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ABSTRACT

A multifluid Eulerian Computational Fluid Dynamics model incorporating the Kinetic Theory of Granular Flows was carried out to simulate the hydrodynamic of a 2D turbulent fluidized bed filled with Geldart B particles. Simulations were conducted using the commercial software package Ansys Fluent. In order to get an optimal modelization of the fluidized bed hydrodynamic, the effect of various drag models including those of Gidaspow, Syamlal & O'Brien, Wen & Yu and McKeen have been investigated. The numerical results obtained were compared to experimental data available in literature. Different specularity coefficients were also tested in the present work in a try to find out which fits better the handled case. The results showed that the Gidaspow drag model and the no slip boundary condition give a good prediction of experimental data.

INTRODUCTION

Turbulent fluidized beds were extensively used in industrial applications during the last decades. They are characterized by their ability to handle continuous powder, their vigorous gas-solids contacting, their ability of favorable heat and mass transfer and their relatively low axial gas dispersion.

Turbulent fluidization regime has commonly been acknowledged as a distinct flow regime occurring between the bubbling and the fast fluidization regimes. It is characterized by its high dispersion solid-coefficient as well as by two different coexisting regions: a bottom dense bubbling region and a dilute dispersed flow region. In the literature, significantly less attention has been dedicated to turbulent fluidization due to current deficiencies in experimental and theoretical works. Fundamental understanding of its hydrodynamic behavior is therefore required.

Computational Fluid Dynamics (CFD) has become a very promising tool for the better understanding of physical phenomena involved in these systems. Nevertheless, CFD is still at the verification and validation stages for modeling multiphase flow, and more improvements regarding the flow dynamics and computational models are required to make it a standard tool in designing large scale industrial reactors. In the literature, there are two main approaches to apply CFD modeling to gas-solid hydrodynamic: the Eulerian-Lagrangian approach and the Eulerian-Eulerian approach. The Newtonian equation of motion are solved for each individual solid particle in the Eulerian-Lagrangian approach by using discrete particles models and then the trajectory of every particles can be tracked. The drawbacks of this approach are the limited efficiency (this approach is efficient only for a flows containing a low solid volume fraction), the large memory requirement and the large computational time. The second approach treats the different phases mathematically as continuous and fully interpenetrating.

The main advantage of this approach is its application on the multiphase flow processes containing large volume fractions of dispersed phase. In fact, this continuum model suffers from some limitations in modeling of gas-solid flow. It does not give information about the hydrodynamics of individual particles and thus has limitations to prediction certain discrete flow characteristics such us the size of solid particle and density effect. Nevertheless, it remains the most realistic approach for performing parametric investigation and scale up studies of industrial scale systems (Benyahia et al. (1), Zheng et al. (2), Neri and Gidaspow (3)). Comparisons between numerical models based on the multifluid model and the discrete particle model have been reported in the literature (e.g., Ibsen et al. (4), van der Hoef et al. (5)). Owing to describe the rheology of the solid phase, the Eulerian model (or the Eulerian Two Fluid Model (TFM)) requires additional closure laws. At the present, the most commonly used is the Kinetic Theory of Granular Flow (KTGF) which is the extension of the classical kinetic theory of gases. Numerous studies on the hydrodynamic of gas-solid fluidized bed incorporating the KTGF have shown the theory's efficiency in modeling such flow. These studies were conducted by Sinclair and Jackson (6), Pain et al (7), Taghipour et al (8), etc…

