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Numerical Studies of Vertical, Nonisothermal Gas-Solid Flows Subjected to an Adiabatic Wall: Effect of Particle Size

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Abstract

In the present paper, the effect of particle size (ranging from 100µm to 400µm) on heat transfer and pressure drop in nonisothermal gas-solid flows through a vertical, adiabatic pipe is studied numerically, using the two-fluid model. The inlet gas (air) and solid (sand particles) temperatures are 443K and 308K respectively, and the heat transfer takes place from hot air to cold sand particles. The validation of the present numerical model is carried out with the available experimental results in the literature. It is noticed from the simulation results that the heat transfer decreases with increasing the particle size. However, the pressure drop shows negligible variation with respect to the particle size. Therefore, the smallest particles are more suitable in nonisothermal gas-solid flows based on the present study.

Keywords**:** Two-fluid model, particle size, heat transfer, pressure drop.

1. Introduction

Gas-solid flows are found in many industries such as chemical, process and food industries. Pneumatic conveying is such an application in the above industries. Particle size plays an important role in gas-solid flows. Particles of various sizes ranging from micron to mm alter the flow dynamics of gas-solid flows and therefore affect the heat transfer and pressure drop. Depew and Farbar[1] found that small particles create a large change in the local Nusselt numbers in gas-solid flows. Moreover, Farbar and Depew[2] noticed that decreasing the particle size increases the heat transfer. However, the large particles of size 200µm did not affect the heat transfer[3]. El-Behery et al.[4] found that the pressure drop increases as the particle size increases in vertical gas-solid flows. However, in isothermal gas-solid flows, the pressure drop increases, reaches a peak and then decreases as the particle size increases[5,6]. Ibrahim et al.[7] noticed that the smaller particles respond rapidly to the swirling flow than the larger particles. The effect of particle size (30µm-50µm) on suspension heat transfer in vertical pipes was numerically studied by Patro[8] and found that the heat transfer increases with the particle size. Recently, El-Behery et al.[9] found that the minimum pressure drop velocity increases as the particle size increases. Jiang et al.[10] noticed that the pressure fluctuations are related to the particle size in gas-solid fluidization systems. The effect of particle size on nonisothermal gas-solid flows in adiabatic pipes are rare in the literature. Hence, in the present study, the effect of particle size on heat transfer and pressure drop in nonisothermal gas-solid flows in a vertical, adiabatic pipe is presented.

2. Mathematical Model

The two-fluid model of Ansys Fluent 15.0 is used to describe the mathematical model. The two-fluid model is based on Eulerian- Eulerian approach. The Continuity equation is

$$\frac{\partial}{\partial t}\left(\alpha_j\rho_j\right) + \nabla\cdot\left(\alpha_j\rho_j\vec{v}_j\right) = 0 \tag{1}$$

where j is either gas or solid phase and $\sum \alpha_j = 1$. α is the volume fraction of the individual phase, ρ is the density of the individual phase in kg/m^3 and $\vec{v}$ is the mean velocity of the phase in m^3/s.

The Momentum equations for gas and solid phases are

$$\frac{\partial}{\partial t}\left(\alpha_g\rho_g\vec{v}_g\right) + \nabla\cdot\left(\alpha_g\rho_g\vec{v}_g\vec{v}_g\right) = -\alpha_g\nabla\bar{p} + \nabla\cdot\bar{\bar{\tau}}_g + \alpha_g\rho_g g + K_{sg}(\vec{v}_s - \vec{v}_g) \tag{2}$$

$$\frac{\partial}{\partial t}(\alpha_s\rho_s\vec{v}_s) + \nabla\cdot(\alpha_s\rho_s\vec{v}_s\vec{v}_s) = -\alpha_s\nabla\bar{p} - \nabla\bar{p}_s + \nabla\cdot\bar{\bar{\tau}}_s + \alpha_s\rho_s g + K_{as}(\vec{v}_g - \vec{v}_s) \tag{3}$$

Here, g denotes gas and s denotes solid. $\bar{p}$ is the mean pressure in Pa, $\bar{\bar{\tau}}$ is the stress tensor in kg/ms^2, g is the acceleration due to gravity in m/s^2 and K_{gs}=K_{sg} is the gas-solid momentum exchange coefficient in kg/m^3s.

