Effect of dust particle distribution characteristics on the flow and heat transfer performance of parallel-plates flow channel

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Abstract. The fluid flow and heat transfer of the particle-laden flow in pipes is a common phenomenon in the industrial field. In previous studies, many studies have focused on studying particle migration and deposition behavior through experimental measurements and numerical simulations. However, the influence of particle distribution characteristics on the flow and heat transfer characteristics of the flow is often ignored. In this study, a numerical simulation was used to study the flow and heat transfer characteristics of dust-containing gas in the parallel-plates channel. The products of *fRe*, local Nussel number (Nu_L), and average Nussell number (Nu_{avg}) were used to characterize the flow and heat transfer properties, respectively. As the particle volume increases, the *fRe* increases while the Nu_{avg} first increases and then decreases. In addition, the effects of the particle size and flow velocity were calculated, and it was found that large particles and low velocity show a more pronounced effect on flow and heat transfer performance.

1. Introduction

In industrial sectors, such as fluidized bed systems and heat exchanger systems, the flow of particle-laden gas streams is a common phenomenon [1-2]. Ramezani et al. compared the results of experiments and numerical simulations and found that the interaction between the airflow and the particles was mainly determined by the drag coefficient applied on the spherical particles [3]. In previous studies, extensive research has been carried out on the deposition characteristics of particles.

However, the above studies focus on the influence of fluid on the dynamic behavior of particles. The influences of dust on the fluid flow are ignored. In fact, this neglected phenomenon is more worthy of discussion and analysis in practical cases. At present, experimental studies were often used to characterize the effects of particles on pipe flow [5-7]. In terms of numerical simulation, the influence of particulate matter on fluids is usually ignored when scholars study dusty gas flows [8-10]. This method does address low concentrations of dust particles, but it is not suitable for dusty airflows with high concentrations of particles. In addition, some scholars have also conducted the numerical studies on heat transfer performance in turbulent and laminar flows, and applied full-particle simulations to obtain the interaction between particles and fluids.

In this study, a mesoscale numerical simulation method was used to trace the effect of the particles on the airflow. The particle size is much smaller than the pipe size, which is similar to the real environment. The effects of the particle volume and flow velocity on the flow and heat transfer performance were studied.

2. Numerical method

Lattice Boltzmann Method is an effective tool for simulating complex flows, including porous media flow, thermal flow, reaction, mass transfer, turbulence and multiphase flow[11]. In this study, LBM was used to calculate the fluid flow characteristic and heat transferand particle-fluid interactions. The LBM equations can be described as follows:

$$f_i(x+e_i\delta_t, t+\delta_t) - f_i(x,t) = -\frac{1}{\tau}[f_i(x,t) - f_i^{eq}(x,t)] \quad (1)$$

$$g_i(x+e_i\delta_t, t+\delta_t) - g_i(x,t) = -\frac{1}{\tau}[g_i(x,t) - g_i^{eq}(x,t)] \quad (2)$$

Where $f_i(x,t)$, $g_i(x,t)$ represents the fluid density distribution function and τ represents the relaxation time. The left side of the formula is stream step while the right side represents the collision step. The equilibrium distribution function can be described as follows:

$$f_i^{eq}(x,t) = \rho w_i[1 + \frac{e_i u^{eq}}{Cs^2} + \frac{(e_i u^{eq})^2}{2Cs^4} - \frac{(u^{eq})^2}{2Cs^2}] \quad (3)$$

The weight coefficient w_i is different for different direction. Finally, The fluid density and the velocity at each node can be calculated by

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$$\rho = \sum_i f_i \tag{4}$$

