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Comparison of Heat Transfer in Gravity-Driven Granular Flow near Different Surfaces

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Abstract: Heat transfer in gravity-driven granular flow has been encountered in many industrial processes, such as waste heat recovery and concentrated solar power. To understand more about Moving Bed Heat Exchanger (MBHE) applied in this field, numerical simulation was carried out for the characteristics of granular flow near different surfaces through discrete element method (DEM). In this paper, both the performances of particles motion and heat transfer were investigated. It's found that, even though the macroscopic granular flow is similar to fluid, there is still obvious discrete nature partly. The fluctuations of parameters in granular flow are inevitable which is more obvious in the circular tube cases. A special phenomenon, where competition motion is found, is resulted from discrete nature of particles. In terms of heat transfer, overall heat transfer coefficients for plate are higher than that of tube owing to better contact between particles and wall. However, due to competition motion, particles in high temperature tend to contact the tube, which is beneficial to heat transfer in some local zones. The heat transfer characteristics above will also affect the temperature distribution near the outlet of different geometries.

Keywords: gravity-driven granular flow, discrete element method (DEM), heat transfer, numerical simulation

1. Introduction

Nowadays, heat recovery from dense gravity-driven granular flow has been more concentrated on. It makes a vital contribution to waste heat recovery in industrial process [1, 2] and to the system of Concentrated Solar Power [3–5], which is critical to sustainable development of human society. Especially, solid powder produced in industrial process contains huge high-temperature waste heat [1]. In the past, fluidized bed was commonly known in the occasion. Nowadays, moving bed heat exchanger (MBHE) is gradually implemented due to lower cost [6, 7], which could also provide a potential alternative with lower heat loss [8]. Thanks to their meaningful applications, the interest in gravity-driven granular flow with heat transfer has increased recently.

The granular flow is sensitive to geometry factors, particles parameters and loading conditions. There have been different types of heat exchange surface researched and adopted before. Patton et al. [9] presented the heat transfer correlation about granular flow around the incline plate through their experiment. Natarajan and Hunt [10] studied the correlation between flow rate and heat transfer coefficients experimentally, where heat transfer would be worse in larger flow rate. As a simple geometry, the plate is still used to design the MBHE system [8] and study the characteristics of granular flow [11]. In addition, the circular tube is the common type.

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Nomenclature

A	area of surface/m^2	**Greek symbols**	
c_p	specific heat capacity/J·kg^{-1}·K^{-1}	α, β	angle/rad
E	Young modulus/Pa	δ	thickness of gas layer/m
F	force/N	ε	emissivity
h_{loc}	local heat transfer coefficient/W·m^{-2}·K^{-1}	Θ	dimensionless temperature
h_{tot}	overall heat transfer coefficient/W·m^{-2}·K^{-1}	ρ	density of particle/kg·m^{-3}
k	thermal conductivity/W·m^{-1}·K^{-1}	σ	Stefan-Boltzmann number/W·m^{-2}·K^{-4}
l	distance between particles/m	**Subscripts**	
q	average heat flux/W	f	gas phase
R	heat transfer resistance/K·W^{-1}	i, j	particles index
r	radius of particle/m	in	particles inlet
T	temperature/K	n	normal direction
Δt	time step/s	s	solid phase
u	velocity/m·s^{-1}	t	tangential direction
X	view factor	wall	surface wall

Many researches were developed with the employment of circular tube. The arrangement of tubes [2–4] and the flow rate of particles [3, 5, 6] were key factors and frequently analyzed. What's more, Morris et al. [12, 13] designed arrays of hexagonal tubes in their MBHE, which means special section tube has been applied gradually. From the view of particles, the type of particles was regarded as an important factor, which decided the physical parameters of particles. Single type [2, 5] and mixing type [6] of particles were all studied. It is pointed that proper mixing of particles could improve heat transfer performance. Moreover, to enhance heat transfer more, heat performance changed by fin and vibration in the granular system have been researched [5, 7, 11, 14]. Fin could increase the heat exchange area and then more heat may be gained [5, 7, 11]. As for vibration, the strength plays a vital effect on heat transfer, where frequency and amplitude were frequently discussed [7, 14]. Mass and thermal diffusion in granular system could be strengthened by proper vibration. Based on the previous work, it is obvious that low heat transfer coefficients are attributed to indirect heat transfer way in MBHE, which should be improved. However, the mechanism of heat transfer enhancement remains issues worth of explaining. Even though fin tube and vibration could improve heat transfer performance in some occasions, there were also failed applications [7, 11]. More understanding about granular flow with heat transfer is still required to develop the enhancement method. To accomplish it, there are some problems for debate. Although granular flow is analogized to fluid, there are still many differences, where discrete particle nature is included and should be investigated as clearly as possible. In addition, the researches aforementioned are more based on the experimental method in macroscopic view. To gain detailed explanations, more connections between discrete particle nature and heat transfer are expected by numerical simulation.

