A parametric study of powder holdups in a packed bed under decreasing gas velocity condition

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Abstract

The injection of pulverised coal along with the hot air blast in an iron-making blast furnace has contributed to lower the green house emissions and improve both the stability and productivity of the furnace. However, at high injection rates, some coal in the form of powder accumulates in the lower part of the furnace and obstructs the gas and liquid flows. Therefore, there is an urgent need to understand the physics and aerodynamics of gas-powder flow in such systems to improve the flow conditions. In this article, the flow of gas and fines in a packed bed is studied under decreasing gas velocity as it represents the blast furnace aerodynamics more accurately if it is not being considered as a moving bed reactor. A two-dimensional (2-D) model was developed for this purpose. More specifically, a parametric study is performed to determine the effects of the gas blast velocity, particle size and powder loading on the powder holdups. Results are presented in terms of fines accumulation area. This work shows the dependency of the powder holdups on the packed bed flow parameters.

Keywords: Packed bed, turbulent flow, mathematical modelling, decreasing gas velocity, gas-fines flow, powder holdups.

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1. **INTRODUCTION**

The modern iron-making blast furnace (BF) is a highly complex multiphase flow reactor involving coke and ore in the form of solid, metal and slag in the form of liquid, hot blast gas, pulverized coal, other injectant residues and coke fines in the form of powders. The recent technological advancement of Pulverised Coal Injection (PCI) has greatly contributed to decrease the emission of CO_2 gases from the furnace and reduce significantly the coke consumption and hence the production cost (Lu *et al.*, 2001; Shibata *et al.*, 1991). However, the physics and aerodynamics of the pulverised coal within the BF is still not well understood. Previous studies have shown that the complete combustion of pulverized coal in the raceway is not possible, especially at high PCI rate, and consequently the unburnt coal accumulates in the lower part of the furnace (Deguchi *et al.*, 1988; Matsui *et al.*, 1990 and Tamura *et al.*, 1991). This reduces the permeability of the BF and affects the gas flow and liquid drainage (Chen *et al.* 1994). To develop effective methods for ensuring stable operation of the BF at higher PCI level and improve the furnace performance, it is important to study and understand the behaviour of the different phases in the BF.

Mathematical modelling based on multiphase fluid dynamics and reaction kinetics is one of the essential tools to study the operation of the BF since direct measurement is difficult due to the high temperature and gaseous conditions. In literature, several numerical models have been proposed to study the aerodynamics in the iron-making blast furnace. Some examples are the two-fluid models of Shibata *et al.* (1991), Ichida *et al.* (1992) and Dong *et al.* (2003) and the four-fluid or multi-fluid model of Yagi (1993) and Dong *et al.* (2009). However, most of the reported studies have been mainly focused on the increasing gas velocity condition. Rajneesh *et al.* (2004) and Gupta & Rudolph (2006) have reported that BF aerodynamics can be represented more accurately by a packed bed under deceasing gas velocity condition if it is not being considered as a moving bed reactor. Therefore, the decreasing gas velocity condition is employed in this study.

In a previous work, we have shown the difference on the results for increasing and decreasing gas velocity cases under various conditions (Lollchund *et al.*, 2009). In this article, a parametric study is performed to determine the effects of the gas blast velocity, particle size and powder loading on the powder accumulation within the BF. A two-dimensional (2-D), two-fluid mathematical model was developed for this purpose. The model verification and validation were carried out by comparing numerical results with published experimental data. The model can predict the gas-fines aerodynamics and estimate powder accumulation regions in the bed. Such a simulation tool allows the study of the process for different bed input parameters.

2. MATHEMATICAL MODEL

Figure 1 illustrates a schematic representation of the packed bed studied in this work. It consists of a rectangular bed of width W=0.6 m and complete height H=1.2 m. Gas and fines are injected through a slot tuyere which has an opening D_T=5 mm and protrusion in the bed is r=5 cm. The tuyere is located at a height h=0.2 m above the bottom wall of the apparatus. The outlet is at the top. The bed is completely filled with plastic (ρ=1080 kg/m^3) beads. Other operating parameters are given in Table 1. This system configuration has been used for all the simulations presented in this paper, unless stated otherwise.

