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DETERMINING OF FLOW BEHAVIOR OF SOLID-GAS TWO-PHASE FLOW VIA 1D NUMERICAL MODEL

Afsin Gungor
Nigde University, Faculty of Engineering and Architecture
Department of Mechanical Engineering, 51100 Nigde
Turkey

ABSTRACT

The numerical simulation of solid-gas two-phase flow is an important tool in the prediction of its flow behavior. Predicting the axial pressure profile is one of the major difficulties in modeling of solid-gas two-phase flow. A model using a Particle Based Approach (PBA) is developed to accurately predict the axial pressure profile in a vertical annular tube. The simulation model accounts for the axial and radial distribution of voidage and velocity of the gas and solid phases, and for the solids volume fraction and particle size distribution of the solid phase. The model results are compared with and validated against experimental data. The computational results agreed reasonably well with the experimental data.

Keywords: two-phase flow, annular flow, pressure drop, numerical simulation

1. INTRODUCTION

The motion of solids in vertical gas/particle flow is very complex. According to Yerushalmi et al. [1], transport velocity is defined as the velocity at which it is possible to carry all of the solids fed into the riser out again, and thus it is impossible to maintain a fluidized bed without continuous recycle of solids back into the fluid bed. This is the critical gas velocity defining the transition between turbulent and fast fluidization flow regimes. A qualitative fluidization map is initially proposed by Yerushalmi et al. [1] and, later completed by Van de Velden et al. [2]. The occurrence of both mixed flow, required in most gas/solid reactions, and plug flow, required for most catalytic gas phase reactions, is strongly dependent upon combined operational parameters of gas superficial velocity and solids circulation rate. The gas mixing mode is strongly affected by the operating conditions, however with a specific dominant mode within a specific (U_0, G)-range. At high velocities (U_0>approx. (U_{tr}+1) m/s) and high solids circulation rate (G>approx. 200 kg/m^2s) plug (dominant core) flow is achieved. Mixing occurs at lower G or lower U_0. When mixing occurs, the hydrodynamics of the riser can be modeled by a core/annulus approach [3]. In the mixing mode, a dilute region with rapidly rising particles exists in the core of the riser. This core is surrounded by a denser annulus of particles descending near the wall. In plug flow mode, most of the particles move upwards, and downward particles are randomly distributed across the section of the riser. At ambient conditions, reactors requiring pure plug flow must operate at high gas velocities (U_0>approx. (U_{tr}+1) m/s) and high solids circulation rate (G>approx. 200 kg/m^2s). If back-mixing is required, as in gas/solid reactors, operation at high enough velocities (U_0>approx. (U_{tr}+1) m/s) but at lower values of solids circulation rate (G<approx. 150 kg/m^2s) is recommended and the operating mode can be described by the core/annulus approach [2].

An accurate model is needed to predict the pressure profiles. In this study, a model using PBA is developed to accurately predict the axial pressure drop profile especially in the acceleration zone of circulating fluidized beds (CFBs). Simulation model takes into account the axial and radial distribution of voidage and the velocity for gas and solid phase, and the solids volume fraction and particle size distribution for the solid phase. The model results are compared with and validated against atmospheric cold CFB experimental literature data [4-7].

2. MODEL DESCRIPTION

The model of this paper uses PBA which considers the two-dimensional motion of single particles through fluids. According to the axial solid volume concentration profile, the riser is axially divided into the bottom zone and the upper zone. In the present model, the bottom zone in turbulent fluidization regime is modeled as two-phase flow which is subdivided into a solid-free bubble phase and a solid-laden emulsion phase. The structure and details of the bottom zone are given in the literature [8].

The upper zone is located between the bottom zone and the riser exit. The upper zone is assumed to be axially composed of three zones: (i) The acceleration zone is at the bottom part of the upper region, (ii) The fully developed zone is located above the acceleration zone, where the flow characteristics are invariant with height, (iii) The deceleration zone is located above the fully developed zone, where the solids are decelerated depending on the exit geometry of the riser. For the upper zone, the core-annulus flow structure is used [7]. The particles move upward in the core and downward in the annulus. Werther and Wein [9] proposed a correlation which is further confirmed by data from large-scale CFBs. This correlation is used for the calculation of the thickness of the annulus along the riser height.

