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Evaluation of wall friction models for riser flow

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ABSTRACT

Two different approaches for modelling the particle-wall collisions, the frequently employed Johnson & Jackson model and the recently proposed Schneiderbauer model, were evaluated in a fluidized bed riser by comparing simulation results to experimental data over a range of fluidization velocities and solids fluxes. For the Johnson & Jackson model, it was shown that partial slip settings recommended for denser fluidization conditions (a specularity coefficient in the order of 0.1) failed to predict cluster formation at the walls at higher gas flow rates due to unrealistically large granular temperature generation in the near-wall regions. By reducing wall friction to settings approaching a free-slip condition (specularity coefficient in the order of 0.001), this problem is overcome by eliminating excessive granular temperature generation from over-predicted strain rates at the walls. However, this approach results in an overestimation of the downward velocity of the clusters at the wall in dense cases. Despite this shortcoming, predictions are remarkably accurate for most of the cases. The Schneiderbauer model, with model parameters close to recommended settings, performs similarly well for most of the cases, slightly under-predicting cluster formation at the walls in the dilute cases. Generally, it also predicts more realistic flow behaviour since it prevents dense clusters from falling rapidly at the walls. The Schneiderbauer wall friction model is therefore recommended for use in future studies of risers, since it is able to deliver reasonable results over a wider range of flow conditions than the Johnson and Jackson model, using a single set of friction parameters. Furthermore, it has the benefit of using experimentally measurable quantities as input.

1. Introduction

Circulating fluidised beds (CFBs) are used in the chemical, petrochemical, energy and metallurgical industries for applications such as fluid catalytic cracking (FCC), coal and biomass gasification and chemical looping combustion (CLC). In the riser section of the CFB the solid particles are transported vertically in a gas stream, enabling high gas throughput rates and excellent contact between the gas and solid phases for reactions and heat transfer. It is known that during this transport process the solids will gather in clusters of particles due to local instabilities and that this behaviour has an important impact on the hydrodynamic and reactive performance of these reactors [1]. Due to this complex multiphase flow behaviour, these processes face many challenges regarding operation, design and scale-up.

Computational fluid dynamics (CFD) has emerged as a valuable tool through which the understanding of these systems can be improved. A common approach is to use a two-fluid model (TFM) where the particle phase is assumed to be continuous [2–4]. The solid phase is governed by the kinetic theory of granular flow (KTGF), where the behaviour of the solid phase is analogous to the kinetic theory for gases and the granular temperature represents the kinetic energy of unresolved random motions of the solid particles. It has been shown that the TFM can qualitatively capture the phenomena observed in experimental setups of fluidised beds, including the formation of particle phase clusters. Good quantitative comparisons have also been made with experimental data for certain conditions, but in many cases it has proved difficult to achieve a good match between experimental and numerical results in risers [5,6].

Two complicating factors can be identified in risers. Firstly, small particle sizes and large gas velocities are essential to facilitate the transport of solids, demanding small grid sizes and time steps. As a result, risers are computationally demanding to simulate and simplifying assumptions are often used in the literature, such as using 2D simulations and coarse grids. Recent research has placed much emphasis on developing sub-grid models to achieve better results from coarse grid simulations [7–9].

Secondly, particle-wall collisions play a critical role in the behaviour of risers due to the large ratio of wall area to reactor volume and the high velocity of particles typical of risers. There is general agreement in the literature that the choice of wall boundary condition for the

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solid phase have a significant influence on the overall hydrodynamics of the riser [10,11]. However, it remains unclear what the correct approach is for including the wall effects, as boundary conditions in the literature include anything from free-slip to no-slip.

The most popular model for the particle-wall boundary condition, by a considerable margin, is that of Johnson and Jackson [12]. At the time of writing, the original paper describing the model had over 700 citations in the literature. This is despite the well-known limitations of the approach [13,14]. In the Johnson and Jackson model the effect of particle-wall friction and wall roughness on the shear force is incorporated into a single heuristic constant, called the specularity coefficient. The specularity coefficient is not a physically measurable property and its desired value may change with flow conditions. This is a problem in systems such as circulating fluidised beds, which may contain dense and dilute regions, requiring very different specularity coefficients for accurate results in these different regions. The dependence on flow conditions leads to a disparity in the values of the specularity coefficient used in literature studies of risers, with one group assuming partial slip (specularity coefficients of 0.1 to 0.5) [15,16] and another group assuming near free-slip (values smaller or equal to 0.001) [11,17].

Furthermore, the Johnson and Jackson model assumes a linear relationship between the shear stress and the slip velocity. However, it is well known that at high slip velocities all the particles will slide at contact and that the shear stress will be limited by Coulomb friction [18–21]. The Johnson and Jackson model therefore tends to overpredict the shear stress and granular temperature generation for rapid flows, which explains the use of very low specularity coefficient values in the literature.

Despite the dominance of the Johnson and Jackson model, there are alternative methods available in literature. Jenkins [18] proposed expressions for the shear stress and granular temperature flux in terms of measurable quantities, the friction coefficient (μ_w) and the tangential (β_0) and normal (e_w) particle-wall restitution coefficients. However, their theory was restricted to the limits of either non-sliding or all-sliding collisions; therefore a-priori knowledge of the flow domain is required for using their model. Jenkins and Louge [22] improved these correlations for the flux of the granular temperature based on computer simulations of Louge [19] for the limits of non-sliding and all-sliding collisions.