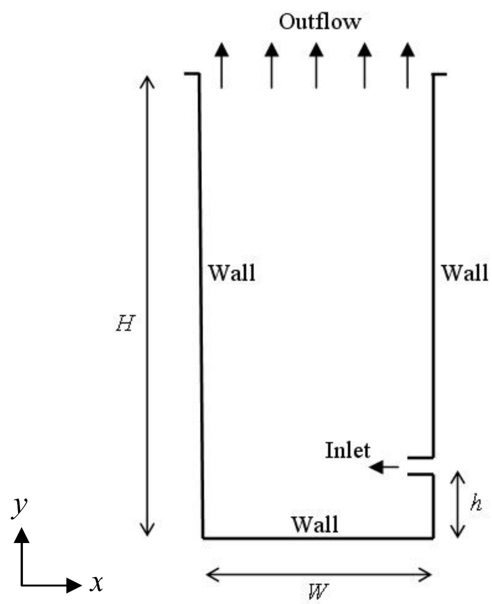


Figure 1: *Schematic of the packed bed system.*

Parameters	Value	Units
Bed voidage (α_g)	0.47 (outside raceway) 0.85 (within raceway)	
Gas density (ρ_g)	1.178	kg/m^3
Gas viscosity (μ_g)	1.983×10^{-5}	Pa s
Particle diameter(d_p)	3.0 – 5.5	mm
Powder diameter (d_f)	70	µm
Powder density (ρ_f)	1080	kg/m^3
Powder viscosity (μ_f)	0.8	Pa s
Inlet gas velocity (v_{in})	55 – 95	m/s
Powder loading	0.0001– 0.01	

Table 1: *Simulation parameters.*

2.1 The governing equations

It is assumed that the flow is two-dimensional, incompressible and steady. The phases present in the system are solid, gas and fines. They share space in proportion to their volume fractions (α) so that

$$\alpha_s + \alpha_g + \alpha_f = 1 \tag{1}$$

where the subscript "*s*" refers to solid, "*g*" to gas and "*f*" to fines. Gas and fines are considered to be continuous and fully interpenetrating continuum.

The solid phase is assumed to be stationary whereas the behaviour of the other phases are described in terms of mass and momentum conservation equations. The flow is turbulent and is modelled using the *k-ε* model. The governing equations are given as (Davidson, 2004)

$$\nabla \cdot \left(\rho_i \alpha_i \mathbf{u}_i \right) = 0 \tag{2}$$

$$\nabla \cdot \left(\rho_i \alpha_i \mathbf{u}_i \mathbf{u}_i \right) = -\alpha_i \nabla p + \nabla \cdot \tau_i - \frac{2}{3} \rho_i \nabla \left(\alpha_i k_i \right) + \alpha_i \rho_i g - \sum_{j=\{g,f,p\}, j \neq i} \mathbf{S}_{i,j} \tag{3}$$

$$\nabla \cdot \left(\rho_i \alpha_i \mathbf{u}_i k_i \right) = \nabla \cdot \left(\frac{\mu_{eff,i}}{\sigma_k} \nabla k_i \right) + G_i - \rho_i \alpha_i \varepsilon_i \tag{4}$$

$$\nabla \cdot \left(\rho_i \alpha_i \mathbf{u}_i \varepsilon_i \right) = \nabla \cdot \left(\frac{\mu_{eff,i}}{\sigma_k} \nabla \varepsilon_i \right) + \frac{\varepsilon_i}{k_i} \left(c_1 G_i - c_2 \rho_i \alpha_i \varepsilon_i \right) \tag{5}$$