The model adopts the following simple expressions for the axial profile of the solid fraction along the upper zone. This expression is equivalent to Zenz and Weil [10].

$$\frac{\varepsilon-\varepsilon_{mf}}{1-\varepsilon}=\exp\left[\alpha\left(h-h_{bot}\right)\right] \tag{1}$$

where α, the decay coefficient, is a parameter to express the exponential decrease of the solid flux or solid fraction with the height and determined by the following relationship fitted by Cheng and Xiaolong [11] with experimental data:

$$\alpha d_p=3.8\times10^{-5}\left(\frac{G_\infty}{U_0\rho}\right)^{-0.96}\left(\frac{U_0}{\sqrt{gD}}\right)^{-0.84}\left(\frac{\rho-C}{\rho}\right)^{0.37} \tag{2}$$

To calculate the cross-sectional average solids concentration, the relationship suggested by Rhodes et al. [12] is used in the model.

In a conventional fluidized bed, the pressure drop through the bed is just equal to the weight of the solids in the bed. Pugsley and Berruti [13] stated that the total pressure drop per unit length along the riser is assumed to be comprised of four main components:

$$\left(\frac{dP}{dz}\right)_{total}=\left(\frac{dP}{dz}\right)_{s}+\left(\frac{dP}{dz}\right)_{acc}+\left(\frac{dP}{dz}\right)_{fs}+\left(\frac{dP}{dz}\right)_{fg} \tag{3}$$

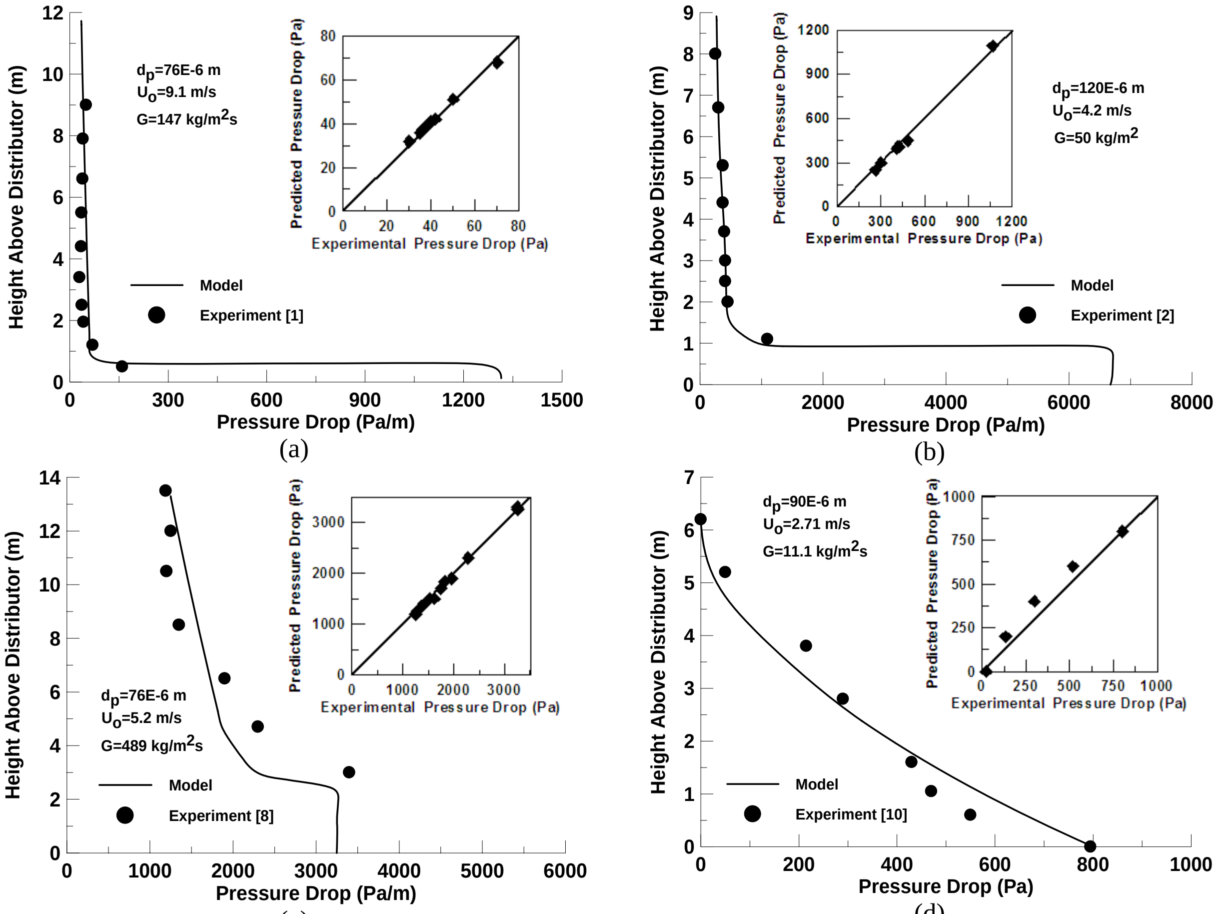
where $(dP/dz)_s$ is the pressure drop due to the hydrodynamic head of solids, $(dP/dz)_{acc}$ is the pressure drop due to solids acceleration, and $(dP/dz)_{fs}$ and $(dP/dz)_{fg}$ are the pressure drops due to solids and gas frictions, respectively. The pressure drop through the bottom zone is equal to the weight of the solids in this region and considered only in axial direction. Again in the upper zone, the pressure drop, in the axial direction due to the hydrodynamic head of solids is considered while pressure drop due to the solids acceleration is considered in axial and radial directions, the model calculates the acceleration component of pressure drop as follows:

