized. The previous model presented a formulation to determine the probability of single collision with probability analysis method, but it is still unclear what essentially causes and controls the multiple collisions. It requires much more information to understand the multi-collision process.

This paper makes great efforts to develop a wall roughness model considering the particle motion history effect to predict particle–wall collision in the light of a virtual-wall-group concept. Here, the model is abbreviated as particle history effect model, whose core consists of two aspects: a particle history effect–probability distribution function (PHE–PDF) and a refined particle–wall collision process. It begins with solving the real distribution of roughness angle, and then rebound angle is rebuilt with the coordinate rotation operation to predict the different types multiple rebound. The history coefficients are discussed by comparison with measurements. The calculated results are compared to the experiment. Finally, the new wall roughness model is applied to simulate a particulate two-phase flow in the confined planar jet.

Particle–wall collision model

Particle–wall collision process can be described by the momentum equations, whose solutions give a series of equations about the changing of particle translational and angular velocities with a critical condition for identifying a sliding and non-sliding rebound (Sommerfeld, 1992; Sommerfeld and Huber, 1999; Matsumoto and Saito, 1970b). Meanwhile, the previous work has done some modification on the particle–wall interaction model to simulate the particulate two-phase channel or pipe flows (Kuan et al., 2007; Tian et al., 2008). For a particle colliding with the smooth wall as shown in Fig. 1, the collision process is instantaneous. The present work adopts modified equations given as:

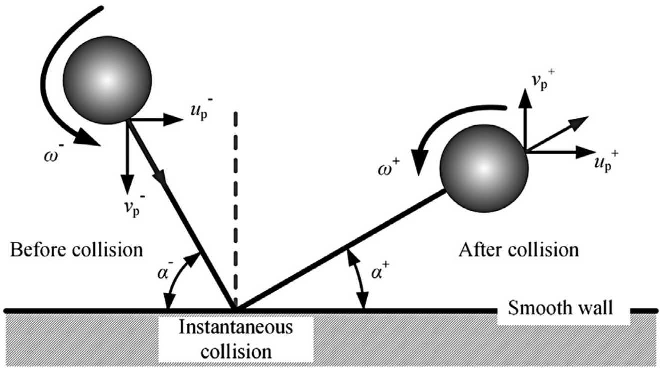

Fig. 1. Illustration of the velocities and angles before and after a collision between particle and smooth wall.

$$\text{Tangential velocity} \qquad u_p^+ = e_t u_p^- \tag{1}$$

$$\text{Normal velocity} \qquad v_p^+ = e_n v_p^- \tag{2}$$

$$\text{Angular velocity} \qquad \omega^+ = e_a \omega^- \tag{3}$$

Where, the subscript p refers to the particle variables, the superscript “–” and “+” refer to the impact parameters before and after collision, separately, and e is the restitution coefficient with the subscripts t, n and a identifying the tangential, normal and angular velocities of a particle. u is the tangential velocity component, v is the normal velocity component, and ω is the angular velocity. The corresponding collision restitution coefficients can be written as follows:

Tangential restitution coefficient:

$$e_t = \begin{cases} 5/7 + d_p\omega^-/(7u_p^-), & |\Delta u| \le u_c(\text{non}-\text{sliding collision}) \\ 1.0 - \mu_d(1+e_n)\varepsilon_0 v_p^-/u_p^-, & |\Delta u| \ge u_c(\text{sliding collision}) \end{cases} \tag{4}$$

Normal restitution coefficient:

$$e_n = \max\left(\frac{e_h - 1}{\alpha_e}\alpha^- - 1, e_h\right) \tag{5}$$

Angular restitution coefficient:

$$e_a = \begin{cases} 2/7 + 10u_p^-/(7d_p\omega^-), & |\Delta u| \le u_c(\text{non}-\text{sliding collision}) \\ 1.0 + 5\mu_d(1+e_n)\varepsilon_0 v_p^- /(d_p\omega^-), & |\Delta u| \ge u_c(\text{sliding collision}) \end{cases} \tag{6}$$

Here, μ_d is the dynamic friction coefficient, which is function of impact angle. It is can be obtained based on the theory of Sommerfeld and Huber (1999)

$$\mu_d = \max\left(\frac{\mu_h - \mu_0}{\alpha_\mu}\alpha^- + \mu_0, \mu_h\right) \tag{7}$$

Δu represents the relative velocity between particle surface and wall, and ε_0 refers to its directions. They are given as

$$\Delta u = u_p^- - 0.5 d_p\omega^- \tag{8}$$

$$\varepsilon_0 = \text{sign}(\Delta u) \tag{9}$$

u_c is the critical value of sliding and non-sliding collision, and it can be written by

$$u_c = 3.5\mu_d(1+e_n)v_p^- \tag{10}$$

For simulating the effect of wall roughness, the stochastic approach of Sommerfeld and Huber (1999) is employed. It works with a virtual-wall concept, namely, particles are assumed to collide with a smooth