The interphase momentum transfer between the two phases which is represented by the drag force play in important role in modeling gas-solid system. In effect, in the TFM, the two phases are coupled through the interphase momentum transfer, hence it is one of the most dominant force in multiphase flow. Due to the high relevance of the phenomenon, numerous empirical correlations have been reported in the literature in order to calculate the momentum transfer coefficient of gas-solid systems. The most commonly used drag models were the Gidaspow model (9), Syamlal-O'Brien (10) and Wen-Yu model (11). These models have been compared and validated by different researchers such as Taghipour et al. (8) and Gao et al. (12). Although, great progress has been made on the hydrodynamics of fluidized bed filled with Geldart B and D particles by this conventional drag models, few successful have been performed on the bubbling or turbulent beds of Geldart A particles. Therefore, for proper prediction of experimental results, the momentum transfer coefficient should be investigated with great care. Further parameter may affect the success of TFM, is the wall boundary condition of the solid phase which represent the interaction between particles and wall. The reported works in the literature have investigated the effect of gas-solids interactions between particles on the fluidized bed flow, unfortunately, less attention has been given to the influence of interaction between particles and wall on the hydrodynamics of fluidized bed. Li et al. (13) investigated the effect of this parameter and recommended that the solid phase boundary condition needs to be specified carefully. The wall boundary condition who represented the interaction between particles and wall involves two different coefficients, the restitution coefficient and the specularity coefficient. The former represents the kinetic energy of solid phase dissipated by collision with the wall and the second coefficient specifies the shear condition at the wall.

In the current work, a multifluid Eulerian Computational Fluid Dynamics model incorporatingthe Kinetic Theory of Granular Flows is carried out to simulate the hydrodynamic of a 2D turbulent fluidized bed filled with Geldart B particles. Simulations were conducted using the commercial software package Ansys Fluent. In order to get an optimal modelization of the fluidized bed hydrodynamic, the effect of various drag models including those of Gidaspow, Syamlal& O'Brien, Wen & Yu and McKeen have been investigated. The numerical results obtained are compared to experimental data available in literature. Different specularity coefficients were also tested in this study in a try to find out which one fits better the handled case.

NUMERICAL MODELING

Governing Equations and Closures

In the present study, we propose to solve the governing equations of mass (a), momentum (b-c) and granular energy (d) for both the gas and solids phase by means of a multifluid Eulerian Computational Fluid Dynamics model incorporating the Kinetic Theory of Granular Flow (KTGF) available in the commercial software package Ansys Fluent.

$$\frac{\partial(\varepsilon_q\rho_q)}{\partial t} + \nabla.\left(\varepsilon_q\rho_q u_q\right) = 0 \quad \text{(q=g for gas and q=s for solid)} \quad \text{(a)}$$

$$\frac{\partial(\varepsilon_g\rho_g u_g)}{\partial t} + \nabla.\left(\varepsilon_g\rho_g u_g u_g\right) = \nabla.\left(\tau_g\right) - \varepsilon_g\nabla \mathrm{P} - \beta\left(u_g - u_s\right) + \varepsilon_g\rho_g g \quad \text{(b)}$$

$$\frac{\partial(\varepsilon_s\rho_s u_s)}{\partial t} + \nabla.\left(\varepsilon_s\rho_s u_s u_s\right) = \nabla.\left(\tau_s\right) - \varepsilon_s\nabla \mathrm{P_s} - \beta\left(u_g - u_s\right) + \varepsilon_s\rho_s g \quad \text{(c)}$$

$$\frac{3}{2}\left(\frac{\partial(\varepsilon_s\rho_s\Theta)}{\partial t} + \nabla.\left(\varepsilon_s\rho_s u_s\Theta\right)\right) = \left(-\mathrm{P_s I} + \tau_s\right):\nabla u_s - \nabla.q - \gamma - J \quad \text{(d)}$$

To solve the set of equations, closures laws are required. In this work, we propose to apply the closure relations based on the (KTGF). The closure models, and the physical properties and simulation parameters used in this study are shown respectively in Tables 1 and 2.

Table 1: Closure models

Parameter	Model (Fluent)	Ref.
Drag law	Gidaspow	(9)
	Syamlal-O'Brien	(10)
	Wan & Yu	(11)
	Mckeen	(14)
Solid viscosity	Gidaspow	(9)
	Syamlal-O'Brien	(10)
Solid bulk viscosity	Lun et al.	(15)
Frictional viscosity	Schaeffer	(16)
Frictional pressure	Johnson et al.	(17)
Solid pressure	Lun et al.	(15)
Radial distribution function	Lun et al.	(15)

SIMULATION PROCEDURE AND BOUNDARY CONDITIONS

Our simulation is based upon the experimental work of Van Den Moortel (18) in order to allow a direct comparison with experimental. In their experiments, Van Den Moortel (18) considered a fluidized bed with a cross section of 0.2 x 0.2 m^2 and a height of 2 m. A particles glass beads with density of 2400 kg/m^3 and a sauter mean diameter of 120 µm were fluidized with air at ambient conditions. The present 2D computational domain is discretized using a uniform quadratic mesh with 16000 cells. The shape of the column and the simulation parameters are illustrated respectively in Figure 1 and Table 2.