$$\rho u = \sum_i e_i f_i \tag{5}$$

3. Results and discussions

3.1 Effect of particle volume fraction on fluid flow and heat transfer of the parallel-plates duct

In a previous study, Pan et al. analyzed the effects of dust particles on fluid flow and heat transfer performance in a parallel-plates duct, and they proposed the concept of a "relatively fully-developed" [11]. However, they did not consider the effect of the integral number of particulate matter within the entire pipe on the flow. Therefore, here, we first analyze the effect of the particle volume fraction on the fluid flow inside the pipe. Fig. 1 shows the local *fRe* along the flow direction with different particle volume fractions throughout the pipe. It can be seen that when the particle volume fraction is 0, the fluid is pure fluid, and the overall change trend of the *fRe* value is consistent with the previous study. The local *fRe* gradually decreases from the higher value near the entrance of the duct to a stable low value at the end of the inlet section, and then meet the value in the fully developed section, with a value close to 96. However, as the particles enter the pipe, the effect of the particles on the flow characteristics become obvious. When the particle volume fraction was 2%, the particle concentration in the pipe is low and it has little effect on the flow characteristics. As the number of particulate matter in the pipe increases, the influence of particles on the flow characteristics becomes apparent. When the particle volume fraction was 8%, the value in the fully- developed section *fRe* increases about 50%. Fig. 2 shows the number of local Nusselt number along the direction of flow. It can be seen that the effect of particles on heat transfer performance is similar to that of flow properties. As the volume fraction of particles increases, the heat exchange in the pipe is inhibited, and the local Nussel number decreases along the flow direction.

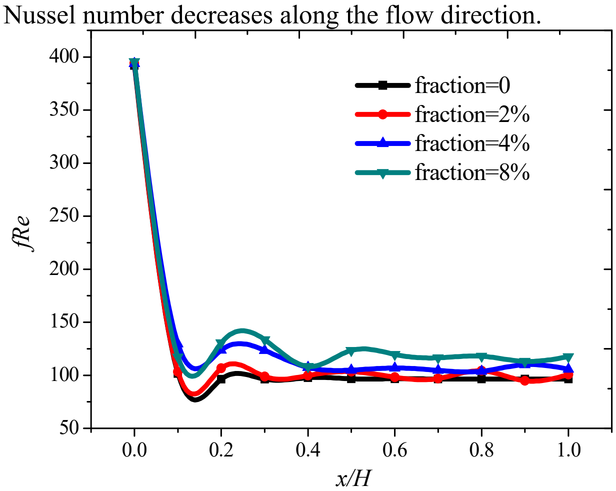

Fig. 1. (*fRe*) along flow direction under different particle volume fraction

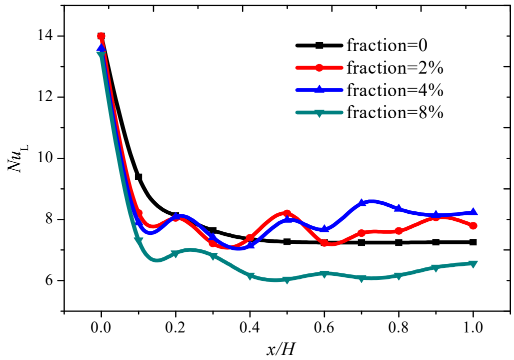

Fig. 2. Local Nusselt number along flow direction under different particle volume fraction

In addition, the average Nusselt number in the pipe with and without particles were compared. The parameters of γ_{fRe} and γ_{Nu} are defined as:

$$\gamma_{\mathrm{fRe}} = \frac{fRe}{fRe_0} \tag{6}$$

$$\gamma_{\mathrm{Nu}} = \frac{Nu_{\mathrm{avg}}}{Nu_{\mathrm{avg0}}} \tag{7}$$

where γ_{fRe} is the ratio of the (*fRe*) between the particle-laden flow and pure airflow. (fRe_0) represents the (*fRe*) of the duct flow without particles. γ_{Nu} is the ratio of the average Nusselt number between the particle-laden airflow and pure airflow while the Nuavg0 represents the average Nusselt number of the duct flow without particles. In this study, (fRe_0) is 96 while Nu_{avg0} is 7.54. With the increase of the flow time, the γ_{fRe} increased while the γ_{Nu} increased and then decreased. The particles inside the duct would increase the whole friction of the duct. With the particle concentration increased, the particle number in whole duct would significantly increase, which can greatly increase the flow resistance. The maximum of the γ_{fRe} can be up to 1.4.

3.2 Effects of particle sizes on flow and heat transfer performance of particle-laden flow

In this section, the effects of the particle size on flow and heat transfer characteristics were analyzed and discussed.