Equations (2) and (3) represent the mass and momentum conservation respectively and equations (4) and (5) are used to calculate the turbulent kinetic energy and dissipation of kinetic energy respectively. The subscript "*i*" refers to either gas (*i*=*g*) or fines (*i*=*f*). The other symbols used in the equations are described in the nomenclature. The values of the constants in equations (4) and (5) are listed in Table 2.

c_μ	c_1	c_2	σ_k	σ_ε
0.09	1.44	1.92	1.0	1.3

Table 2: *Constants for k-ε turbulence model.*

2.2 Interaction between the phases and boundary conditions

The interaction forces between the phases are due mainly to friction and collisions. The details of how these forces (gas-fines, gas-solid and fines-solid interactions) are evaluated in the model are given elsewhere (Gunjal *et al.*, 2009; Lollchund *et al.*, 2009; Mullay, 2009).

For the boundary conditions at the walls, the no-slip condition is applied to the gas phase and a partial-slip boundary condition is applied to the fines phase. In the no-slip boundary condition, the normal and tangential components of velocity at the walls are set to zero. In the partial-slip boundary condition, the velocity tangential to the wall is assumed to be proportional to its gradient. Zero normal gradients are set for k_i and ε_i at the walls. At the inlet, all the dependent variables are known and at the outlet, outflow boundary condition is specified for both phases and the pressure is set as atmospheric.

2.3 The computational algorithm

Equations (2) to (5) are discretised using the finite volume approach based on a staggered and non-uniform grid system, with finer grids in the vicinity of the tuyere and coarser grids elsewhere. The grid size used for all calculations was ensured to be acceptable by grid dependence tests. The central difference scheme is employed for the diffusion terms whereas the convective transport term is evaluated using the Power-law scheme (Patankar, 1980). The SIMPLER scheme is employed to treat the pressure-velocity link from continuity condition and the resulting set of algebraic equations is solved using the line-by-line TDMA (Tri-diagonal Matrix Algorithm). Raceway size is calculated based on the correlation formula proposed by Sarkar *et al.* (2007).

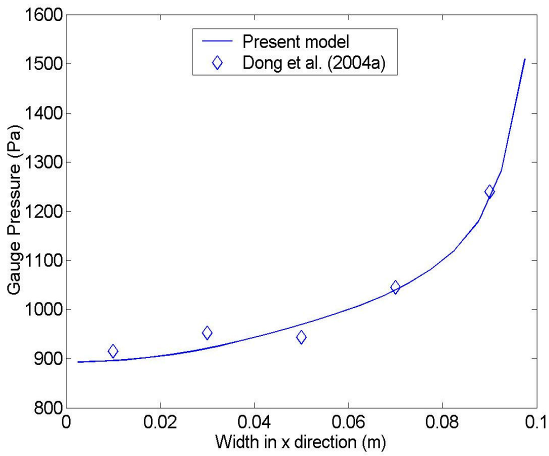
To determine the accumulation regions of static fines, we used a solution technique proposed by Dong *et al.* (2004b). In this technique, the initial gas and powder flow fields are first determined which are used to calculate the powder holdups. Update the gas and powder flow fields based on the new profile of powder accumulation and again calculate new powder holdups. The procedure is repeated until convergence of all phases is reached. It must be noted that in this work the correlation formulas given by Hidaka *et al.* (1998) have been used to compute the powder holdups. Moreover, the volume fraction of fines which is used to define an accumulation region is taken as 60 percent of the bed voidage. This value was determined theoretically using the linear-mixture packing model of Yu & Standish (1991).