Table 2: Modeling parameters

Description	**Value**
Bed height H	2 m
Bed width	0.2 m
Static bed height H_0	0.1 m
Gas density ρ_g	1.2 Kg/m^3
Particle density ρ_s	2400 Kg/m^3
Particle diameter d_s	120 µm
Initial solid volume fraction ε_0	0.6
Inlet gas velocity U_g	1 m/s
Solid flux G_s	0.22 kg/m^2s
Angle of internal friction	30°
Restitution coefficient e_S	0.9
Specularity coefficient φ	0, 0.001, 0.25 and 1
Maximum particle packing limit	0.64
Time step	10^{-4}s

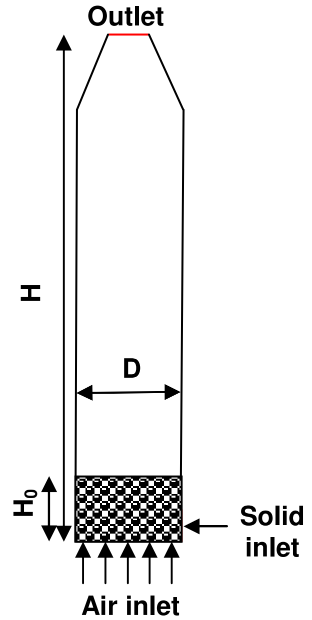

Fig.1: Schematic drawing of 2D bed

The computational geometry used for the simulation (see Fig.1) consisted of a bottom gas inlet, a side inlet for solid entry and a top outlet. The velocity inlet boundary condition was used for both the gas and the solid inlet while the pressure outlet boundary condition was applied for the outlet. Particles are free to leave if flow in, and the initial solid inventory in the bed was set using available experimental data. At the wall, the Johnson and Jackson (19) boundary which assumes no slip for the gas phase and partial slip for the solid phase was applied. The velocity-pressure coupling was resolved using the phase coupling algorithm (PCSIMPLE). Second order upwind and QUICK discretization schemes were used respectively for the momentum and the volume fraction equations. The standard k-ε model was used to model the turbulence in the gas phase and its effect on the dispersed secondary phase.

RESULTS AND DISCUSSION

Comparison of different drag models

In order to investigate the suitability of drag laws for modeling the turbulent fluidized bed filled with Geldart B particles, the classical drag models of Gidaspow, Syamlal-O'Brien and Wen-Yu were first investigated. Then, the modified drag model of Mckeen was examined and compared with the classical drag models. Figure 2 depicts the flow structure of the bed by the different drag models. As we can see from this figure, the classical drag models can capture the two coexisting regions characteristics of the turbulent fluidized bed: a bottom dense, bubbling region and a top dilute, dispersed region. Although, the Mckeen drag model captures the bottom dense region, it misses the top dilute region.

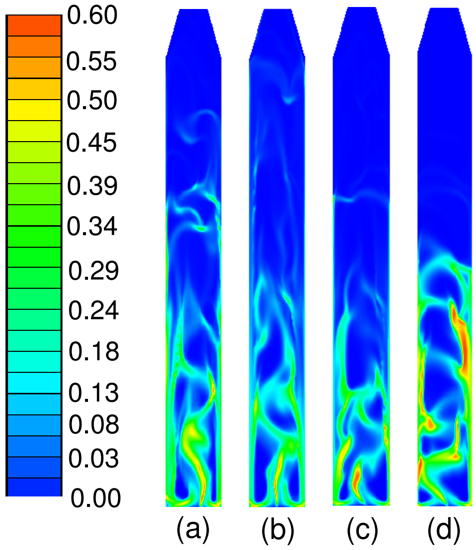

Fig. 2: Flow structures with various drag models: (a) Syamlal–O'Brien (b) Wen-Yu (c) Gidaspow and (d) Mckeen