The objective of the current study is to compare the heat transfer in gravity-driven granular flow near a single plate and single circular tube, which are more ubiquitous. The numerical study was developed through discrete element method (DEM) including heat transfer model. Heat performance between particles and the wall was analyzed with the particle update and contact phenomenon, where the effect of discrete particle nature would be focused on. The work is helpful to understand the characteristic of granular flow with heat transfer and ready for flexible design of MBHE in the future.

2. Methodology

As a matter of fact, gravity-driven particles flow is multiphase flow, which comprises of gas phase and solid phase. However, the flow is slow and dense in current research, where the fraction of solid phase is close to packing limit (~60%). Inertial gas is mainly driven by particles with low velocity. Behavior of particles accounts for a major role in slow granular flow. It has been pointed out that gas flow could affect the overall granular flow little [15]. Meanwhile, due to the slow gas flow, the effect of convection is also limited in the overall heat transfer process [16]. As a result, particle motion is mainly focused on in the present research, while gas flow is neglected.

The simulation algorithm for granular flow could be broadly classified into two types. Because there are similar characteristics between fluid and granular flow, some researchers have regarded granular flow as continuous “pseudo-fluid” [17], and Two Fluid Model is one of representative methods [4]. The method could decrease calculation cost, while simplification of particles would ignore discrete particle nature. The other methods are based on Lagrange view, where discrete element method (DEM) is adopted more [12, 13, 16]. Discrete characteristic of particles could be reflected through the method, which lays its ability to solve parameters required for each particle. As a result, more accurate information could be gained in granular flow. Above all, DEM is adopted in our research.

2.1 Force calculation

In DEM, hard-sphere contact model and soft-sphere contact model have both been applied for the force calculation. In the current work, soft-sphere contact model is adopted with the help of Herz-Mindlin theory [18]. By simplifying contact between particles with the treatment of equivalent spring, damper and slide, overlaps between particles are allowed for the normal force and tangential force, which is more appropriable for dense particles flow.

2.2 Heat calculation

As mentioned above, convection could be ignored because of weak gas flow. Therefore, conduction and radiation are the primary processes considered. For the sake of heat calculation cost, the following assumptions are adopted: (1) Temperature distribution in little single particle is homogeneous. (2) Heat capacity of interstitial gas is negligible, because heat capacity of solid is much larger. (3) Particles are surrounded by gas layer, where heat transfer path normal to surface of particles may exist [12, 13, 19, 20]. (4) Physical properties are regarded as constant to concentrate more on discrete particle motion. Then, heat transfer between particles can be illustrated in Fig. 1.

It should be noted that, there are differences between the force and heat calculation. Force only exists when different surfaces have physical contact, while additional heat transfer may occur between surfaces without physical contact. Once there are overlaps between gas layers, heat transfer should be considered. In current study, the whole heat transfer process consists of conduction inside particles, conduction through the contact surface, conduction through gas layer and radiation. As performed in Fig. 1, they would be all calculated between particles with physical contact, while conduction through contact surface does not exist for the additional heat transfer. Heat resistance model is used to couple different heat transfer processes, as presented in Fig. 2. The related heat resistance equations are listed as follows. The heat resistance inside particles, R_1, is based on Fourier Law [20], and contact heat resistance, R_2, follows the work of Vargas et al. [21].

$$\frac{1}{R_1}=\frac{2\pi k_s r\left(1-\cos\alpha\right)}{\sqrt[3]{2}-1} \tag{1}$$

$$\frac{1}{R_2}=2k_s\left(\frac{3F_n r}{4E}\right)^{1/3} \tag{2}$$

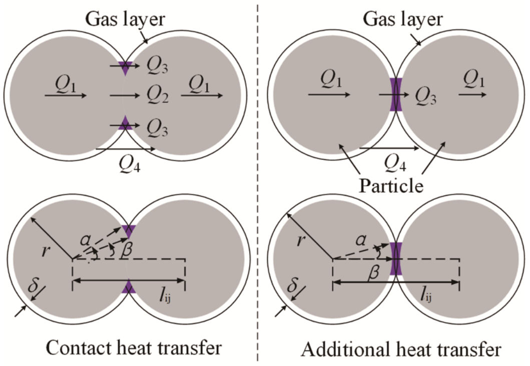


Fig. 1 Heat transfer between particles (Q_1: Conduction inside solid, Q_2: Contact conduction, Q_3: Conduction through gas layer, Q_4: Radiation)

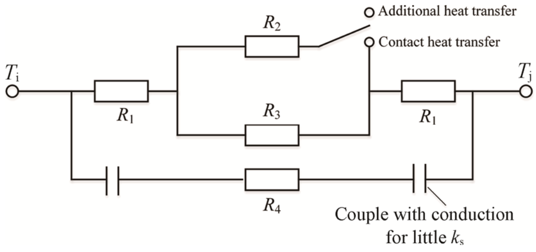


Fig. 2 Schematic diagram of heat transfer resistances

For conduction through gas layer, the thickness is an important factor, which would affect the starting and ending points of integration in Eq. (3). In the present work, the thickness is equal to 0.2r, which refers to Delvosalle et al. [19]. In addition, according to Morris et al. [12, 13], the starting point β is controlled by the mean free path of gas molecules rather than 0, which makes sure that Fourier law is fit.

