A New Model for Two-dimensional Numerical Simulation of Pseudo-2D Gas-solids Fluidized Beds

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Abstract

Pseudo-two dimensional (pseudo-2D) fluidized beds, for which the thickness of the system is much smaller than the other two dimensions, is widely used to perform fundamental studies on bubble behavior, solids mixing, or clustering phenomenon in different gas-solids fluidization systems. The abundant data from such experimental systems are very useful for numerical model development and validation. However, it has been reported that two-dimensional (2D) computational fluid dynamic (CFD) simulations of pseudo-2D gas-solids fluidized beds usually predict poor quantitative agreement with the experimental data, especially for the solids velocity field. In this paper, a new model is proposed to improve the 2D numerical simulations of pseudo-2D gas-solids fluidized beds by properly accounting for the frictional effect of the front and back walls. Two previously reported pseudo-2D experimental systems were simulated with this model. Compared to the traditional 2D simulations, significant improvements in the numerical predictions have been observed and the predicted results are in better agreement with the available experimental data.

Key words: computational fluid dynamics, fluidized bed, pseudo-2D system, gas-solids flow, two-fluid model, wall friction

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1. Introduction

In experimental studies of fluidized beds, pseudo-2D fluidized beds (also referred to as 2D fluidized beds) are frequently encountered in literature. These beds usually have a rectangular cross section with one dimension significantly less than the other, typically by an order of magnitude. There is no strict guideline on how a pseudo-2D column should be designed. A general rule for constructing a pseudo-2D fluidized bed is that the bed thickness should be less than the characteristic length of the flow, i.e., bubble size, to facilitate better observation or imaging measurement (Jin et al., 2001). A unique feature of a pseudo-2D system is its ability to facilitate the employment of non-intrusive visual or imaging techniques to directly observe and measure the complex inside flow movements. With this distinctive advantage, pseudo-2D systems have been widely used in fundamental fluidization studies, such as the studies of bubble properties, jet penetration, solids clustering, solids flow patterns, and solids mixing and segregation, (e.g. Rowe et al., 1965; Lim et al., 1990; Caicedo et al., 2003; Goldschmidt et al., 2003; Zhong and Zhang, 2005; Pallares and Johnsson, 2006; Busciglio et al., 2008; Laverman et al., 2008; Zhang et al., 2008; Xu and Zhu, 2011). The qualitative and quantitative information gathered from these pseudo-2D systems has been used to develop models for describing the gas-solids flow. The established models are then utilized to improve understanding of flow behaviors in three-dimensional (3D) fluidized beds including those used in various industrial processes.

With fast acceleration in computational power and continuous development in numerical algorithms, computational fluid dynamics (CFD) has become an effective complementary tool to the experiment for understanding the complex hydrodynamics in gas-solids flows (Grace and Li, 2010). Prior to application of CFD models to complex industrial processes, extensive validation of the numerical models is needed (Grace and Taghipour, 2004). In this regard, large amounts of accurate experimental data are needed for model validation. Through employment of advanced imaging techniques, such as Particle Image Velocimetry (PIV) and Digital Image Analysis (DIA), a great amount of quantitative information is available for pseudo-2D fluidized beds. Such experimental data are highly useful for CFD model validation owing to the high data quality and simple geometrical configuration.

Abundant numerical studies of different gas-solids fluidization systems can be found in open literature. In most CFD studies, 2D simulations were used to simulate the flow hydrodynamics in both pseudo-2D and 3D cylindrical fluidization systems. The differences between 2D and 3D simulations of gas-solids fluidized beds and the applicability of simulating a 3D cylindrical column by a 2D model have been discussed in several papers (Peirano et al., 2001; Cammarata et al., 2003; Xie et al., 2008a; Xie et al., 2008b; Li et al., 2010b; Cloete et al., 2013a; Li et al., 2013). Unlike the 3D cylindrical gas-solids fluidized beds, it is natural that 2D simulations are used to simulate pseudo-2D experimental systems for predicting the flow hydrodynamics as has been done in previous studies (Busciglio et al., 2009; Li et al., 2010a; Hernandez-Jimenez et al., 2011). Good qualitative agreement on general flow behaviors including patterns of solids mixing and bubble movement, and satisfactory quantitative agreement on bed expansion, bubble size distribution, shape factors between 2D numerical simulations and experimental measurements have been reported. However, there exist significant differences between the predictions of 2D numerical simulations and the experimental data from pseudo-2D columns with respect to bubble rising velocity and solids velocity, especially the latter. It has been reported by several researchers that 2D numerical simulations significantly over-predicted the solids velocity in pseudo-2D bubbling fluidized beds (Li et al., 2010a; Hernandez-Jimenez et al., 2011; Cloete et al., 2013b).

In a thin pseudo-2D fluidized bed, the front and back walls restrict the solids movement in two directions and the friction exerted by the front and back walls further influences the solids movement. This leads to different flow behaviors from a 3D cylindrical system as has been discussed in previous studies (Rowe and Everett, 1972; Geldart, 1970; Cranfield and Geldart, 1974; Glicksman and McAndrews, 1985). For example, the bubble coalescence, bubble properties, and even the bed expansion in a pseudo-2D bed differ from those in a 3D bed. Strictly speaking, the gas-solids flow in a pseudo-2D fluidized bed does not follows an absolute 2D pattern. In some pseudo-2D fluidized beds with considerable thickness, there might exist strong 3D flow behaviors which not only cause issues in detecting small bubbles for most non-invasive visual or imaging techniques, but also prevent the modeler from simplifying the flow into 2D. Even in pseudo-2D beds with small bed thickness where a good 2D flow is expected, the 2D numerical simulations cannot yield reasonable agreement with the experimental solids velocity field. It has been demonstrated that the frictional effect from the front and back walls, which is not accounted for in the 2D simulations, leads to the deviation for solids velocity and bubble rising velocity (Li et al., 2010a; Cloete et al., 2013b). The wall effect in numerical simulations of pseudo-2D gas-solids systems has been investigated in several numerical studies (Kawaguchi et al., 1998; Feng and Yu, 2010; Li et al., 2010a; Li et al., 2012; Cloete et al., 2013b). These studies all recommended a 3D simulation to get more accurate prediction of pseudo-2D gas-solids fluidized beds, i.e. the wall effect must be included. However, for a 3D simulation of thin pseudo-2D column, sufficient grid resolution in the thickness direction is needed to account for the frictional effect from the front and back walls and to resolve the possible 3D flow behavior. The large computational cell aspect ratio tends to cause difficulty in computation convergence when normal grid sizes are used for the other two dimensions. Furthermore, the flow behavior of the third dimension in a thin pseudo-2D column is of less interest for model validation purpose. Considering the expensive computational cost associated with the 3D simulations and the target flow field information for validation, it is therefore preferential to conduct 2D simulations for pseudo-2D fluidized beds.