3. RESULTS AND DISCUSSION

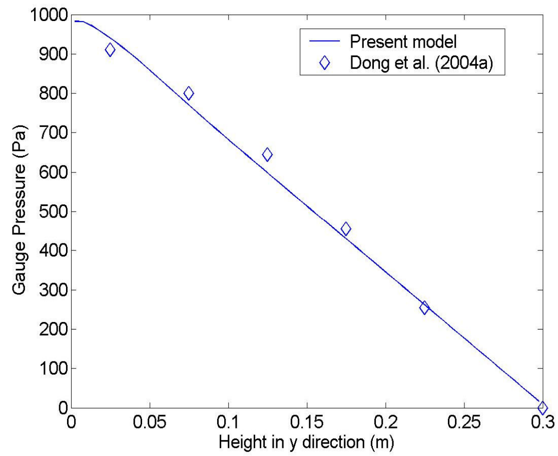
3.1 Validation of the present model

The validation of the present model is performed by comparing the predictions of the model with published experimental results of Dong *et al.* (2004a). The 2-D packed bed considered here is rectangular with dimensions of 0.1 m in width and 0.3 m in height. Gas and powder are injected through a lateral inlet opening of 10 mm which is located 25 mm from bottom of the bed. The experimental details can be found elsewhere (Dong *et al.*, 2004a).

Figure 2 compares both the horizontal pressure drop (at tuyere level) and vertical pressure drop (at centre of the bed) between the computed and experimental data of Dong *et al.* (2004a). One can observe that there is a good agreement between both the data, providing an excellent support to the model.



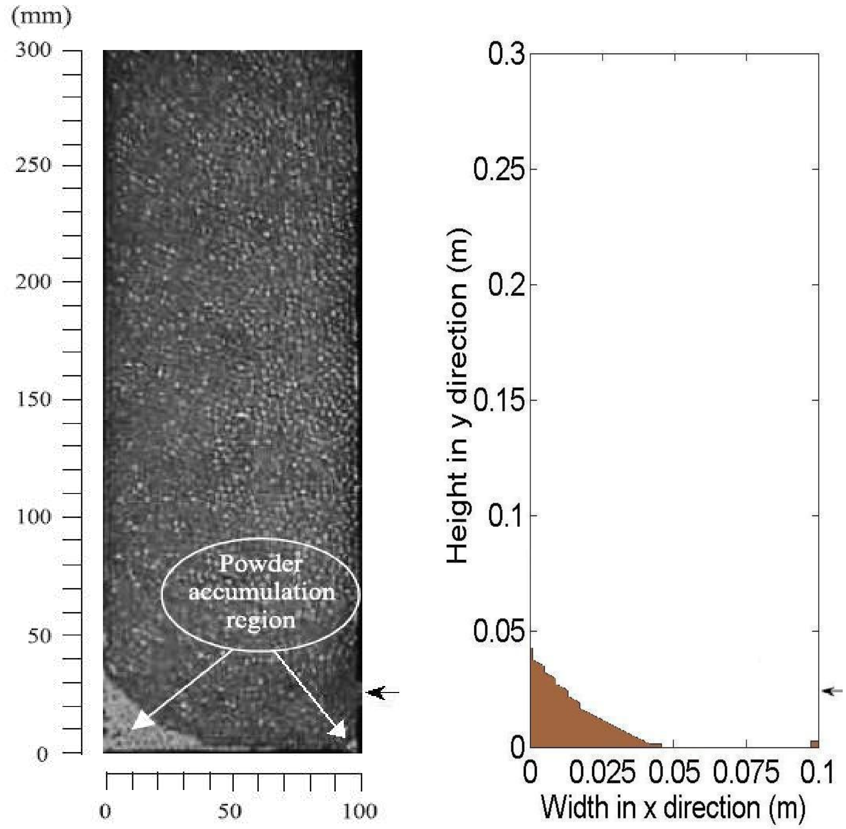
(a) Horizontal pressure at tuyere level



(b) Vertical pressure

***Figure 2**: Gauge pressure along the packed bed.*

Figure 3 depicts a visual comparison of computed results with experimental results of Dong *et al.* (2004a). In this figure, the regions of powder accumulation are shown. It is pleasing to note such a good comparison between the modelling and experimental results which indicate that the developed two-fluid model can be applied to the analysis of the packed bed under various conditions realistically.



