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Numerical Study on Gravity-driven Particle Flow around Vertical Plate Out-wall: Effect of Mixing Part on the Heat Transfer

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ABSTRACT

Nowadays, Moving Packed Bed Heat Exchanger (MPBHE) are being gradually applied in the field of industrial waste heat recovery and solar energy due to its clean energy and low cost. In this paper, heat transfer performance of plate with three different mixing parts are researched by discrete element method. The results show that, there is strong mixing between particles after flowing through the mixing part. Compared with elliptical mixing plate (ELL-MP) and trigonal mixing plate (TRI-MP), the mixing ratio and feature velocity of trapezoidal mixing plate (TRA-MP) are the largest. The mixing parts can significantly improve the heat transfer performance, and TRA-MP is the best. The heat transfer coefficient of TRA-MP increases by an average of 40% than that of plate in the downstream region of the mixing part.

Keywords: gravity-driven particle flow, vertical plate with mixing part, moving packed bed heat exchanger, heat transfer enhancement, discrete element method

NONMENCLATURE

Abbreviations

ELL-MP	Elliptical mixing plate
TRA-MP	Trapezoidal mixing plate
TRI-MP	Trigonal mixing plate

Symbols

h	heat transfer coefficient, W/(m^2·K)
k	thermal conductivity, W/(m·K)
T	Temperature, K
t	time, s
v	velocity, mm/s
w	mixing ratio

1. INTRODUCTION

Nowadays, the world's energy problems become increasingly prominent, and it very urgent to improve energy efficiency and sustainable energy development. Moving Packed Bed Heat Exchanger (MPBHE) is gradually applied to industrial high temperature waste heat recovery [1] and Concentrated Solar Power [2]. Compared with the fluidized bed, the particle is driven by gravity in the MPBHE, which means that the MPBHE does not need additional fluidizing gas supply, and does not cause heat loss. However, the heat transfer coefficient of MPBHE is lower. Improving the heat transfer performance is the key issues in MPBHE.

The arrangement of heat exchangers in MPBHE can be roughly divided into horizontal tubes and vertical plates. Vertical plates have higher heat transfer coefficient than horizontal tubes due to narrow channels and large surface area [3]. However, thermal gradients along the flow direction will affect the heat transfer performance [4]. Many scholars have carried out a lot of research on the shell-and-plate moving packed bed heat exchanger. Natarajan and Hunt [5] studied the effects of shearing on the heat transfer coefficient of particle flow in vertical channels. The results showed that the average heat transfer coefficients were higher for the shear flows at a low flow rate, when comparable values of flow velocity was close to the wall. Albrecht et al. [6] explored the effect of particle thermophysical properties by the steady-state reduced-order model for the shell-and-plate moving packed-bed heat exchanger and found that the particle thermal conductivity and packed bed void fraction have important effects on the total heat transfer performance. Fang et al. [7] numerically studied the velocity and temperature fields of dense particle flow by

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the single component continuum mode, and found that the performance of heat exchangers mainly depended on particle flow rates and channel width at low particle flow rates, while the effective particle flow conductivity became the decisive factor at high particle flow rates.

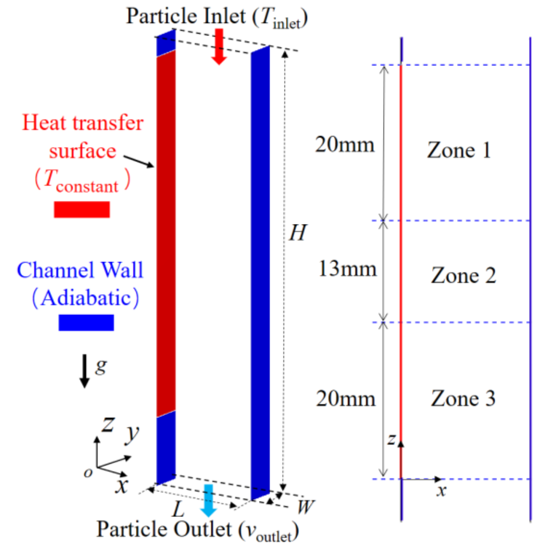
This paper attempts to enhance the heat transfer between the particle and the plate by changing the structure of the plate surface on particle side. The heat transfer of particles flow along plate with different mixing parts were investigated by discrete element method. The variation of mixing ratio, feature velocity, local heat transfer coefficient and other parameters are analyzed in detail, which may provide a reference for the design and optimization of the MPBHE.

