

FLOW AND DEPOSITION CHARACTERISTICS OF NANOPARTICLES IN A 90° SQUARE BEND

by

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Large eddy simulation and discrete particle model have been used to study the nanoparticles through a 90° square bend flow considering the effects of Brownian motion and turbulence diffusion. The penetration rate and the residence time of particles are evaluated under different flow conditions and various particle sizes. Results show that particles penetration rate increases with an increase in Dean and Schmidt numbers. The particle size and flow Dean number have significantly effects on the particles residence time in the bend.

Key words: nanoparticles, large eddy simulation model, discrete particle model, deposition

Introduction

Particles, especially nanoparticles, exist everywhere, and their movement patterns have been caught much attention in recent years. It is important to study the deposition of ultrafine particles in the strengthen of heat conduction of micro devices, the powder particles transportation of human lung, and the removal of particulates from industrial duct bends [1].

A number of studies have been reported to investigate the flow field of a square bend and the particles deposition process. Taylor *et al.* [2] adopted the laser Doppler velocimetry (LDV) technology to study the laminar flow and the turbulence flow in a square cross-section bend and found out the larger pressure gradient along with the flow direction and the secondary flow vertical to the flow direction. Lin and Lin [3] simulated the deposition efficiency and distribution of particles in circular bends. Liu and Zhang [4] studied the deposition and the diffusion characteristics of micro particles in the gas-solid two phase flow in the bends. Chiou *et al.* [5] studied the particle deposition in a fully developed turbulent flow influenced by Brownian diffusion, turbulent eddy diffusivity and thermophoresis.

The size of particles in these studies are mostly larger than one micron. If the diameter of the particle is down to nanometer, the main factor affecting particle motion in the flow field is not inertial effect, but Brown movement [6]. Effect of Brown force on nanoparticles through a 90° square bend has been not investigated in the earlier works. The main goal of this study is to extend the knowledge on particle deposition in a bend to a very small size (nanometer) and to understand the principle of flow and nanoparticles deposition characteristics.

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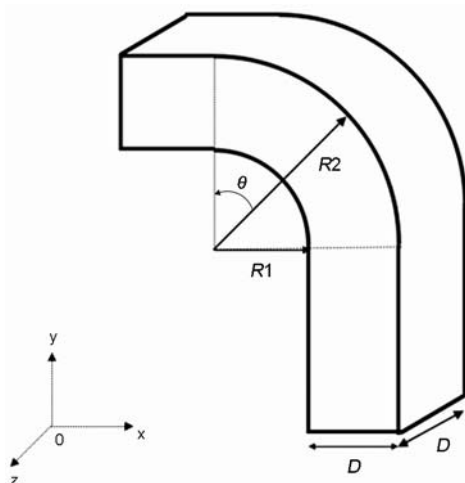


Figure 1. Physical model of the 90° square bend

Physical model

The physical model of the 90° square cross-section bend adopted in this study is shown in fig. 1. The pipe is composed of a horizontal inlet section, a bending section and a vertical downward outlet section, the cross section is a square of 10 mm side length. In order to enable a fully developed flow state, the vertical section length is designed to be much longer than the cross section side length. The whole computational region is structured by the hexahedral mesh and the total grid number is about one million changing with the length of the pipe. The simulation is performed using the FLUENT platform and the walls are considered as perfectly absorbing, which means if a particle hits a wall it sticks to the surface.

Governing equations of gas-solid two-phase flow

The air is used as the continuous phase and the large eddy simulation (LES) method is chosen to describe the turbulent flow in this study. Assuming that the fluid flow is 3-D, viscous, steady isothermal, incompressible, the continuity equation, and the Navier-Stokes equation are given as:

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \quad (1)$$

$$\frac{\partial}{\partial t} (\rho \bar{u}_i) + \frac{\partial}{\partial x_j} (\rho \bar{u}_i \bar{u}_j) = - \frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j} \left(\mu \frac{\partial \bar{u}_i}{\partial x_j} \right) - \frac{\partial \tau_{ij}}{\partial x_j} \quad (2)$$

where the gas density ρ is a constant for the incompressible field, \bar{u}_i – the filtered velocity, \bar{p} – the filtered pressure, μ – the viscosity, τ_{ij} – the subgrid-scale stress, proposed by Smagorinsky [7].

The discrete particle model (DPM) has been used to track the particles so as to acquire the trajectory. The governing equation of the motion of particles is given as:

$$\frac{du_i^p}{dt} = \frac{18\mu}{d_p^2 \rho_p} \frac{C_D Re_p}{24} (u_i - u_i^p) + g_i \frac{(\rho_p - \rho)}{\rho_p} + F_i \quad (3)$$

where u_i^p is the particle velocity, C_D – the drag coefficient, $g_i(\rho_p - \rho)/\rho_p$ – the resultant force of gravity and buoyancy per unit mass, d_p – the particle diameter, ρ_p – the particle density, Re_p – the particle Reynolds number, and F_i – the additional force contains the Saffman lift force, and the Brownian force.