Considering the dust size in real environment, the selected particle diameter in this study was 6 μm, 10 μm, 14 μm and 18 μm, respectively. It should be particularly emphasized that the number of the particle at the inlet is a constant, so the particle volume fraction in inlet laden flow varies with the particle sizes. In last part, we found that the particle effects mainly focus on the fully developed areas. Fig. 3 shows the effects of the particle size on flow characteristics at different times when the particle-laden flow through the parallel-plate duct. It can be found that the particles with different sizes would have adverse effect on the airflow in the channel. As the time increased, the particle volume fraction in the whole channel increased, the particle effect on the flow characteristic became more obvious. By comparing the effects of different particles on flow characteristics, it can be seen that when the particle diameter became larger, the increase of the flow resistance in duct flow became more overt. When the t* was 400, the γfRe was 1.05,1.41,1.47 and 1.51 for the particle diameter of 6 μm, 10 μm, 14 μm and 18 μm, respectively. This can be analyzed combining with the particle distribution in the duct. When the particle size was large, the drag force obtained from the airflow has a small effect while the gravity effect played a more significant role during particle migration process. The exerted gravity force would change the moving behaviors of the particle, leading to particle deposition and rebound behaviors, which would obviously influence the flow characteristics. Besides, the gravity force would cause a larger amount of particles to periodically deposition and rebound on the bottom rather than leaving the duct, which would greatly increase the flow resistance.

Moreover, when the particle volume fraction in the duct is same, the effects of the particle size on flow characteristics may be different. The comparison of the effects of different particles on the flow characteristics were displayed in Fig. 4. It can be observed that the larger the particles, the greater the influence on the flow characteristics. Under the same particle volume fraction in duct (4%), the γ_{fRe} is 1.06, 1.08, 1.095 and 1.1 for the particle diameter of 6 μm, 10 μm, 14 μm and 18 μm, respectively. The larger particles were easier affected by the gravity and collide the bottom surface. In contrast, the smaller particles may migrate with the airflow. The collisions between the particles and surface may not occur for smaller particles. The phenomenon of particle migration in parallel-plates duct may not have a significant impact on flow characteristics. Therefore, it can be preliminarily concluded that the moving particles with airflow may have less effect on the flow characteristics

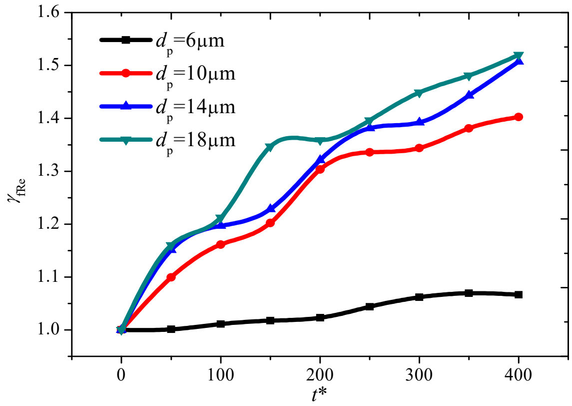

Fig. 3. Effects of the particle sizes on flow characteristics at different times

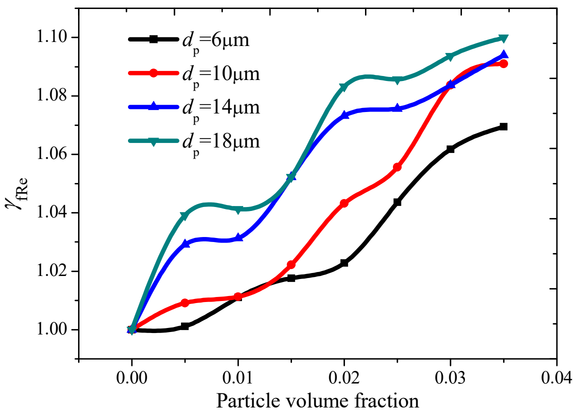

Fig. 4. Effects of the particle sizes on flow characteristics under similar particle volume fraction

3.3 The effects of Reynolds number on flow and heat transfer performance of particle-laden flow

When the particle-laden flow passes the duct, the migration behaviors of the particles are different under different inlet velocities while the flow and heat transfer performance may be affected. Therefore, the effects of inlet velocities are meaningful to be further analyzed and discussed.