$$\frac{1}{R_3}=\int_{\beta}^{\alpha}\frac{2\pi k_f r^2\sin\theta\cos\theta}{l_{ij}-r_i\sin\theta-\sqrt{r_j^2-\left(r_i\sin\theta\right)^2}}\mathrm{d}\theta \tag{3}$$

As for radiation, it’s obtained by the Stefan-Boltzmann format.

$$\frac{1}{R_4}=\frac{\sigma\left(T_i^2+T_j^2\right)\left(T_i+T_j\right)}{\left(\left(1-\varepsilon\right)/\varepsilon A\right)_i+1/\left(A_i X_{ij}\right)+\left(\left(1-\varepsilon\right)/\varepsilon A\right)_j} \tag{4}$$

The areas and view factors are important in Eq. (4). When R_4 is for two particles, areas are both $4\pi r^2$ and the view factors could be obtained by Eq. (5) [22]. When one of particles is replaced by the tube wall surface, the related area and view factor could refer to the research of Antwerpen et al. [23]. Here, it should be noted that, once conductivity of solid is little enough, radiation and conduction inside solid should be also coupled.

$$X_{\mathrm{ij}} = \left[1-\sqrt{1-\left(r_{\mathrm{i}}/l_{\mathrm{ij}}\right)^2}\right]\left[1-\sqrt{1-\left(r_{\mathrm{j}}/l_{\mathrm{ij}}\right)^2}\right]\left(l_{\mathrm{ij}}/r\right)^2 \quad (5)$$

2.3 Velocity control in the outlet

The granular flow is controlled in the outlet instead of inlet in MBHE [2, 3, 5]. It prevents particles from flowing too fast, which allows particles transfer heat to the surfaces enough and then the higher efficiency is gained. Therefore, the control of granular flow in the simulation keeps consistent with actual processes. Particles near the outlet are kept in constant velocity in vertical direction during the simulation.

The simulation would be developed through EDEM 2.6, which succeeded in particles motion solving. To obtain heat transfer characteristics, the additional heat transfer model is coupled in EDEM.

3. Simulation

3.1 Geometry and boundary conditions

In the present work, heat transfer performances nearby tube and plate out-wall surface are compared. To pay more attention to the main feature and decrease computation cost, geometry model and boundary conditions are simplified. As shown in Fig. 3, a single tube and single plate are adopted. The main difference between geometry models are the shape and position of the surface heat transfer happens. For the tube cases, a circular tube is located in the center of box, and particles flow between the box walls and tube wall. For the plate cases, the plate is located in the wall of box, and the inside of box is the channel of particles flow. In fact, the plate is equivalent to which produced by half of out-wall surface of tube flattening. The areas of heat exchange surface on single side of particles flow are equal. It is beneficial to the comparison below. The other treatments for geometry models are similar. The size of the channel should be selected carefully, which avoids clogging of particles and make sure adequate quantity of particles to reflect the law. The relative value between size of the channel and diameter of particles refers to the work of Zhang et al. [24], whose ratio is larger than 4. As for the thermal boundary condition, particles enter the box with constant temperature. Here, it strives for heat transfer between particles and the surface of tube or plate. Besides, heat resistance in MBHE existing in the granular side attracts more attention in granular flow study. Therefore, box walls are regarded as adiabatic and different out-walls are kept in constant temperature. The effect of the other fluid in MBHE is neglected.

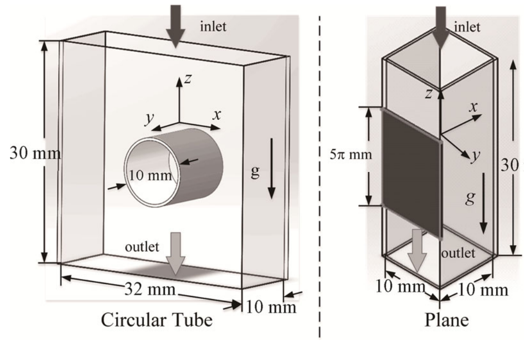


Fig. 3 Schematic diagram of geometry model

3.2 Basic simulation progress

In the beginning, random dense packing particles are generated. Then, the outflow of particles is controlled. When some particles escape from the outlet, equal quantity of particles would enter the box from the inlet at the same time. As a result, particles in the vicinity of box would keep dense without increasing of computation costs. The overall simulation process lasts 31 s. Heat flux between particles and the walls expected is counted at each time step. Finally, heat transfer coefficient is used to evaluate the heat transfer, which is defined as Eq. (6). The q is the average heat in the final 11 s, when change tendency of heat over time is almost linear in the stage. Main parameters in simulation are summarized in Table 1, which refers to the work of Liu et al. [2] for validation after.