The Energy equations for gas and solid phases are

$$\alpha_g\rho_g C_{pg}\left(\frac{\partial T_g}{\partial t} + \vec{v}_g.\nabla T_g\right) = -\nabla.q_g + h_{gs}\left(T_s - T_g\right) \tag{4}$$

$$\alpha_s\rho_s C_{ps}\left(\frac{\partial T_s}{\partial t} + \vec{v}_s.\nabla T_s\right) = -\nabla.q_s - h_{gs}\left(T_s - T_g\right) \tag{5}$$

where C_p is the constant pressure specific heat in J/kgK, T is the temperature in K, q is the phase heat flux in W/m^2 and h_{gs} is the heat transfer coefficient between phases in W/m^2K.

The various closure equations are given in Table 1. The details of various closure equations are given in the study of Patro et al.[11].

Table 1. Closure equations

Description	Models
Solid pressure	Lun et al.[12]
Granular viscosity (μ_s)	Syamlal et al.[13]
Granular bulk viscosity (λ_s)	Lun et al.[12]
Granular temperature	PDE granular temperature model[14]
Radial distribution function	Lun et al.[12]
Turbulence	Standard $k-\varepsilon$ turbulence model[15]
Drag force	Gidaspow model[16]
Particle Nusselt number	Gunn model[17]

The density of gas is defined as per the incompressible ideal gas conditions. The operating pressure is 1 atm. A temperature dependent piecewise-polynomial profile is used to define the dynamic viscosity of gas (μ_g).

$$\mu_g(T) = A - BT + CT^2 - DT^3 + ET^4 - FT^5 + GT^6 - HT^7 \tag{6}$$

where A, B, C, D, E, F, G and H are the coefficients and the values are: A=1161.482, B=2.368819, C=0.01485511, D=5.034909×10^{-05}, E=9.928569×10^{-08}, F=1.111097×10^{-10}, G=6.540196×10^{-14} and H=1.573588×10^{-17}.

The thermal conductivity of gas (k_g) and the specific heat of gas (C_{Pg}) are[18]

$$k_g = 0.02624\left(\frac{T_g}{300}\right)^{0.8646} \quad (7)$$

$$C_{Pg} = 1002.5 + 275 \times 10^{-6}\left(T_g - 200\right)^2 \quad (8)$$

The average gas-solid Nusselt number is calculated as described below.

$$Nu_{avg} = \int_0^L Nu_l.\, dz/L \quad (9)$$

where L is the pipe length in m and z is the axial distance in m.
The local gas-solid Nusselt number (Nu_l) is calculated as

$$Nu_l = UD/k_g \quad (10)$$

where D is the internal diameter of the pipe in m. The overall heat transfer coefficient (U) is calculated by assuming the system as a direct contact type parallel flow heat exchanger.

The boundary conditions are given in Table 2.

Table 2. Boundary conditions

Boundary condition type	Gas phase	Solid phase
Inlet	Velocity inlet	Velocity inlet (equal to gas velocity)
Wall	No-slip	Partial-slip[19]
Outlet	Outflow	Outflow

The computational geometry is a vertical pipe of ID 58mm and length 6m. The inlet gas temperature is 443K and the inlet solid temperature is 308K. The wall is maintained at adiabatic condition. The gas phase is air and the solid phase is sand. The sand properties are: density 1500kg/m^3, specific heat 800J/kgK and thermal conductivity 0.8W/mK. The restitution coefficients for the particle-particle and particle-wall collisions are 0.9 and 0.95 respectively. A specularity coefficient of 0.05 is used in the simulation. Lift is not considered due to the vertical case. A convergence criteria of 10^{-3} are used.

3. Results and Discussion

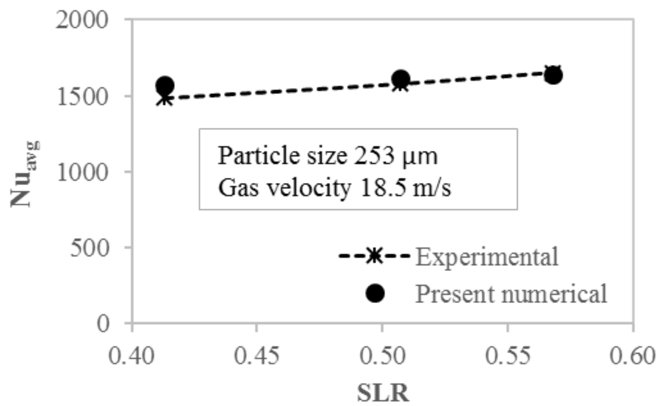

Fig. 1. Validation of computational Nusselt numbers with the experimental values[20]