The objective of this study is to propose a model for 2D simulations to account for the front and back wall effect in a pseudo-2D gas-solids fluidized bed for better numerical prediction. This paper is organized as follows. First, a brief summary of the two-fluid model is presented. The new model is then proposed to account for the frictional effect of the front and back walls in a 2D simulation after introducing certain assumptions for the pseudo-2D fluidization system modeling. The newly proposed method is utilized to simulate two experimentally studied pseudo-2D bubbling fluidized beds. Finally, the numerical results are analyzed and compared to the experimental data for validation.

2. Two-Fluid Model

In this study, a two-fluid model (TFM), which treats both gas and solids phases as interpenetrating continuums, is used to simulate the gas-solids flow in fluidized beds. The governing equations derived from an appropriate averaging procedure are solved using the finite volume method. In order to close the governing equations, constitutive correlations derived from the granular kinetic theory are used for describing the solids phase stress. The governing equations, along with constitutive correlations, are solved in an open-source CFD code, MFIX, which is developed at the U.S. Department of Energy’s National Energy Technology Laboratory. A brief summary of equations solved in MFIX is provided in Table 1. More details on the theory and numerical techniques used by MFIX can be found at https://mfix.netl.doe.gov (Syamlal et al., 1993; Syamlal, 1998).

Table 1. Summary of MFIX equations.

A. Governing equations

(a) Continuity equations

Gas phase $$\frac{\partial}{\partial t}(\varepsilon_g \rho_g) + \nabla \cdot (\varepsilon_g \rho_g \vec{V}_g) = 0$$

Solid phase $$\frac{\partial}{\partial t}(\varepsilon_p \rho_p) + \nabla \cdot (\varepsilon_p \rho_p \vec{V}_p) = 0$$

(b) Momentum equations

Gas phase $$\frac{\partial}{\partial t}(\varepsilon_g \rho_g \vec{V}_g) + \nabla \cdot (\varepsilon_g \rho_g \vec{V}_g \vec{V}_g) = \nabla \cdot \bar{\bar{\tau}}_g - \varepsilon_g \nabla P + \varepsilon_g \rho_g g - I_{gp}$$

Solid phase $$\frac{\partial}{\partial t}(\varepsilon_p \rho_p \vec{V}_p) + \nabla \cdot (\varepsilon_p \rho_p \vec{V}_p \vec{V}_p) = \nabla \cdot \bar{\bar{\tau}}_p - \varepsilon_p \nabla P + \varepsilon_p \rho_p g + I_{gp}$$

B. Constitutive equations

(a) Gas stress tensor

$$\bar{\bar{\tau}}_g = 2\mu_{ge} \bar{\bar{S}}_g$$

$$\bar{\bar{S}}_g = \frac{1}{2}\left(\nabla \vec{V}_g + (\nabla \vec{V}_g)^T\right) - \frac{1}{3}(\nabla \cdot \vec{V}_g)\bar{\bar{I}}$$

(b) Solid stress tensor

$$\bar{\bar{\tau}}_p = \left(-P_s + \eta \mu_b \nabla \cdot \vec{V}_p\right)\bar{\bar{I}} + 2\mu_p \bar{\bar{S}}_p$$

$$\bar{\bar{S}}_p = \frac{1}{2}\left(\nabla \vec{V}_p + (\nabla \vec{V}_p)^T\right) - \frac{1}{3}(\nabla \cdot \vec{V}_p)\bar{\bar{I}}$$

$$P_s = \varepsilon_p \rho_p \Theta_p [1 + 4 g_0 \varepsilon_p \eta]$$

$$\mu_p = \left(\frac{2+\alpha}{3}\right)\left[\frac{\mu_p^*}{g_0\eta(2-\eta)}\left(1+\frac{8}{5}\eta g_0\varepsilon_p\right)\left(1+\frac{8}{5}\eta\left(3\eta-2\right)g_0\varepsilon_p\right)+\frac{3}{5}\eta\mu_b\right]$$

$$\mu_p^* = \frac{\varepsilon_p\rho_p\Theta_p g_0\mu}{\varepsilon_p\rho_p\Theta_p g_0 + \dfrac{2\beta\mu}{\varepsilon_p\rho_p}}$$

$$\mu = \frac{5}{96}\rho_p d_p\sqrt{\pi\Theta_p}$$

$$\mu_b = \frac{256}{5\pi}\mu\varepsilon_p^2 g_0$$

$$\eta = \frac{1+e}{2}$$

(c) Frictional stress

$$P_f = \begin{cases} 10^{24}(\varepsilon^* - \varepsilon_g)^{10} & \varepsilon_g < \varepsilon^* \\ 0 & \varepsilon_g \geq \varepsilon^* \end{cases}$$

$$\mu_f = \begin{cases} \min\left(\dfrac{P_f \sin(\phi)}{\sqrt{4I_{2D}}},\ \mu_s^{\max}\right) & \varepsilon_g < \varepsilon^* \\ 0 & \varepsilon_g \geq \varepsilon^* \end{cases}$$