Results and discussion

In this study four groups of particles with different sizes ranging from 1 nm to 100 nm have been simulated. The curvatures of bend are set as 60, 100, 140, and 180, and the

velocities of the air are 2 m/s to 10 m/s. The temperature, dynamic viscosity coefficient and density of the air are $T = 288$ K, $\mu = 1.7894 \cdot 10^{-5}$ Ns/m², and $\rho = 1.225$ kg/m³, respectively.

Figure 2 shows the streamline in the cross-section when $\theta = 90^\circ$. Due to the centrifugal force of the fluid flow in the bend, the secondary flow vortex core symmetrically appears in the semi center section, which is agree with the result of Taylor [2].

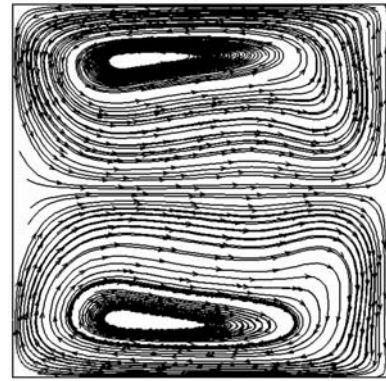


Figure 2. The streamlines in the bend with $\theta = 90^\circ$

Figures 3 and 4 depict the impact of the Dean number (De) on the penetration rate in cases of different particle sizes. When the flow state transits to turbulence with De increasing, the turbulent diffusion plays a major role in the particles motions and the particles penetration rate (p) decreases significantly. With the increase of Dean number, the particles penetration rate increases at first and then decreases because the growth of turbulence intensity aggravates the particle deposition. As what is illustrated in figs. 3 and 4, particles of larger size have higher penetration rate.

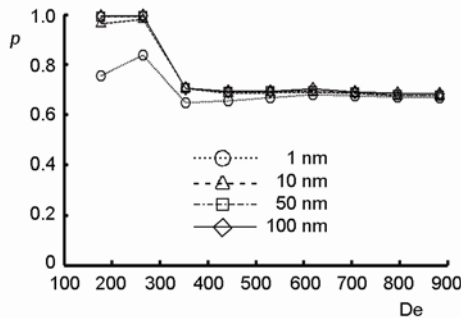


Figure 3. p vs. De with $R_0 = 60$

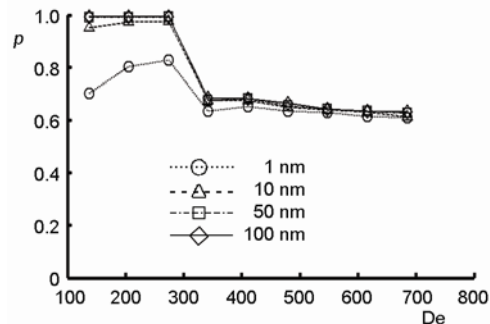


Figure 4. p vs. De with $R_0 = 100$

Figure 5 indicates the impact of Schmidt number on the penetration rate at different air velocities. It is shown that higher Schmidt number leads to increase the particles penetration rate.

Figure 6 shows the residence time t of particles in the bend with different Dean number. From this figure we can see that the particle residence time decreases slowly when

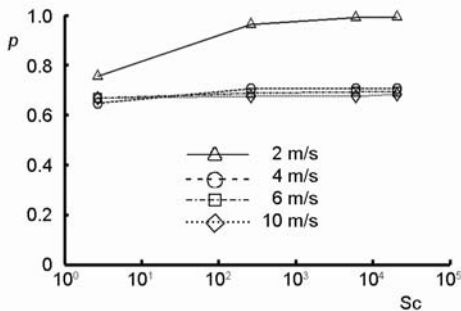


Figure 5. p vs. Sc with $R_0 = 60$

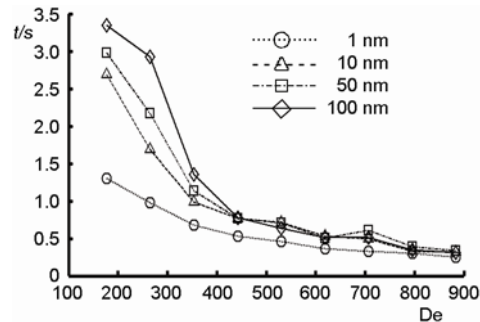


Figure 6. t vs. De with $R_0 = 60$

the Dean number increase, while the effect of particle size is different. With the increase of Dean number, the main factor impacting particles changes from Brown diffusion to turbulent diffusion.

Conclusions

The current work is conducted to study the nanoparticles deposition in a 90° square bend flow using LES and DPM models. The main finding can be drawn as:

- particles penetration rate increases with the increase of Dean and Schmidt numbers in turbulent for nanoparticles;
- the particle with larger size has high penetration rate;
- the residence time of particles in the bend decreases when Dean number increases, while the effect of particle size on residence time is opposite.

Acknowledgment

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