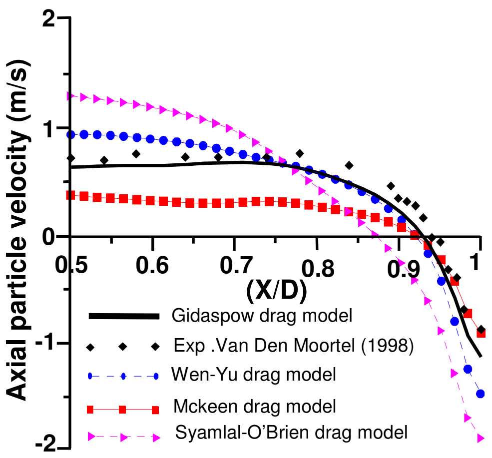

Fig.3: The time-averaged axial particle velocity predicted along the radial direction by various drag

Further parameters may support the choice of suitable drag model, such as the particle velocity. In fact, this parameter plays an important role in determination of hydrodynamic characteristics of gas-solid fluidized beds. Figure 3 illustrates the axial particle velocity for the different drag models and at the height of 1.2 m. as can be seen the existence of traditional core-annulus structure which is characterized by negative axial particle velocity near the wall and positive away from it, was clearly predicted by all drag models. The Syamlal-O'Brien drag model shows an overproduction of particles' velocity within the riser's core and near the wall region.

On the other hand, though the Mckeen model predicted the core-annulus structure of flow, it under predicts the velocity near the central region. For the Wen-Yu drag model, the particle velocity profile showed a reasonable qualitative and quantitative agreement when compared with the experimental data than the result of other models. However, for the Gidaspow drag model the prediction axial particle velocity profile is in better agreement with the experimental data and hence chosen to be the drag model for subsequent simulations. Similar results were also reported by Lu et al. (20). Therefore, the following investigation regarding the fluidization behaviors was based on the Gidaspow drag model.

Comparison of different specularity coefficients

Figure 4 presents the time-averaged axial solid velocity across the height of 1 m for different specularity coefficients (φ=0, 0.25 and 1). It is noteworthy that the traditional core-annulus structure was clearly predicted by different φ. When φ=0, free slip boundary condition, the particle can freely slip on the wall and hence the particle have a higher velocity at the wall. Increasing the specularity coefficient leads to the decreases of the slip velocity at the wall and then to the reduction of the downflow of particles. This result is consistent with the conclusions by Armstrong (21). The specularity coefficient close to one showed a reasonable reproduction of the experimental data for all models carried out.

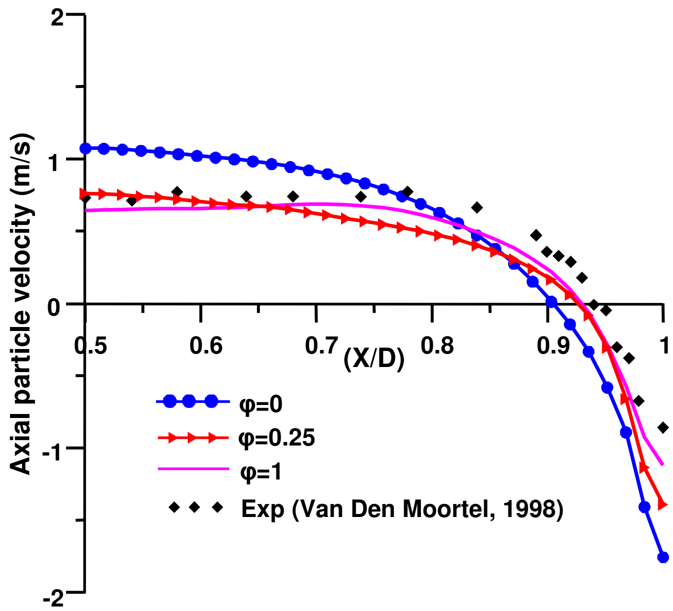

Fig. 4: The time-averaged axial particle velocity predicted along the radial direction by several specularity coefficients at H=1.2 m.