(a) Experimental (b) Modelling

Figure 3: *Comparison between experimental results given by Dong et al. (2004a) and numerical results obtained by the present model. The horizontal arrow on the right of each figure indicates the direction of the gas-fines inlet flow.*

3.2 Application of the model

The model is applied to simulate the flow of gas and fines in the packed bed shown in Figure 1. The vertical gauge pressure distribution, at a distance of 0.06 m away from the tuyere side wall, for different values of powder loading is shown in Figure 4. The powder loading is defined as the ratio of powder mass flux to the product of inlet velocity and powder density. In the figure, the tuyere location is marked by an arrow.

It can be observed that in general, the pressure is higher in front of the tuyere and decreases as one goes on either side of it, i.e. above or below the tuyere level. Moreover, the pressure drop is lower below the tuyere level than above it. This is expected as the bottom of the apparatus is closed. When the powder loading is increased, the gas pressure also increases. This can be attributed to the larger gas-powder interaction force that occurs for higher powder mass flux and to the increase in collision rate between the fines and the packed solid.

Figure 5 depicts the total powder holdup distribution within the packed bed for two different values of the powder loading. For both cases, a remarkably higher concentration of powder is predicted by the model to accumulate along the lower section of the bed and close to the wall which is opposite to the tuyere opening. Some powders are also deposited in the area just above and below the tuyere. These are mainly due to the low velocity of gas which is unable to drive out the fines from these locations as the interactive forces are more than the drag forces. It can also be observed that the area of powder deposited expands as the injection flow rate of fines is increased.

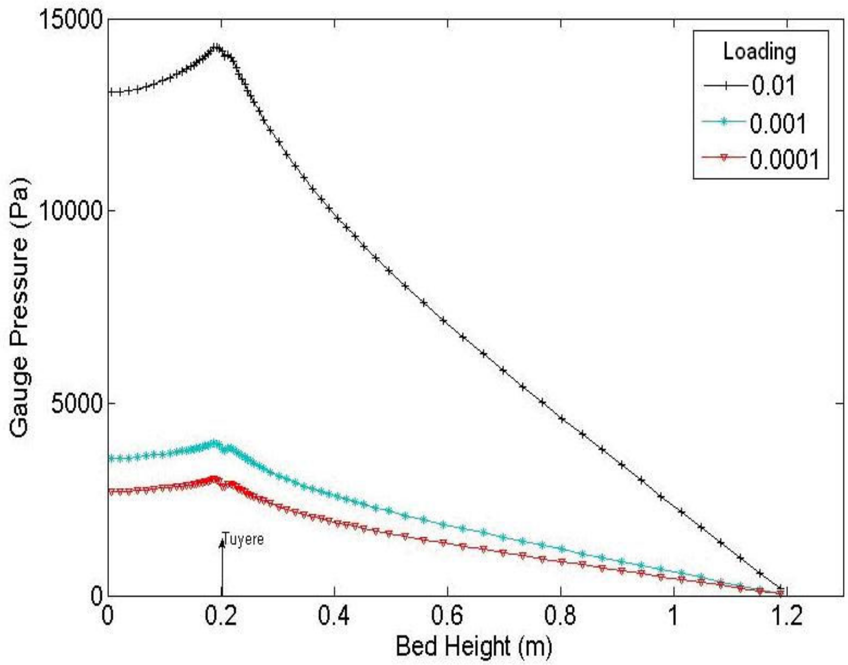
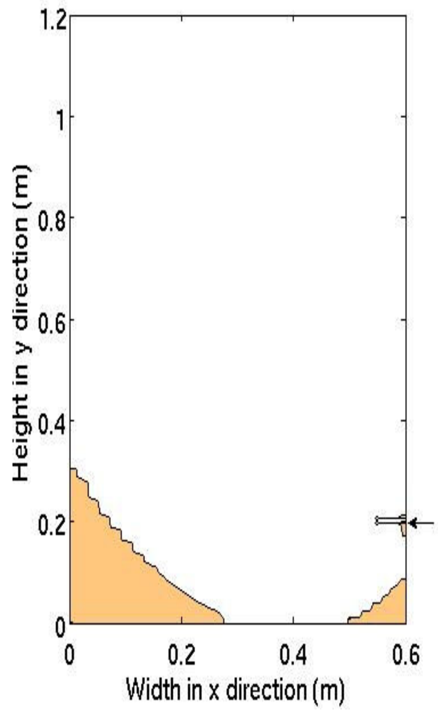
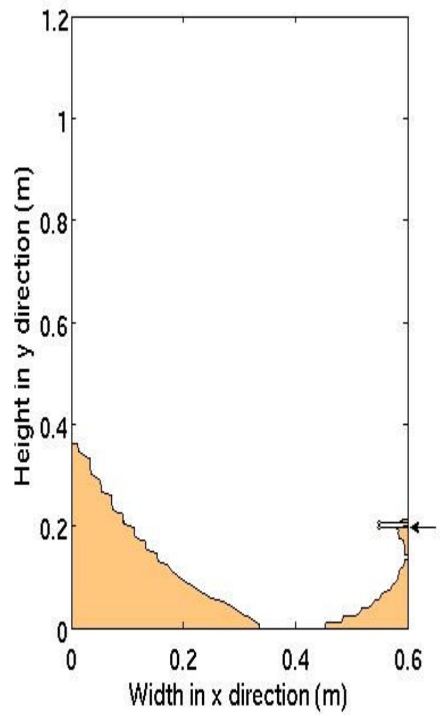