(d) Granular temperature

$$\frac{3}{2}\left[\frac{\partial}{\partial t}(\varepsilon_p\rho_p\Theta_p) + \nabla\cdot(\varepsilon_p\rho_p\vec{V}_p\Theta_p)\right] = \overline{\overline{\tau}}_p : \vec{V}_p + \nabla\cdot\left(\kappa_{p,\Theta}\nabla\Theta_p\right) + \Pi_{gp} - \varepsilon_p\rho_p J_p$$

$$\kappa_{p,\Theta} = \frac{\kappa_p^*}{g_0}\left[\left(1+\frac{12}{5}\eta\varepsilon_p g_0\right)\left(1+\frac{12}{5}\eta^2(4\eta-3)\varepsilon_p g_0\right)+\frac{64}{25\pi}(41-33\eta)\eta^2\varepsilon_p^2 g_0^2\right]$$

$$\kappa_p^* = \frac{\rho_p\varepsilon_p g_0\Theta_p\kappa}{\rho_p\varepsilon_p g_0\Theta_p + \dfrac{6\beta\kappa}{5\rho_p\varepsilon_p}}$$

$$\kappa = \frac{75\rho_p d_p\sqrt{\pi\Theta_p}}{48\eta(41-33\eta)}$$

$$J_p = \frac{48}{\sqrt{\pi}}\eta\left(1-\eta\right)\frac{\varepsilon_p g_0\Theta_p^{3/2}}{d_p}$$

$$\Pi_{gp} = -3\beta\Theta_p + \frac{81\varepsilon_p\mu_g^2\left|\vec{V}_g - \vec{V}_p\right|^2}{g_0 d_p^3 \rho_p \sqrt{\pi\Theta_p}}$$

(e) Inter-phase momentum exchange

$$I_{gp} = \beta\left(\vec{V}_g - \vec{V}_p\right)$$

$$\beta = \begin{cases} 150\dfrac{\varepsilon_p^2\mu_g}{\varepsilon_g d_p^2} + 1.75\dfrac{\varepsilon_p\rho_g\left|\vec{V}_p - \vec{V}_g\right|}{d_p} & \text{if } \varepsilon_p > 0.2 \\ \dfrac{3}{4}C_d\varepsilon_g^{-2.65}\dfrac{\varepsilon_p\varepsilon_g\rho_g\left|\vec{V}_p - \vec{V}_g\right|}{d_p} & \text{if } \varepsilon_p \le 0.2 \end{cases}$$

$$C_d = \begin{cases} \dfrac{24}{\mathrm{Re}\cdot\varepsilon_g}(1 + 0.15(\mathrm{Re}\cdot\varepsilon_g)^{0.687}) & \text{if } \mathrm{Re}\cdot\varepsilon_g < 1000 \\ 0.44 & \text{if } \mathrm{Re}\cdot\varepsilon_g \ge 1000 \end{cases}$$

$$\mathrm{Re} = \frac{\rho_g\left|\vec{V}_p - \vec{V}_g\right| d_p}{\mu_g}$$

3. Friction Model for Front and Back Walls

For the gas phase, a non-slip boundary condition is usually applied in gas-solids flow simulations, which is believed to be reasonable for most cases. For a pseudo-2D fluidized system with mono-dispersed solid particles, it has been demonstrated that the solids phase behavior dominates the flow and the effect of the gas flow boundary condition is negligible (Li et al., 2012). Different wall boundary conditions for the solids phase can be found in literature covering free-slip, partial-slip, and non-slip boundary conditions. It is generally believed that the partial-slip boundary condition is more physical, which accounts for both shear force and flux of fluctuation energy imposed by the wall on the solids flow. (Johnson and Jackson, 1987; Jenkins, 1992; Schneiderbauer et al. 2012).

The effect of front and back walls cannot be modeled through the wall boundary conditions as these walls are not included in the computational domain of 2D simulation. To account for the wall effect on the solids flow, the shear stress and flux of fluctuation energy applied by the front and back walls must be taken into account. To simplify this analysis, the collisions between particles and the front and back walls are assumed to be sliding (Jenkins, 1992; Li and Benyahia 2012). Hence, the shear force applied to the granular flow by these walls can be calculated based on the boundary condition proposed by Jenkins and Louge (1997) at the small friction/all sliding limit. This simplification is justified by the fact that the small distance between front and back walls confines the solids velocity, $V_{p,z}$, and its fluctuation, $V'_{p,z}$, in the thickness direction. According to Jenkins (1992) and Li and Benyahia (2012), the resultant high normalized slip velocity, $r = \left|\vec{V}_{sl}\right| / \left|V'_{p,z}\right|$, indicates a high possibility of sliding collisions. Based on this assumption, analytical expressions for the shear stress and the flux of fluctuation energy at the wall were derived by Jenkins and Louge (1997) based on Maxwellian velocity distribution function.

$$S = \mu_{fric} N \tag{1}$$

and

$$Q = N\sqrt{3\Theta_p}\,\frac{2}{1+e_w}\sqrt{\frac{2}{3\pi}}\left(\frac{1}{7}\mu_0^2 - \frac{1}{2}\left(1-e_w^2\right) - \mu_0\mu e_w\left(\frac{1+e_w}{e_w + 2/e}\right)\right) \tag{2}$$

where, S is the shear stress, N is the normal stress due to particle interaction, μ_{fric} is the particle-wall frictional coefficient, e and e_w are particle-particle and particle-wall restitution coefficients, respectively, and μ_0 is defined as

$$\mu_0 = \frac{7}{2}\left(1+e_w\right)\mu_{fric} \tag{3}$$

It should be noted that the above expressions are derived based on granular kinetic theory for the rapid flow regime in which particle collisions dominate. It does not account for the frictional flow when the solids concentration is high and particles start to endure long, sliding, and rubbing contacts. In this regime, the solids flow is slow and the surface friction between particles becomes significant. This reflects the transition between two limiting flow regimes: rapid flow and quasi-static flow. It is extremely difficult to construct theoretical models for the frictional flow regime. For the frictional flow regime, the constitutive models are largely based on soil mechanics (Savage, 1982; Johnson and Jackson, 1987; Shaeffer, 1987; Tardos, 1997; Srivastava and Sundaresan 2003). An *ad hoc* patching approach was suggested by Savage (1982) to unify the available models for rapid flow regime and quasi-static regime. To account for the frictional flow, the normal stress is rewritten as

$$N = P_s + P_f \tag{4}$$

where, P_s is the collisional solids pressure closed by granular kinetic theory, and P_f is the normal frictional stress or frictional solids pressure, usually calculated based on empirical correlations (Johnson and Jackson, 1987; Syamlal et al. 1993).