Figures 5 and 6 show respectively, the solid volume fraction contour and the radial solid volume fraction profiles predicted by three different values of specularity coefficients. It is observed that the volume fraction of particle is low in the center region, while it is high near the wall region. The decreases of the specularity coefficient improve the increasing of solid phase concentration in the dilute dispersed region. In fact, when φ=0 there is no friction between particles and wall. The free slip of particles on the wall results in a higher particles velocity which consequently leading the giving rise of more particle in the dilute dispersed region.

CONCLUSION

An Eulerian-Eulerian CFD model incorporating the Kinetic Theory of Granular Flow (KTGF) was applied by a mean of commercial CFD package Ansys Fluent in order to study the solids behavior of a turbulent fluidized bed. The effect of various drag models including those of Gidaspow, Syamlal & O'Brien, Wen & Yu and Mckeen have been investigated. Compared the experimental data, the Gidaspow drag model gives a reasonable hydrodynamic prediction. The computational results indicated that there is certain sensitivity to the coefficient of specularity coefficient in the turbulent bed behavior for glass beads. The specularity coefficient close to one showed a reasonable reproduction of the experimental results.

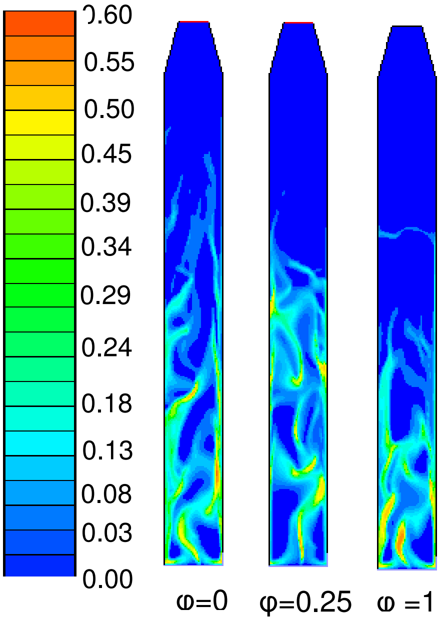

Fig. 5: Predicted solids volume fraction distribution for different specularity coefficients.

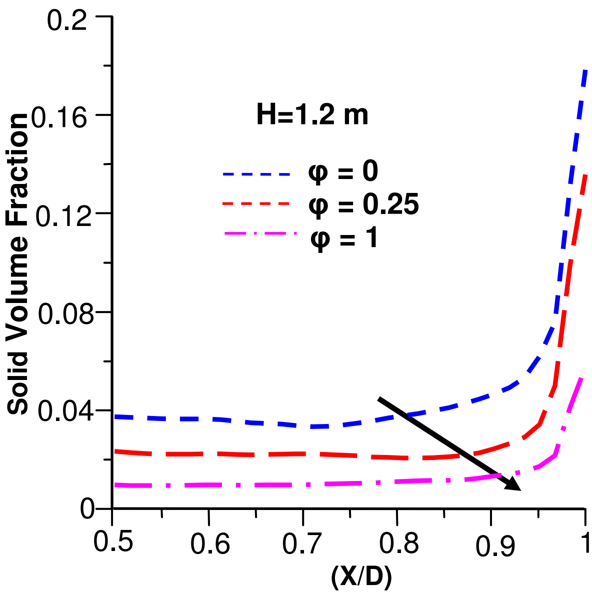

Fig. 6: Radial solid volume fraction profiles predicted by different specularity coefficients.

NOTATION

Symbols:

u Velocity, m/s
P Pressure, Pa
g Gravitational acceleration, m/s^2
q Diffusive flux of granular energy, Pa/s
t Time, s
I Unit tensor
J Transfer of random fluctuations kinetic energy, Pa/s

Greek letters:

β Inter-phase drag coefficient, $kg/m^3/s$
ε Volume fraction
φ Specularity coefficient
Θ Granular temperature, m^2/s^2
ρ Density, kg/m^3
γ Dissipation of fluctuating energy, Pa/s
τ Shear stress tensor, N/m^2

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