Figure 4: *Effect of loading on pressure drop in the packed bed (v_{in} = 75 m/s, d_p = 5.5 mm).*



(a) Loading = 0.0001



(b) Loading = 0.01

Figure 5: *Total powder holdup in the packed bed (v_{in} = 75 m/s, d_p = 5.5 mm). The horizontal arrow on the right of each figure indicates the direction of the gas-fines inlet flow.*

Figure 6 shows the effect of inlet gas velocity on powder accumulation area in the packed bed for different powder loading. It is evident that as the inlet gas velocity is increased, the powder holdup decreases and hence will affect the bed/furnace permeability the least. The high gas velocity leads to high gas drag force so that the powder can easily flow away. Due to this reason a higher fines accumulation occurs for low gas inlet velocity than at high gas velocity.

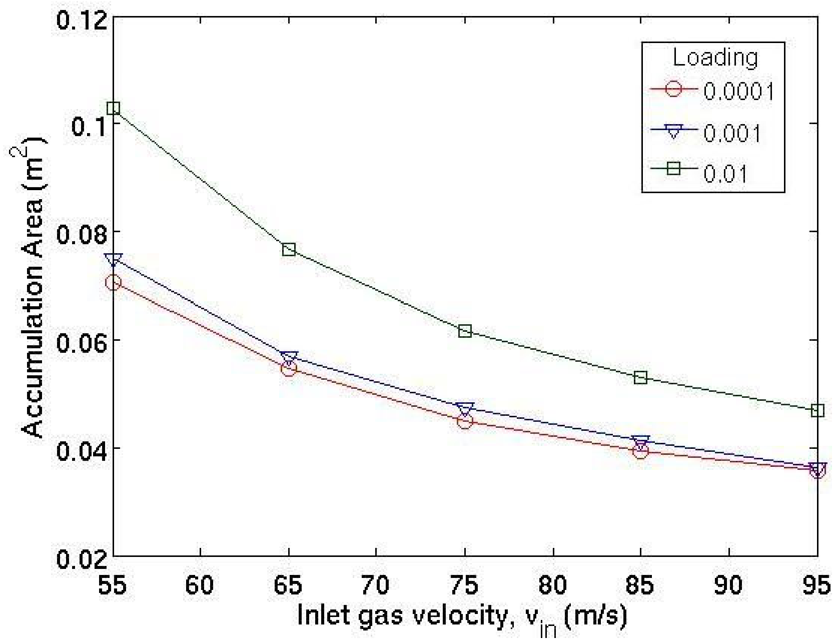


Figure 6: *Effect of inlet gas velocity on fines accumulation in packed bed for different values of powder loading (d_p = 5.5 mm).*