For a pseudo-2D column with limited bed thickness, the solids flow is expected to manifest good 2D flow behavior, i.e. the variation of solids velocity along the thickness direction is negligible. It can be safely assumed that the shear stress imposed by the wall propagates throughout the thickness. This is usually true for the emulsion phase of a dense fluidized bed where the frictional force dominates and propagates a certain distance into the inner region from the wall (Nedderman and Laohakul, 1980). For the dilute solids flow inside bubbles, it is unclear how the walls frictional force propagates toward the inner region along the thickness direction. However, it is believed that the wall's frictional effect is small in the dilute phase compared to the dense phase. With this in mind, the shear force imposed by the front and back walls can be interpreted as a body force, $\vec{s}$, acting on the solids flow in the 2D simulation, defined as

$$\vec{s} = -\frac{2S}{h}\frac{\vec{V}_p}{\left|\vec{V}_p\right|} \tag{5}$$

where, h, is the thickness of the pseudo-2D column. Clearly, the frictional effect tends to hinder the movement of solids phase relative to the wall. The equivalent body force due to wall friction increases as the bed thickness decreases. On the other hand, the equivalent body force becomes negligible for a system with great bed thickness. It should be noted that the system should exist considerable 3D flow behaviors under such circumstances and the current model is not applicable any more.

Similarly, the flux of fluctuation energy supplied by the wall to the solids flow can be considered as an energy source written as

$$q = \frac{2Q}{h} \tag{6}$$

As has been discussed that the flux of fluctuation energy from the wall is calculated for the rapid granular flow regime, only the solids pressure due to particle collisions, P_s, is used in Equation (2). While both collisional and frictional solids pressures as indicated in Equation (4) are used to calculate the shear stress. It will be demonstrated that the flux of fluctuation energy supplied by the wall has less effect on the flow hydrodynamics compared to the frictional force by the wall.

4. Numerical Results

The model proposed above was implemented into MFIX to conduct numerical simulations of two pseudo-2D bubbling fluidized beds. Comparisons between numerical results with and without the proposed model are made, as well as a brief validation against the available experimental data.

4.1 Case 1: System of Laverman et al. (2008)

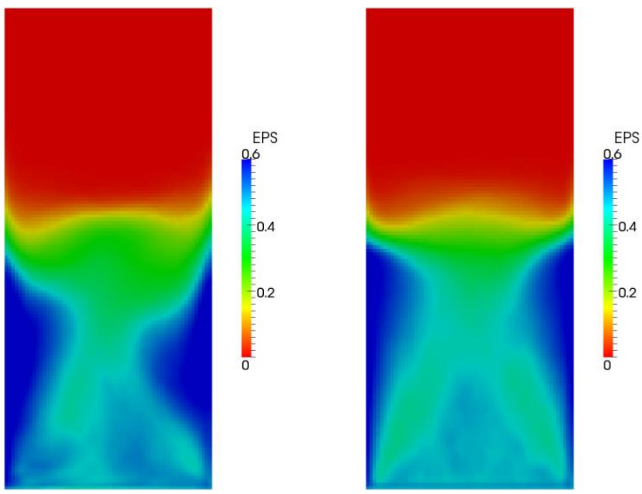
The first simulation is based on the experimental set-up of Laverman et al. (2008). In their experiments, a pseudo-2D fluidization system that is 0.30m wide, 0.7m high, and 0.015m thick was tested. Glass beads with a narrow particle size distribution of 400-600 μm and an average particle diameter of 485 μm were fluidized by air at different superficial gas velocities. The hydrodynamics were investigated experimentally for various conditions through PIV and DIA techniques. Both bubble behavior and emulsion phase circulation patterns were measured. Here, an experimental condition with a static bed height of 0.30m and a superficial gas velocity of 0.45 m/s, corresponding to $2.5U_{mf}$, is simulated to evaluate the new model for 2D simulations. Conditions and physical parameters for the numerical simulations are summarized in Table 2.

Table 2. Conditions and physical parameters used in the numerical simulations.

Property	**Value**
gas density, kg/m^3	1.2
gas viscosity, Pa.s	1.8×10^{-5}
particle diameter, μm	485
particle density, kg/m^3	2500
minimum fluidization velocity, m/s	0.18
column width, m	0.30
column height, m	0.70
column thickness, m	0.015
superficial gas velocity, m/s	0.45
particle-particle restitution coefficient, -	0.95
particle-wall restitution coefficient, -	0.8
specularity coefficient, -	0.005
particle-wall friction coefficient, -	0.3
initial bed voidage, -	0.40
initial bed height, m	0.30

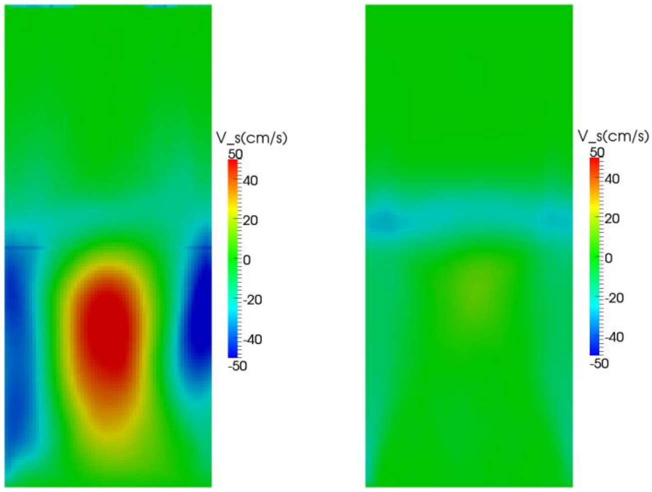
At the top boundary, a constant pressure is assumed and particles are allowed to leave the domain. For the bottom distributor, a uniform gas velocity is specified, with no particle entering the domain. For the lateral sidewalls, a non-slip boundary condition for the gas phase and the Johnson and Jackson (1987) partial-slip boundary condition for the solids phase with a specularity coefficient of 0.005, which was reported to yield the best agreement with experimental data for 3D simulations, are adopted. All numerical simulations use a uniform grid size of 5mm according to a previous grid study for the same system (Li et al., 2010a). The simulation has been conducted for 100s of real time, with the last 90s being used to extract the mean flow field information for analysis.