$$h = \frac{q}{A_{\mathrm{wall}}\left(T_{\mathrm{in}} - T_{\mathrm{wall}}\right)} \quad (6)$$

3.3 Model validation

The validation of model above is shown in Fig. 4. By comparing overall heat coefficients for the tube cases, it could be seen that, h_{tot} of simulation are in relatively good agreement with that of Liu's experiment [2]. h_{tot} would increase with growth of velocity. The maximum relative deviation is less than 16%. It may be mainly caused by the simplification of geometry, which transfers tubes bank to single tube. Therefore, the deviations are acceptable and the numerical model is credible on the whole.

Table 1 Main parameters in simulation

Parameters	Values
ρ/kg·m^{-3}	2848
c_p/J·kg^{-1}·K^{-1}	1210
k_s/W·m^{-1}·K^{-1}	0.55
r/mm	0.86
E/Pa	5.5×10^8
Poisson ratio	0.25
k_f/W·m^{-1}·K^{-1}	0.0257
Δt/s	2.6×10^{-6}

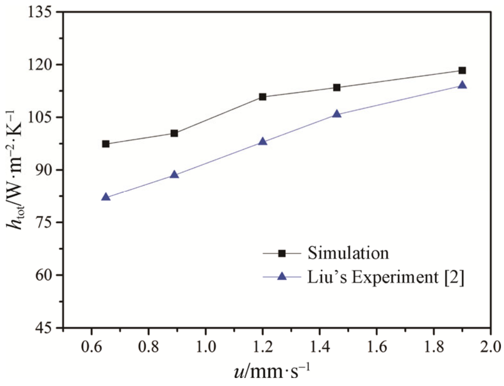


Fig. 4 Model validation for DEM in granular flow

4. Results and Discussion

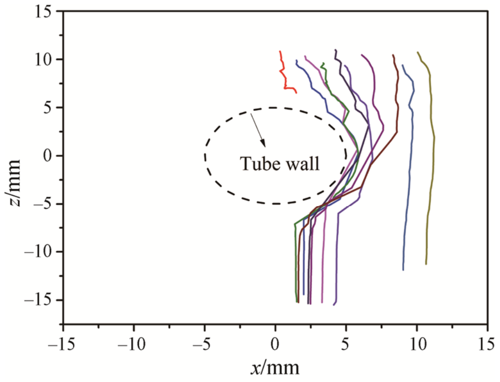
4.1 Flow pattern near different surfaces

Fig. 5 presents motion trajectories of some particles in x-z coordinate system from different initial positions, which are broken up once particles escape from the outlet or simulation has finished. When particles flow around the plate, it is obvious that particles tend to move in straight line smoothly. While for the tube, it could be found that the trajectories of a particle right above the tube develop slowly, and the trajectories hardly pass right under the tube. The phenomenon demonstrates the stagnation above the tube and the void in the bottom. Moreover, due to the disturbing of the tube for flow, trajectories tend to be more circuitous.

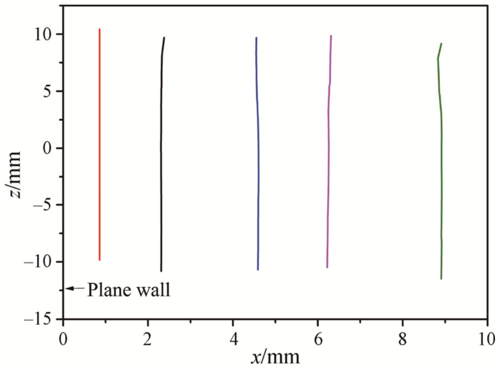
To analyze the influence of different surfaces on particles motion, contact number and contact time are utilized to reflect the granular characteristics. Contact number is defined as the numbers of particles which contact the target zone of wall at each time step, which illustrates the status of dense or dilute. As for contact time, it's related to particles, which records the total time for each particle contacting the surface. Larger contact time for a particle usually means the temperature of the particle is lower. To compare the law clearly, the tube and plate are divided into four zones to analyze local features, as presented in Fig. 6. The tube is divided equally in height, and the division of plate keeps the same ratio between each zone of different surfaces. Then, contact number and average contact time for particles in the case in 0.65 mm·s^{-1} are shown in Fig. 7.

It could be seen that, there are obvious fluctuation characteristics in granular flow. It's related to the discrete particle motion in granular flow, which may be in different complex states [25]. Even though granular flow has been treated as pseudo-fluid before, the discrete nature still plays a significantly role, which could not be omitted. From the contact number results, particles are more homogeneous in different zones for the plate, while there are quite differences for the tube. It is caused by the void zone below the tube.