Sliding and non-sliding collisions were first linked into one expression by Li and Benyahia [20], who provided an expression for the specularity coefficient based on the friction coefficient, particles-wall restitution coefficients, slip velocity and granular temperature. This approach therefore solves the problem of the specularity coefficient not being a measurable quantity, as well as its dependency on the flow conditions. However, it was recently noted that this approach does not differentiate between sliding and non-sliding collisions in the dissipation term of the boundary condition for the granular temperature, leading to an over-prediction of the granular flux in rapid granular flows [13].

The model by Schneiderbauer [21] also included sliding and non-sliding collisions in one expression, dependent on the friction and particle-wall restitution coefficients. However, an improved treatment of the granular flux leads to better comparisons with the simulation data of Louge [19], compared to the work of [20]. Additionally, the model can also account for a boundary moving in a normal direction relative to the flow, making it the only approach suitable to systems with moving parts.

Most recently, Zhao [14] achieved an even better comparison with the data of Louge [19] by also considering the rotational granular temperature of the particles. However, the approach of using a rotational granular temperature is not common practice due to the added computational expense of solving an extra conservation equation and the complexity added by the additional closures.

For this reason it can be argued that currently the model by Schneiderbauer [21] is the best alternative for replacing the Johnson and Jackson model [12] as the most commonly used wall-friction model for granular flows. It has the primary advantages of requiring only measurable quantities as input and achieving a very good match with simulation data by Louge [19] by accounting for the effect of a transition from non-sliding to sliding collisions on both the shear stress and the granular flux. Additionally, it retains most of the simplicity that makes the Johnson and Jackson model popular.

The potential benefit of the Schneiderbauer wall-friction model has been demonstrated in a spouted bed [23] for fluidised beds. However, its true advantage is expected to be best illustrated in risers, where rapid granular flow occurs at the walls. For this reason, this paper will aim to evaluate the Schneiderbauer model as an alternative to the Johnson and Jackson model by comparing numerical results with experimental data in risers over a range of superficial gas velocities and solids fluxes.

2. Simulations

The setup for the numerical simulations is similar to that used in a previous study [10], but the most important equations are repeated here for clarity. A more detailed discussion of the equations used can be found in [24].

2.1. Model equations

This study will use Eulerian two-fluid modelling to simulate the flow behaviour inside a riser. In this modelling framework, the gas and solid phases are each treated as a separate, continuous phase, with conservation equations being solved for each phase. The continuity equations for the gas and solids are written as follows:

$$\frac{\partial}{\partial t}\left(\alpha_g\rho_g\right)+\nabla\cdot\left(\alpha_g\rho_g\vec{v}_g\right)=0 \quad (1)$$

$$\frac{\partial}{\partial t}(\alpha_s\rho_s)+\nabla\cdot\left(\alpha_s\rho_s\vec{v}_s\right)=0 \quad (2)$$

The momentum conservation equation for the gas phase is

$$\frac{\partial}{\partial t}\left(\alpha_g\rho_g\vec{v}_g\right)+\nabla\cdot\left(\alpha_g\rho_g\vec{v}_g\vec{v}_g\right)=-\alpha_g\nabla p+\nabla\cdot\bar{\bar{\tau}}_g+\alpha_g\rho_g\vec{g}+K_{sq}\left(\vec{v}_s-\vec{v}_g\right) \quad (3)$$

And for the solids

$$\frac{\partial}{\partial t}\left(\alpha_s\rho_s\vec{v}_s\right)+\nabla\cdot\left(\alpha_s\rho_s\vec{v}_s\vec{v}_s\right)=-\alpha_s\nabla p-\nabla p_s+\nabla\cdot\bar{\bar{\tau}}_s+\alpha_s\rho_s\vec{g}+K_{gs}\left(\vec{v}_g-\vec{v}_s\right) \quad (4)$$

The inter-phase momentum exchange coefficient ($K_{gs}=K_{sg}$) was modelled using the Huilin-Gidaspow drag model [25]. It combines the Wen-Yu model [26] with the Ergun equation at high solids volume fractions and uses a blending function to smooth out the discontinuity between the two equations.

The solids stresses in the particle phase momentum equation are solved based on the Kinetic Theory of Granular Flow. In this approach the random motion of the particles is likened to the thermal motion of the molecules in a gas. The kinetic energy of these random fluctuations is quantified by the granular temperature, for which an additional conservation equation is solved.

$$\frac{3}{2}\left[\frac{\partial}{\partial t}(\alpha_s\rho_s\Theta_s)+\nabla\cdot\left(\alpha_s\rho_s\vec{v}_s\Theta_s\right)\right]=\left(-p_s\bar{\bar{I}}+\bar{\bar{\tau}}_s\right):\nabla\vec{v}_s+\nabla\cdot(k_{\Theta_s}\nabla\Theta_s)-\gamma_{\Theta_s}+\phi_{gs} \quad (5)$$

The first term on the right hand side contains the normal and shear solids stresses, with closures required for the solids pressure [4] and the