First the validation of the numerical work is carried out. The numerical values of average gas-solid Nusselt numbers are compared with the experimental values obtained by Mokhtarifar et al.[20] with respect to solid loading ratio (SLR) and are plotted in Fig. 1. It is noticed from Fig. 1 that the numerical results agree satisfactorily with the benchmark experimental values and there is a maximum deviation of 5.8%.

Heat transfer and pressure drop play significant roles in gas-solid flows. There should be a higher heat transfer and a lower pressure drop in the gas-solid flow. The effect of particle size (ranging from 100μm to 400μm spherical particles) on gas-solid Nusselt number is shown in Fig. 2. Here, the inlet SLR is 1. It is noticed from Fig. 2 that the gas-solid Nusselt number decreases when the particle size increases. This behavior is due to the decrease in the turbulent Reynolds number when the particle size increases.

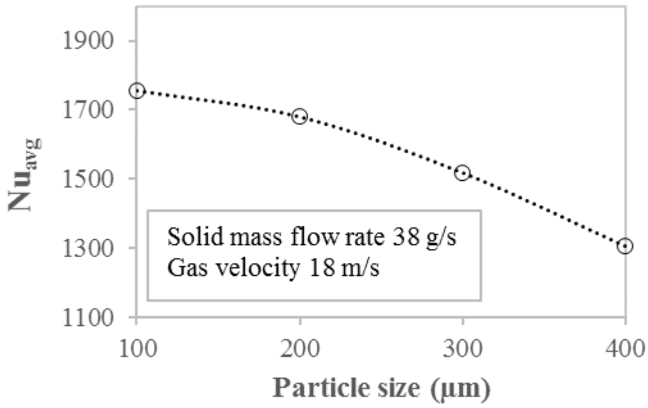

Fig. 2. Effect of particle size on gas-solid Nusselt number

The effect of particle size on overall pressure drop is shown in Fig. 3. It is noticed from Fig. 3 that the pressure is little affected by the particle size. This is due to the reason of change of gas properties.

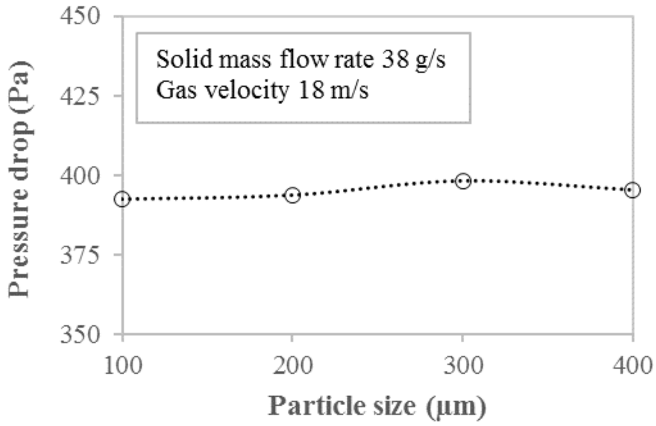

Fig. 3. Effect of particle size on pressure drop

4. Conclusion

Gas-solid flows are found in many industries such as chemical, process and food industries. Pneumatic conveying is such an application in the above industries. Particle size plays an important role in gas-solid flows. Particles of various sizes ranging from micron to mm alter the flow dynamics of gas-solid flows and therefore affect the heat transfer and pressure drop. In the present paper, the effect of particle size (ranging from 100μm to 400 μm) on heat transfer and pressure drop in nonisothermal gas-solid flows through a vertical pipe is studied numerically, using the two-fluid model. The inlet gas and solid temperatures are 443K and 308K respectively, and the heat transfer takes place from hot gas to cold solids, where the pipe wall is at adiabatic condition. The validation of the present numerical model is carried out with the available experimental results in the literature. It is noticed from the simulation results that the heat transfer decreases with increasing the particle size. However, the pressure drop shows negligible variation with respect to the particle size. Therefore, the smallest particles are more suitable in nonisothermal gas-solid flows based on the present study.

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