Figures 1 and 2 compare the mean flow field information of the 2D numerical simulations averaged over 90s with and without consideration of the frictional effect of the front and back walls for the mean solids volume fraction and solids vertical velocity, respectively. With this simple configuration, a reasonably symmetric mean flow field is obtained. A perfectly symmetric flow field demands a much longer time period for the simulation (Dietiker, 2012). One simulation has been extended to 10min, which shows better symmetric flow behavior, but little change in the mean flow field. It is believed that 100s simulation is long enough to get meaningful time-averaged flow information for the current study. The comparison between Figures 1 and 2 reveals that the friction from the front and back walls has a significant impact on the flow behavior. For the solids volume fraction results, there is no remarkable differences when the frictional effect is accounted for. Both simulations show dense flow along the side walls and a low solids concentration in the central region. However, there do exist subtle differences in the mean solids volume fraction distributions. For example, there is a wider transition from dense flow to the freeboard in Figure 1(a) comparing to Figure 1(b). Moreover, Figure 1(b) presents better symmetric pattern. Since the solids concentration distribution is closely related to the movement of bubbles inside the bed, it can be concluded that the bubble distribution and movement are affected by the frictional effect of front and back walls. When the solids velocity field is examined, there is a much stronger solids upward flow in the central region and downward flow along two side walls by the conventional 2D simulation. This indicates a strong internal solids circulation and hence vigorous solids mixing. However, with the front and back frictional effects considered, the solids mixing is dampened substantially. This can be demonstrated from the simulated maximum solids velocity which, as seen in Figure 2(b), decreases by an order of magnitude.



(a) (b)

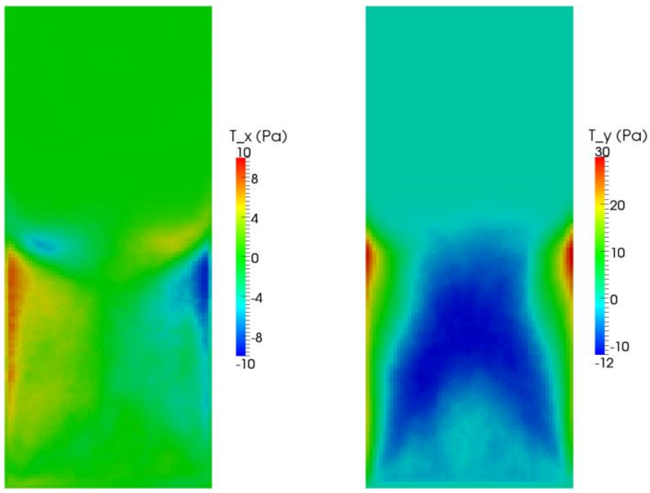
Figure 1. Mean solids volume fraction averaged over 90s for (a) the conventional 2D simulation and (b) the 2D simulation with the new model to account for the frictional effect of the front and back walls.



(a) (b)

Figure 2. Mean solid vertical velocity averaged over 90s for (a) the conventional 2D simulation and (b) the 2D simulation with the new model to account for the frictional effect of the front and back walls.

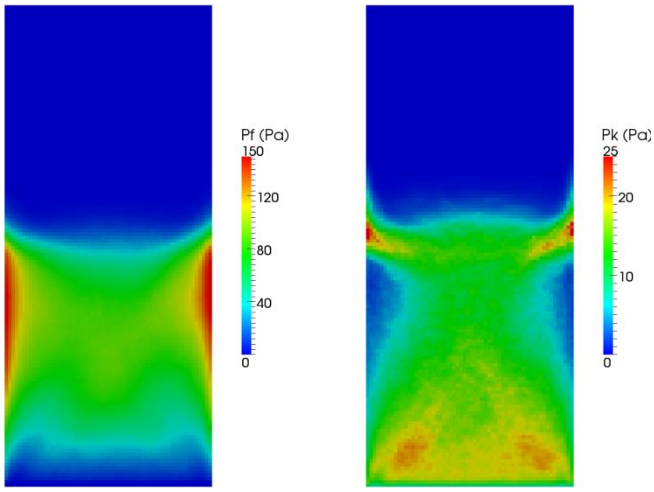
To understand how the frictional force from the front and back walls affects the flow inside the system, the mean shear stress calculated through Equation (5) in two directions of the simulated domain is shown in Figure 3. The shear stress from the front and back walls prevents the solids from flowing, hence reduces the internal solids velocity and mixing intensity. The strong frictional force exists in the regions close to the wall with high solids concentration which leads to high normal force on the wall, i.e. solids pressure.



(a) (b)

Figure 3. Mean shear stress applied to the solids flow by the front and back walls (a) component in x direction; (b) component in y direction.

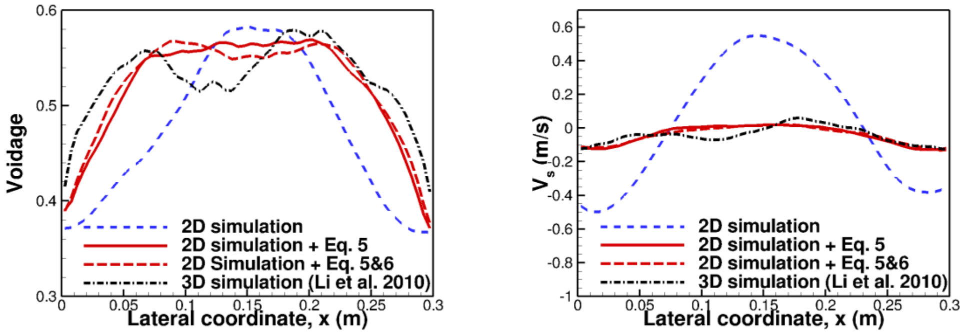
The shear stress shown in Figure 3 is originated from the normal force applied by the particle flow to the wall. As previously discussed, normal force consists of a kinetic component due to particle-wall collisions and a frictional component due to long-period particle-wall contacts. The solids pressures are examined in Figure 4 to help further understand the origin of shear stress by the wall friction. The emulsion phase with solids concentration close to packing dominates the flow for the dense bubbling fluidized bed. The normal stress is mainly from the dense frictional flow close to the left and right walls that displays much higher magnitude compared to the collisional solids pressure. Considering the collisional solids pressure derived from the kinetic granular theory is closely related to the bubbling behavior, it shows a different pattern of distribution than the frictional solids pressure.



(a) (b)

Figure 4. Mean solids pressure distributions averaged over 90s (a) frictional solid pressure and (b) collisional solid pressure.