Besides, the contact time levels of different zones are significantly different. For the plate, the contact time develops along the flow direction. While for the tube, there is obvious overlap between the levels of different zones. It is caused by particles mixing around the wall, which includes stagnation of particles contacting the wall and supplement of particles not contacting the wall before. For further intuitive comparison, time-averaged results are presented in Fig. 8. Based on contact number results, it could be concluded that particles could all contact the surface of plate more densely. By comparison, because of the obstruction by the tube, particles are dilute in Zone III & IV.

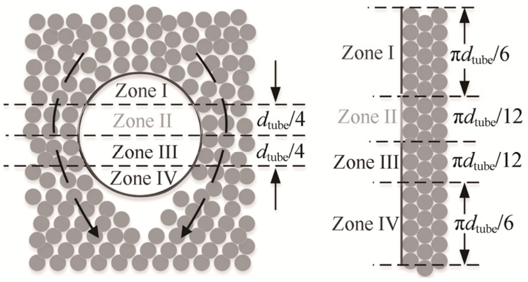


(a) Circular tube



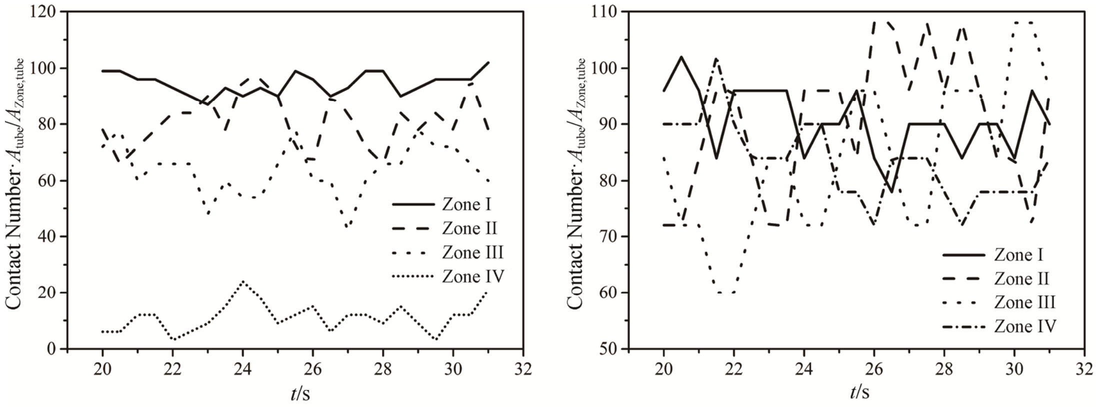
(b) Plate

Fig. 5 Trajectories of particles in 0.65 mm·s^{-1}



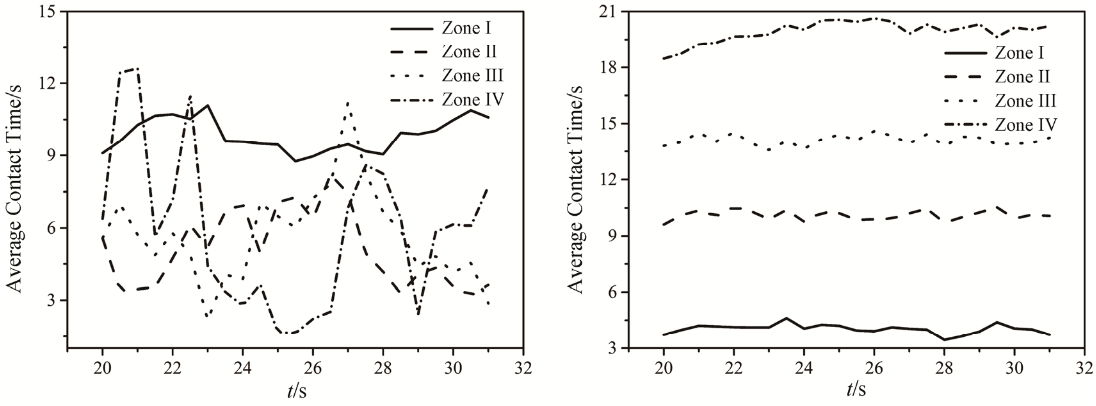
Circular tube Plane

Fig. 6 Schematic diagram of zone division



(a) Circular tube-contact number

(b) Plate-contact number



(c) Circular tube-contact time

(d) Plate-contact time

Fig. 7 Contact number and contact time results with expected outflow in 0.65 mm·s^{-1}

The phenomenon is analogous to fluid separation in the cases that fluid flows around a cylinder rapidly. It is just that the critical velocity of granular flow is far less than common fluid. In terms of the contact time results, quicker flow would all accelerate particles to update, which decreases contact time in each zone for different surfaces. Nevertheless, there are different laws for different zones around dissimilar surfaces. Contact time would increase along the flowing direction for the plate. But the increasing tendency of contact time changes for the tube. The stagnation leads to higher contact time in Zone I. On the other hand, contact time is close in Zone II, III and IV because of the existence of completion motion, which breaks the law around the plate.