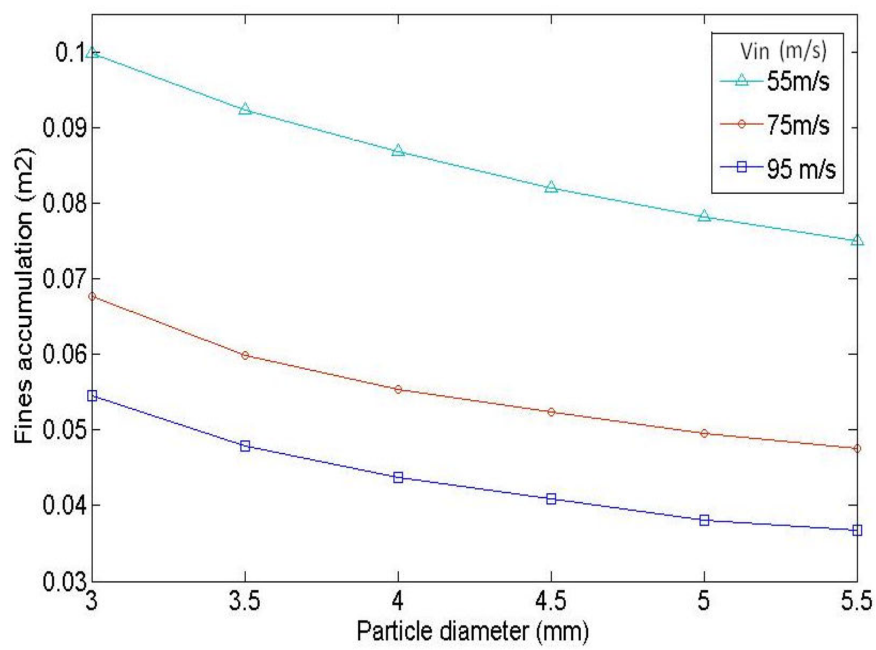


Figure 7: *Effect of particle size on fines accumulation area in packed bed for different gas inlet velocities (loading = 0.001).*

The effect of particle size on powder holdups is shown in Figure 7 for three different inlet gas velocities at powder loading of 0.001. It can be seen that as the particle diameter is increased, the fines accumulation area decreases. The same trend follows for all three inlet gas velocities considered.

4. CONCLUSIONS

A two-fluid mathematical model has been developed for the simulation of gas-fines flow within a rectangular packed bed. The model has been validated by comparing the model results with published experimental data. The present model was then applied to study the effects of the gas inlet velocity, powder loading and particle diameter on the powder holdups. The gas decreasing case has been considered in this work in all cases studied. It was observed that there is significant effect of these parameters on the powder accumulation area.

5. NOMENCLATURE

$\mathbf{u}_i$ = interstitial velocity vector (m/s)

ρ_i = density (kg/m^3)

α_i = volume fraction

p = pressure (Pa)

k_i = turbulent kinetic energy (W/kg)

ε_i = rate of dissipation of kinetic energy (W/kg)

$\mathbf{S}_{i,j}$ = interaction term between phases *i* and *j* (N/m^3)

τ_i = stress tensor (N/m^2); $\tau_i = \mu_{eff,i}\left[\nabla(\alpha_i u_i) + (\nabla(\alpha_i u_i))^T\right]$

G_i = generation term

(W/m^3); $G_i = \mu_{eff,i}\left\{2\left[\left(\frac{\partial u_i}{\partial x}\right)^2 + \left(\frac{\partial v_i}{\partial y}\right)^2\right] + \left[\frac{\partial u_i}{\partial y} + \frac{\partial v_i}{\partial x}\right]^2\right\}$

$\mu_{eff,i}$ = effective viscosity (Pa s); $\mu_{eff,i} = \mu_i + c_\mu \rho_i \frac{k_i^2}{\varepsilon_i}$

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