$$\nabla P_{acc}=\frac{1}{2}\rho\nabla\left(v^2\varepsilon_p\right) \tag{4}$$

The set of differential equations governing mass and momentum for the gas and solid phases are solved with a computer code developed by the author in FORTRAN language. In these equations, the dependent variables are the vertical and the horizontal components of the void fraction, the solid volume fraction, the gas pressure, the gas concentration, the vertical and the horizontal velocity components of the gas and solids. The governing continuity and momentum equations for gas and solid phases at each region given in literature [8], are used in the iterative calculation of the velocity profiles through the calculation domain simultaneously at each time step. The structure and details of the numerical solution are given in the literature [8].

3. RESULTS AND DISCUSSION

In order to determine the validity of the developed model in terms of axial pressure drop profile along the CFB riser, the simulation results are compared with test results using the same input variables in the tests as the simulation program input [4-7]. The measurement conditions of the experimental data used for the comparison of CFB model are shown in Table 1.



(a) (b) (c) (d)

Figure 1. Comparison of model predictions with: a)Bader et al. [4]'s, b)Knowlton [5]'s, c) Benyahia et al. [6]'s, d) Smolder and Baeyens [7]'s experimental data.

Fig.1 shows the time-averaged axial pressure drop in the riser compared with experimental data for conditions of Table 1. Generally, the change in the pressure gradient with height in CFB riser is small. In the riser, the pressure gradient is always negative because the gas phase losses pressure head to accelerate and to suspend the particles. The absolute values of the pressure gradient decrease monotonically with increasing distance from the riser entrance and then gradually approach a constant value as clearly shown in Fig.1. In the model, calculation of total pressure drop also considers the pressure drop due to distributor plate at the primary gas entrance in the bottom zone. The high pressure drop at the bottom zone is due to the effect of solid feeding in that zone as clearly seen from the Fig. 1-c. The pressure drop then decreased along the height of the riser due to the decrease in solid concentration. The solid lines are in fair agreement with experimental data of Fig.1.

The parity plots of predicted pressure drop from the proposed model against the experimental pressure drop are also included for each figure. It could be concluded from these plots that the data points obtained based on the present model are distributed evenly around and close to the parity line which illustrates the fair agreement between the proposed model predictions and the experimental data.

Table 1. Measurement conditions of the experimental data referred to in this study.

Author(s)	Particle Type	Bed Temp. T(°C)	Bed Diameter D(m)	Bed Height H(m)	Superficial Velocity U_0(m/s)	Particle Diameter d_p(μm)	Particle Density ρ(kg/m^3)	Solid Circulation Flux G(kg/m^2s)
Bader et al. [4]	FCC	25	0.305	12.2	9.1	76	1714	147
Knowlton [5]	Sand	25	0.2	14.2	4.2	120	2600	50
Benyahia et al. [6]	FCC	25	0.2	14.2	5.2	76	1712	489
Smolders and Baeyens [7]	Sand	25	0.1	6.47	2.71	90	2600	11.1

4. CONCLUSION

In this study, a model using a PBA is developed to accurately predict the axial pressure profile in a vertical annular tube. As a result of this study, both the experimental data and the model predictions show that the pressure drop profile is affected by the different solid circulation flux and the superficial velocity values in the riser. The pressure drop has an increasing trend along the acceleration region as the solid circulation flux increases and the superficial velocity decreases in this region.

5. REFERENCES

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