The lateral profiles of mean voidage and vertical solids velocity at a 0.2m height from the bottom distributor are compared in Figure 5 for the 2D simulations with and without the friction from the front and back walls. For the same system, both 2D and 3D numerical simulations were reported by Li et al. (2010a) in the previous study to evaluate the wall effect. For comparison, the previous numerical results from a 3D simulation of the same system are also shown in Figure 5. As can be seen from the comparison, without appropriate accounting for the front and back wall friction, the solids concentration by the conventional 2D simulation is low in a narrower central band compared to the 2D simulation with the front and back wall friction and the 3D simulation. The difference is more distinct when the profiles of mean solids velocity are compared. The conventional 2D simulation predicts a much higher magnitude of velocity in the center and wall regions compared to the 3D results. The 2D simulation, with the newly proposed model, predicts a maximum solids velocity is an order of magnitude smaller than the conventional 2D simulation and shows a good resemblance to that of the 3D numerical simulation. It should be noted that the 3D simulation was only 10s, which leads to less smooth profiles compared to the 2D simulation results for a longer time period (Li et al., 2010a).

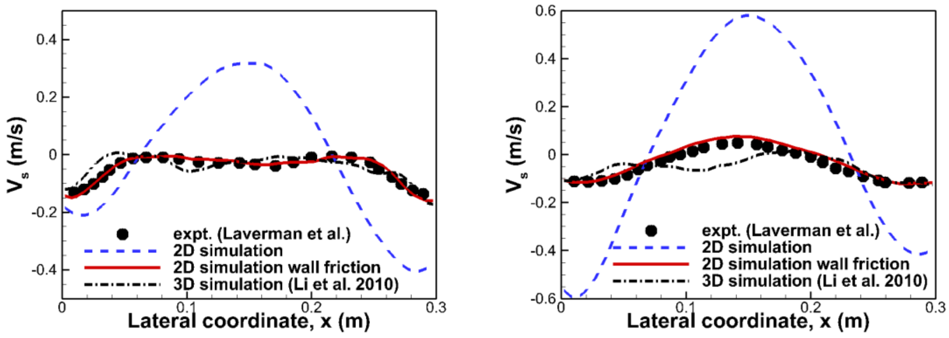


(a) (b)

Figure 5. Lateral profiles of mean (a) voidage and (b) solids vertical velocity at a height of 0.2 m.

The model presented in Section 3 consists of two parts: Equation (5) accounts for the shear force imposed by the front and back walls and Equation (6) accounts for the flux of fluctuation energy supplied by the wall. Since the flux of fluctuation energy by the wall mainly affects the distribution of granular temperature and indirectly affects the solids pressure and solids viscosity, it is expected that the effect of the second part of this model is less important. To confirm this, the numerical results of the new model, with and without Equation (6), are also compared in Figure 5. As can be seen from the comparison, the flow hydrodynamics predicted with and without Equation (6) are very close with respect to voidage and solids velocity. Further comparison of the whole flow field indicates the source term in the granular temperature equation has a negligible effect on the flow field, except in the bed surface region where the solids concentration is relatively low because of bubble bursting.

The numerical results are further compared to the experimental data reported by Laverman et al. (2008) for validation. Comparison is presented in Figure 6 with respect to the lateral solids velocity profiles at two elevations, 0.1m and 0.245m above the distributor. Again, the numerical results of the 3D simulation in the literature are shown for reference. It can be seen that the conventional 2D numerical simulation greatly over-predicts the solids velocity in both central and side wall regions for both levels. With the application of the proposed model to account for the front and back wall effect, the numerical results match the experimental data more accurately. Benefit from the low computational cost of the 2D simulation, a longer time simulation is able to be conducted to produce smoother mean flow field information for validation against the experimental data. This is usually difficult for the 3D simulation even though it is the most accurate way for modeling the pseudo-2D systems.



(a) (b)

Figure 6. Lateral profiles of mean solids vertical velocity at the height of (a) 0.105 m and (b) 0.245 m.

The mean solids velocity shown in Figure 6 is a simple time average of the transient results. However, according to Laverman et al. (2008) and Hernandez-Jimenez et al. (2011), the uncertainty in experimental measurement might be higher because of the solids particles that rain down from the top of the bubbles where the data accuracy is low. Thus, they proposed to use the dense phase solids velocity to quantify the solids movement inside the 2D bubbling bed. The velocity field of the dense phase, V, is calculated from the transient time-series data by coupling PIV and DIA measurements.

$$V(x,y) = \sum_{i=1}^{N} C_i(x,y) v_{s,i}(x,y) \Big/ \sum_{i=1}^{N} C_i(x,y) \tag{7}$$

where, $v_{s,i}$ is the solids velocity measurement by PIV, and C_i is the dense phase fraction with zero for the bubble and one for the dense phase determined from the DIA measurement. Following this experimental approach, similar post-processing is applied to our numerical results. With a threshold value of 0.3 in the solids volume fraction to define the interface between bubble and dense phases (Hernandez-Jimenez et al., 2011), the lateral profiles of time-averaged dense phase velocity profiles at different heights are compared against the experimental data in Figure 7. For three elevations of 0.105, 0.245, and 0.303m above the distributor, the numerical results with consideration of front and back wall friction all agree well with the experimental data. However, for the conventional 2D simulation which does not consider the front and back wall effect, there is still an obvious deviation from the experimental measurements of the dense phase velocity.