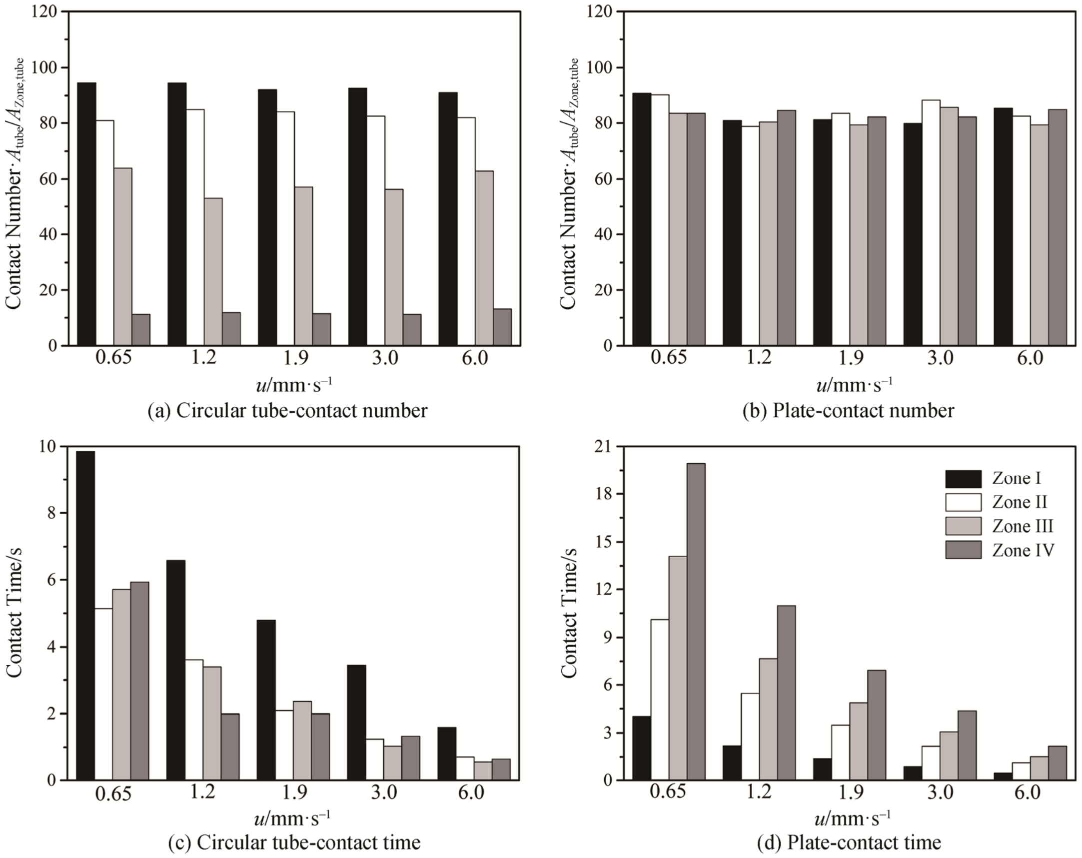
Due to the discrete motion, the relative position of particles may change with time in slow particles flow. For example, particles flowing in other layers before may contact the wall in the next time step, as Fig. 9 shows. The motion occurs in the tube cases more frequently where granular flow is forced disturbing by the tube. In Fig. 5, the intersection of the trajectories for particles in different initial position near the tube also reflects the mode of competition motion, where particles in different layers may contact the same zone, which just happens in different stages. In the plate cases, particles almost move along the wall in sequence with less mixing, which means that the competition motion is less. Therefore, contact time would decrease in the flowing direction and fluctuations over time are slighter. While for the tube, due to the competition motion, there is mixing of particles which moved in different layers before. It's unlike to no-slip boundary condition in fluid flow, but is more like turbulence in some local zone. Therefore, the fluctuations are more obvious in the tube cases, and contact time results are close among Zone II, III and IV. However, with the growth of velocity, the average contact time decreases rapidly, and the results of the plate case and the tube case become closer. Consequently, the effect of competition motion is limited, which will affect the local heat transfer.

4.2 Heat transfer characteristics

In order to illustrate the characteristics more clearly, time-averaged dimensionless temperature Θ of particles around the walls is presented in Fig. 10. The definition is shown in Eq. (7):

$$\Theta = \frac{T - T_{\text{wall}}}{T_{\text{in}} - T_{\text{wall}}} \tag{7}$$

Then, overall heat transfer coefficients for different surfaces are firstly compared. As shown in Fig. 11, h_{tot}



(a) Circular tube-contact number (b) Plate-contact number

(c) Circular tube-contact time (d) Plate-contact time

Fig. 8 Time-averaged contact number and Time-averaged contact time results for different cases