Herein, the flow characteristics of the channel flow at different time under different Reynolds numbers were compared. As shown in Fig. 5, when the Reynolds number was 35, the γ_{fRe} would greatly change with the time increasing. When the time was 400, the value of γ_{fRe} can be up to 1.7. This can be ascribed to that when the Reynolds number is lower, the horizontal movement of the particles was short before they collided with the bottom surface. The deposited particles would adversely affect the flow inside the duct. When the Reynolds number was 140, it can be found that the resistance in the channel remained stable and γ_{fRe} kept a constant of 1.21. When the Reynolds number was high, some particles would directly leave the duct with the airflow and not collide with the bottom surface, leading to little influence on flow characteristics of the channel. Therefore, when the inlet velocity is higher, the particles keep moving in the channel while its impact on the flow is minimal.

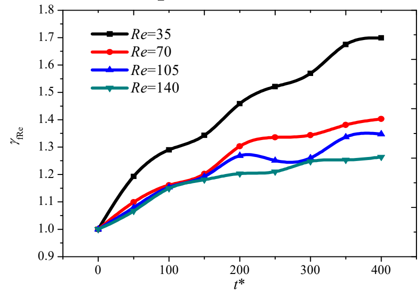

Fig. 5. Effects of the Reynolds number on flow characteristics at different times

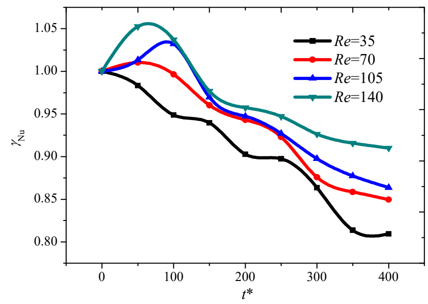

Fig. 6. Effects of Reynolds number on heat transfer characteristics

In addition, the effects of Reynolds number on heat transfer performance were analyzed as well. The average Nusselt number under different simulation cases were shown in Fig. 6. It can be seen that when the Reynolds number was 35, the appearance of the particles was detrimental to the heat transfer of the duct. The average Nusselt number of fully developed section was reduced to 0.80 of the initial value. This phenomenon has been analyzed in previous parts. Meanwhile, when the Reynolds number was higher, the particle distribution in the duct showed a spread state, which would greatly reduce the Nusselt number reduction. Besides, when the Reynolds number was 140, the particles were less likely to contact with the surface before leaving the duct. Moreover, during the particle-surface collision process, the particles with higher velocity were easier to rebound off the surface, leading to little effect on the heat transfer of duct flow. Thereby the Nusselt number of may not be affected obviously. However, even the inlet particles could raise the heat transfer performance when the particle volume fraction was small, the incremental of the Nuavg was pretty small and could be ignored in some situations. Meanwhile, the heat transfer performance reduction caused by the deposited particles was much higher. The maximum incremental Nuavg was just 0.05 while the maximum reduction of the Nuavg was about 0.2. The particle effects on the heat transfer performance were dominated by the particle volume fraction in duct flow. Therefore, it can be concluded that as the Reynolds number increased, particles may not collide or deposit on the surface before leaving the duct with the airflow, leading weak impact on thermal conductivity of the flow in the duct.

4. Conclusions

In this study, a numerical simulation was used to calculate the flow and heat transfer characteristics of the particle-laden gas flow in the parallel-plate duct. The following preliminary conclusions can be drawn:

(1) The particle size has a significant impact on the flow and heat transfer performance of the airflow. Large particles can greatly increase the resistance while small particles have less of an impact. For particles with a diameter of 18 μm, the maximum increment value percentage (*fRe*) is 0.51. For the heat transfer performance, the inhibition effect of large particles on heat transfer performance is more obvious than that of small particles. Under the same particle volume fraction, particles of different sizes have different effects on particles. When the particles are larger, it has a greater impact on the flow characteristics.

(2) The flow and heat transfer performance in duct were significantly affected by the Reynolds number of particle-laden flow. As the Reynolds number increased, the (fRe) of the duct will decrease on the contrary. In addition, a higher Reynolds number can reduce the accumulation and deposition of the particles on the bottom of surface. Some particles may directly leave the channel while some particles are easier to rebound off the surface due to its higher potential energy. In terms of heat transfer performance, as the inlet laden flow velocity increases, the impact of particles on the heat transfer characteristics in the channel decreases. This is caused by the particle deposition and rebound behaviors on the bottom wall, which can obviously destroy the thermal layer and raise the heat transfer performance.

Acknowledgments

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