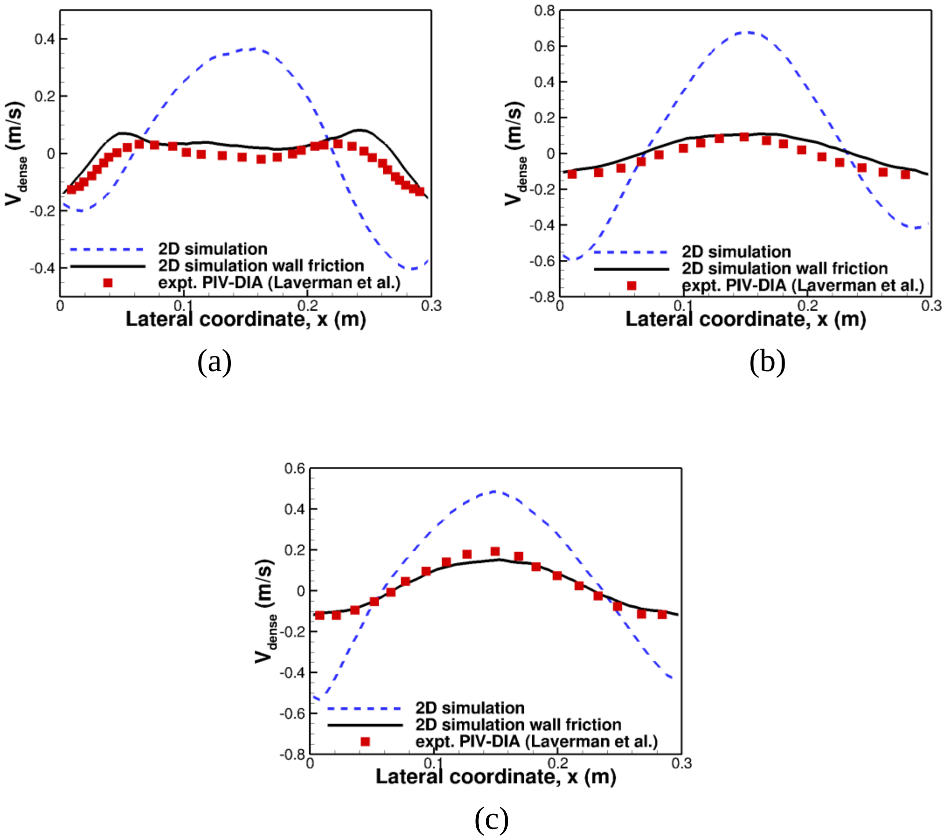


Figure 7. Lateral profiles of mean solids vertical velocity of the dense phase at the height of (a) 0.105 m; (b) 0.245 m; (c) 0.303m.

4.2 Case 2: System of Hernandez-Jimenez et al. (2011)

The pseudo-2D experiment of the bubbling fluidized bed by Hernandez-Jimenez et al. (2011) is also simulated. The experimental facility with dimension of 0.5m×2m×0.005m is simulated by a 2D domain of 0.5m×1m with certain freeboard region excluded. The system was initially filled by glass beads with a mean diameter of 700 μm and a particle density of 2500 kg/m^3 in 0.3m. The computational domain is discretized by a uniform grid of 6.25 mm. The superficial gas velocity of 0.62 m/s is simulated. Detailed parameters used in the simulations are given in Table 3. The boundary conditions are set similar to the previous case. A total of 80s of real-time simulation has been conducted and the last 70s of results are post-processed for analysis.

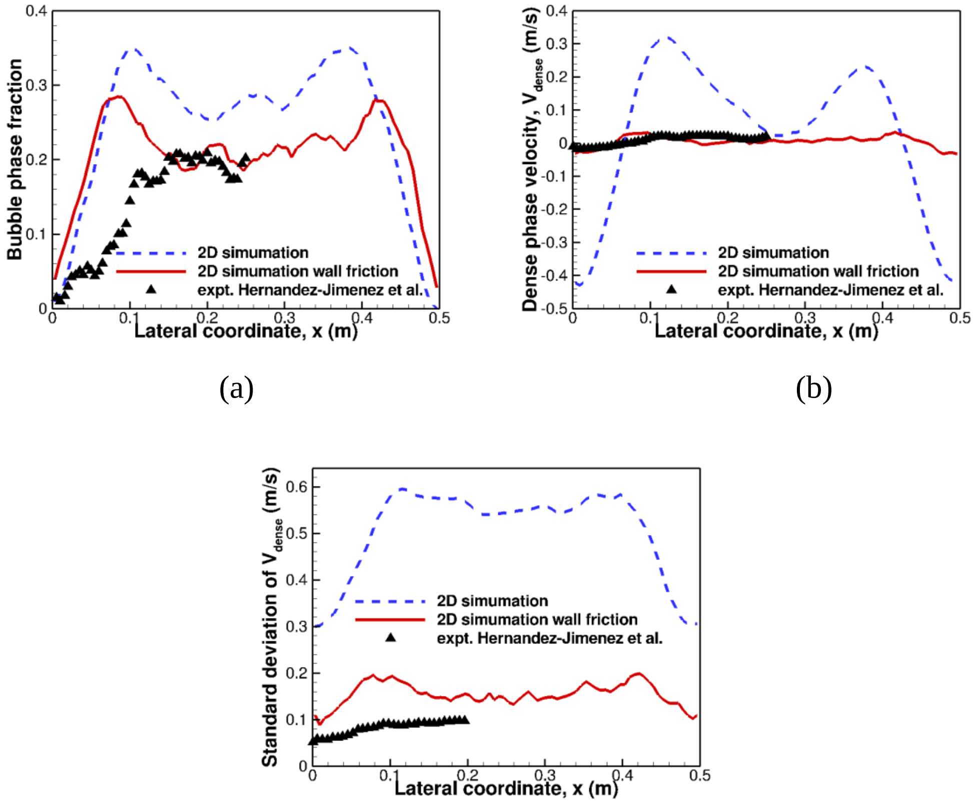
Table 3. Conditions and parameters used in the numerical simulations.

Property	**Value**
gas density, kg/m^3	1.2
gas viscosity, Pa.s	1.8×10^{-5}
particle diameter, μm	700

Property	Value
particle density, kg/m^3	2500
minimum fluidization velocity, m/s	0.35
column width, m	0.50
column height, m	1.0
column thickness, m	0.005
superficial gas velocity, m/s	0.62
particle-particle restitution coefficient, -	0.95
particle-wall restitution coefficient, -	0.8
specularity coefficient, -	0.005
particle-wall friction coefficient, -	0.3
initial bed voidage, -	0.40
initial bed height, m	0.30

Hernandez et al. (2011) conducted a series of 2D numerical simulations of this pseudo-2D gas-solids fluidized bed system to compare their two-fluid model simulation with the experimental data measured by PIV. They found good agreement between their 2D simulations and the experimental measurements with respect to bubble diameter and rising velocity. However, substantial deviations in the dense phase velocities were reported.