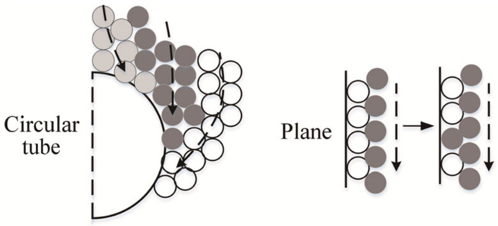
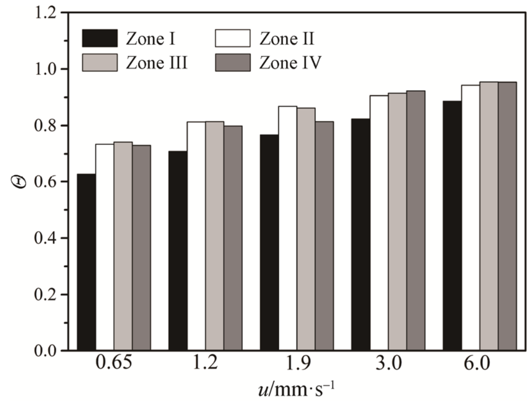


Fig. 9 Schematic diagram of competition motion

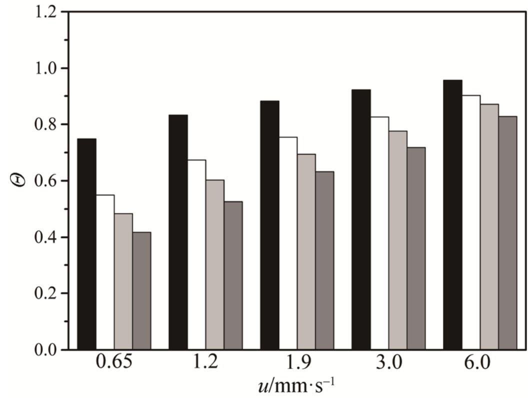
would be larger in more rapid flow under the limited descending rate, whether for the tube or plate. In slow dense granular flow, particles keep contact with each other, and the phenomenon is similar to reduction of boundary layer. With the increasing of particles velocity, particles around the tube or plate are updated more frequently. Therefore, more particles in high temperature could surround the surface in different zones than before. Then, more heat is able to transfer to surface under the larger temperature difference. By comparing results of different surfaces, $h_{\rm tot}$ for the plate is higher than the tube at the same descending rates. It's mainly caused by the contact between particles and different walls. With equal surface facing granular flow in each side, there is void below tube and fewer particles could contact the tube in equal area, as illustrated in Fig. 8. It results in the trend that less heat is transferred to the wall. Moreover, the stagnation of particles above the tube also weakens the heat transfer. Larger contact time in the top means that particles stay longer there with lower temperature difference. The negative factors drive less heat flux to wall. Therefore, the void in the bottom and stagnation in the top worsen the overall heat transfer in the tube cases.

The influence of the stagnation and void zone could be more observed from local heat transfer coefficients in different zones, as shown in Fig. 12. The stagnation makes $h_{\rm loc}$ for the tube less than the plate in Zone I, which partly accounts for the overall difference. In addition, the major difference between the tube and plate is caused by the worse contact in Zone IV of tube with flow rate. Moreover, the worse contact would also broaden the difference in Zone III in quick flow and play a significant role in the overall heat transfer process.

However, it should be noted that $h_{\rm loc}$ for the tube is not always less than the plate. In Zone II, when the outflow rate is less than 3 mm·s^{-1}, heat transfer would be stronger for the tube cases. Moreover, the phenomenon would occur in Zone III in the slow enough flow where the velocity is less than 0.65 mm·s^{-1}, even though fewer particles could contact the zone of tube.