Here, the numerical results of 2D simulations are compared to the experimental data only. Figure 8 shows the lateral profiles of the mean bubble fraction, dense phase vertical velocity, and its standard deviation at the height of 0.25m above the distributor. Again, the threshold value of 0.3 in solids volume fraction to define the interface between bubble and dense phases is used to calculate the mean bubble fraction and dense phase velocity. As can be seen from the comparison, the 2D simulation with wall effect of the front and back walls shows substantial improvement compared to the conventional 2D simulation, especially the dense phase vertical velocity. However, the agreement to the experimental data is not so good compared to the previous case. The main reason is related to the thin bed thickness in the experiment. For such a small bed thicknesses, the wall effect from the front and back walls could be so strong that particles might bridge in the bed and give uncharacteristic results (Lyall, 1969). Overall, the improvement in numerical prediction by the current model is significant, which again indicates the importance of wall friction in simulating such pseuso-2D systems. For both cases, results on bubble characteristics, such as size and shape, are not compared considering its relatively weak dependence on wall friction according to previous studies (Busciglio et al., 2009; Li et al., 2010a; Hernandez-Jimenez et al., 2011; Cloete et al., 2013b).



(c)

Figure 8. Lateral profiles of (a) mean bubble fraction; (b) dense phase vertical velocity and (c) its standard deviation at the height of 0.25m above the distributor.

4.3 Discussion

In the above analyses, the wall effects from the front and back walls are only considered for the solids phase, which is reasonable in a pseudo-2D gas-solids system. To include all of the subtle wall effects on both gas and solids phases and their coupling, a fully 3D numerical simulation with capability of resolving small scale flow behaviors, such as Direct Numerical Simulation (DNS), is necessary, but is computationally expensive for even a small experimental system (Li et al. 2012). Simplifications and assumptions have to be used for practical exercise. Thus, it is important to be aware of the limitations of assumptions introduced in the model to simplify the problem.

The current model is proposed to be used in 2D numerical simulations of pseudo-2D gas-solids systems to account for the effect of front and back walls for better prediction. Certain limitations in the model are discussed here. First, it is assumed that the flow inside the system demonstrates good 2D behavior. Strictly speaking, certain 3D flow behavior always exists in the pseudo-2D gas-solids system no matter how thin the system is. As far as the bulk flow is concerned, usually a good 2D flow behavior can be achieved in a pseudo-2D gas-solids system with small bed thickness.

However, for a pseudo-2D system with a considerable thickness, the flow starts demonstrating 3D behavior and the 2D flow assumption is not valid any more. Hence, a fully 3D simulation is needed. Second, the frictional effect is mainly accounted for through the shear force calculated in Equation (1) by assuming sliding collisions between particles and walls, which is believed to be a reasonable assumption for pseudo-2D systems. However, its accuracy is dependent on the kinetic granular theory and friction model used for modeling the normal stress. For the bubbling fluidized beds investigated in the current study, a major portion of the wall friction has been shown to originate from the interaction between the frictional solids flow and the front and back walls. A simple friction sub-model is used to describe the complex frictional solids flow in this work. Clearly, a more accurate friction sub-model should be used for better prediction. Furthermore, it should be noted that in kinetic granular theory the isotropic assumption on granular temperature based on the Maxwellian velocity distribution is used to calculate the normal force, i.e. the solids pressure. However, the limited bed thickness of pseudo-2D systems inevitably affects the granular temperature component in the third direction and the isotropic distribution may not be appropriate. Appropriate model is needed to account for the anisotropic granular temperature in fluidized bed simulations (Sun et al, 2009). Nevertheless, the granular temperature solved in a 2D space has its inherent limitations when it is used to estimate the velocity fluctuation in the unsolved third direction. Finally, the effect of particle rotation has been ignored in the employed granular kinetic theory. For small scale pseudo-2D gas-solids fluidized bed, a DEM study by Li et al. (2012) indicated that the contribution of particle rotation to the total particle kinetic energy is less than 1%. However, the numerical study by Wang et al. (2012) using the kinetic granular theory for frictional particles suggests that the particle granular temperature, due to rotation, is important in the 2D simulation of a bubbling fluidized bed even though the magnitude is small compared to the kinetic part. Clearly, further investigation on this topic will be an interesting study for future work, but it is beyond the scope of the current study.

5. Conclusion

A simple but effective model was proposed in this study for a 2D numerical simulation to include the wall effect from the front and back walls of pseudo-2D gas-solids fluidization systems, which is believed to be important for an accurate prediction of the solids velocity in these systems. Specifically, the new model accounts for both the frictional force and the generation of solids fluctuation energy. Numerical simulations of two pseudo-2D gas-solids fluidized beds were conducted with the new model, which demonstrated significant improvement in the numerical results compared to the conventional 2D simulations. Especially, the new model overcomes the significant over-prediction of solids velocity in the 2D numerical simulations of pseudo-2D fluidized beds reported in literature. The negligence of the frictional effect of the front and back walls was again proved to be the key cause that results in the over-estimated solids circulation strength in the conventional 2D simulations of pseudo-2D gas-solids fluidization systems. Moreover, this method avoids solving the equations and boundary conditions in the third direction as in 3D simulations, but accounts for the important wall effect reasonably well. It should be noted that the ultimate goal of this work is not to avoid 3D simulation, as a 3D simulation is believed to be the most appropriate way to simulate a pseudo-2D column, but to provide a computationally economic way to carry out long-period simulation to obtain better averaged numerical results for pseudo-2D gas-solids systems with the most important factors appropriately accounted for.

Nomenclature

C	dense phase fraction:	-
d	diameter:	m
e	restitution coefficient:	-
g	gravitational acceleration:	m/s^2
g_0	radial distribution function:	-
h	bed thickness:	m
I	momentum transfer:	$kg/m^2\text{-}s^2$
N	normal stress:	Pa
P	pressure:	Pa
q	fluctuation energy source due to wall friction:	$kg/m\text{-}s^3$
s	body force due to wall friction:	N/m^3
S	shear stress:	Pa
U	superficial velocity:	m/s
V	velocity:	m/s

Greek symbols

ε	volume fraction:	-
μ	viscosity:	Pa.s
μ_{fric}	frictional coefficient:	-
Θ	granular temperature:	m^2/s^2
ρ	density:	kg/m^3

Subscripts

g	gas
p	particle

Abbreviations

2D	two-dimensional
3D	three-dimensional
CFD	Computational Fluid Dynamics
DEM	discrete element method
MFIX	Multiphase Flow with Interphase eXchanges
NETL	National Energy Technology Laboratory
PIV	Particle Image Velocimetry
DIA	Digital Image Analysis
TFM	two-fluid model

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