(a) Circular Tube



(b) Plate

Fig. 10 Time-averaged Θ around different surfaces

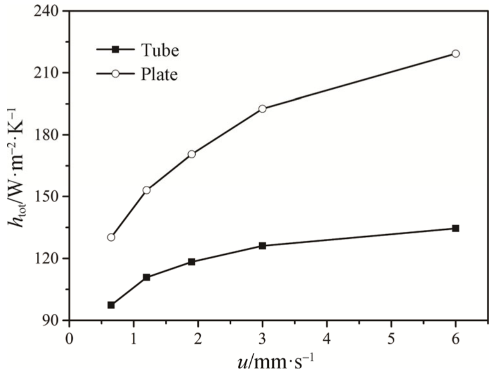


Fig. 11 Comparison of h_{tot} for different surfaces

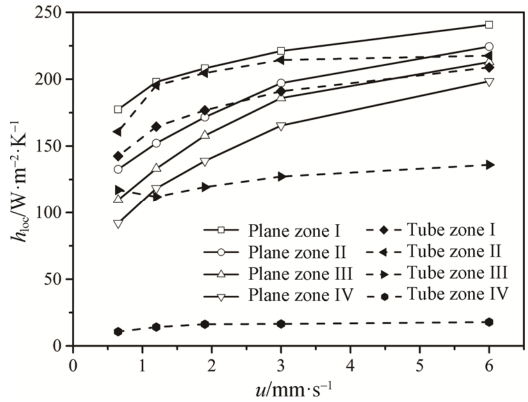


Fig. 12 Comparison of h_{loc} for different surfaces

The phenomenon is related to the competition motion aforementioned. The competition motion happens less in the plate cases. Hence, h_{loc} and Θ of plate all decrease in the direction of particles flow, which are still alike to the characteristic of laminar fluid flow in sum. As for the tube, more competition motion changes the distribution of Θ. In Zone I, Θ for the tube is less than that of the plate because of stagnation. The zone is also the lowest zone for the tube. However, Θ all keep a certain value in Zone II, III and IV rather than decreasing in the flow direction. Especially, they are higher than that of plate in the slow flow. The discrete motion increases the temperature of particles close to wall, which is equal to additional heat diffusion. It could be regarded as boundary layer breaking automatically, which is beneficial to heat transfer. As a result, h_{loc} for the tube may be higher in Zone II and III due to the larger temperature difference. Nevertheless, the quicker granular flow causes the stronger "particles convection" and makes the wall surrounded by particles in higher temperature. It would weaken the positive effect of particles competition. On the other hand, bad contact at the void zone also limits the effect of competition motion. In consequence, heat transfer would still have advantage in quicker flow for the plate.

It is expected that similar boundary layers could be also defined in granular flow, which is helpful to understand the granular flow. Because the continuous particles mix around the tube, the fluctuation leads to that unified qualitative layer thickness is difficultly extracted and discussed around the tube and plate wall. However, other pseudo boundary layers with temperature are found and discussed more easily behind the tube or plate in flow direction, which are able to explain heat transfer performance in granular flow. Here, the average temperature distribution along the x-direction is compared in Fig. 13, which is only for the zones near the outlet with height of $6r$. Obviously, the valley value and the region where particles temperature have changed from initial value, namely $\Theta<1$, could also illustrate heat exchanging with the wall in granular flow. Lower valley value and the sunken scale for T_{s}-x lines mean more heat recovery for unit granular flow, and

$$q \sim u\int\left(T_{\text{in}} - T_{\text{s}}\left(x\right)\right)\mathrm{d}x \tag{8}$$

The uncertainty relation lies on the fraction fluctuation near the outlet. Nothing but, the positive correlation between them is strong enough based on energy conservation. For different surfaces, the increasing of velocity would result in the larger valley value and the wider sunken scale and the overall heat transfer is therefore improved. Meanwhile, with the same expected outflow velocity, it could be seen that the sunken scale for tube is wider. The mixing of particles during flow has an important effect on it. In the plate cases, horizontal position of particles changes little. The trajectories approximate a straight line and particles flow with less mixing. It could be illustrated by particle kinematic model [26]. In the tube cases, the curve of tube drives the horizontal motion of particles towards tube wall, and the mixing of particles is strengthened. Mass diffusion caused by mixing of particles would result in equivalent heat diffusion. Thus, the lower valley value and wider sunken scale occur for tube, which is conducive to uniform heat recovery.

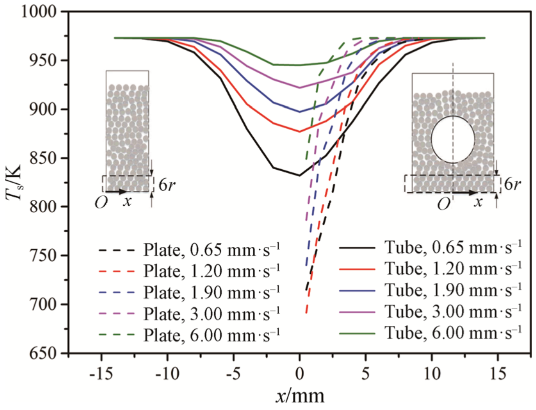


Fig. 13 Average temperature distribution near outlet

5. Conclusions

In the present study, dense gravity-driven granular flow was simulated by DEM. The cases of a single plate and single tube were compared, and the influences of discrete particles motion on heat transfer were discussed. There would be obvious discrete nature in granular flow, including the fluctuation of properties. The work is beneficial to design of MBHE in the future. The major findings are summarized as shown below:

(1) The overall heat transfer coefficients of the plate are better than that of the circular tube because of the better contact in sum. Stagnation zone in the top and void zone in the bottom are the negative factors for the circular tube in the heat recovery from granular flow.

(2) A special phenomenon, competition motion, exists in granular flow. It has a positive effect on heat transfer with existence of particles mixing. The phenomenon hardly occurs around the surface horizontal to flow direction. It results in that local heat transfer coefficients in the middle zone of tube would be higher than plate under lower particle velocity.

(3) In granular flow, pseudo boundary layers with temperature are found and discussed behind the tube or plate in flow direction, which could also reflect the heat transfer performances.

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