2. METHOD AND SIMULATION

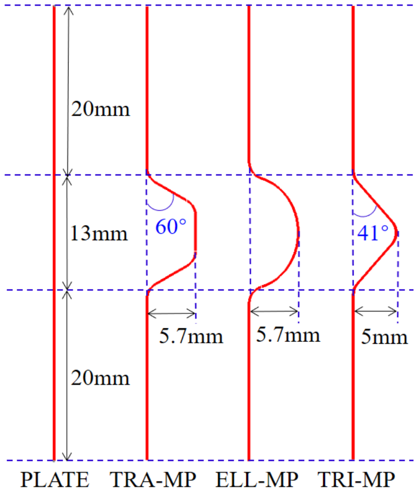
Particle flow simulation methods can be divided into continuous method and discrete method. The discrete element method has been proved to be a reliable and effective method to characterize particle behavior [8]. In this study, the Hertz-Mindlin (no slip) model is used to calculate the contact force of particle to particle (P-P) and particle to wall (P-W). More details about the model can be found in the work of Deng et al. [9]. Discrete element method coupled with the heat transfer model is adopted for detailed study of particles.

The heat transfer of P-P and P-W are including conduction, convection and radiation. Particles move slowly in MPBHE and the velocity is only several millimeters per second [10]. Gas flow has little effect on particle flow [11], and gas convection heat transfer accounts for a small proportion of heat transfer [12]. So heat transfer includes conduction and radiation. The heat transfer model is based on the following assumptions: 1) particles are spherical particles with the same diameter; 2) the heat capacity of the gas is neglected, and the average temperature is assigned to each particle; 3) particles are wrapped by gas film, and the film thickness is 0.1 d_p. More details about the heat transfer model can be found in the work of Tian et al. [13].

The geometry model used in the simulation are shown in the Fig. 1. The heat transfer zone is divided into three zones along the flow direction, as shown in Fig. 1(a). The mixing part is located in the center of the heat transfer surface. Plate, trapezoidal mixing plate (TRA-MP), elliptical mixing plate (ELL-MP) and trigonal mixing plate (TRI-MP) are studied, as shown in Fig. 1(b). The particle diameter (d_p) is 1 mm. The thermal conductivity of gas is the function of temperature: $k_f=5.66\times10^{-5}T+0.011$. The main parameters are shown in Table 1.



(a) Geometry model and zone division



(b) Three types of mixing parts

Fig. 1. Geometry model

Table 1: Main parameters in simulation

name	parameter	value	name	parameter	value
geometry	L (mm)	16	particle	ρ/(kg/m^3)	2848
	W (mm)	5		C_p/(J·kg^{-1}·K^{-1})	730
	H (mm)	66		k_p/(W·m^{-1}·K^{-1})	1.3
	$r_{chamfer}$ (mm)	2		E/(Pa)	5.5*10^8
	$T_{constant}$/(K)	300		T_{inlet}/(K)	800
time step	$\triangle t$/(s)	1.5*10^{-6}	gas	k_f/(W·m^{-1}·K^{-1})	f(T)

In the simulation process, the temperature of the heat transfer surface is constant and the channel wall is adiabatic. Periodic boundary conditions are adopted in the y direction. The random packing and high temperature particles are generated at the entrance of the channel and driven by gravity to enter the channel. At the outlet of the channel, a constant velocity of particles in the z direction is controlled to ensure the dense filling of particles in the channel. The heat transfer is counted over time during simulation. When the change rate of heat flux with time is less than 0.1%, the simulation reaches the steady state (t=t_f). The simulation results of 40s after reaching the steady state are analyzed.

3. RESULTS AND DISCUSSION

The influence of the mixing part on the particle flow with different colors are shown in Fig. 2. The channel is divided into 8 areas equally in the x direction. Particles generated at the inlet of the channel are marked with different colors in different areas. In Zone3, the particles are no longer arranged in a regular color pattern, and there is strong mixing between particles after flowing through the mixing part. The variations of the mixing ratio in Zone3 are shown in Fig. 3. The mixing ratio is defined as Eq. (1), where N is the number of particles. The w of TRA-MP is the largest, while that of TRI-MP is smallest. The w of TRA-MP is 48% higher on average than that of TRI-MP.

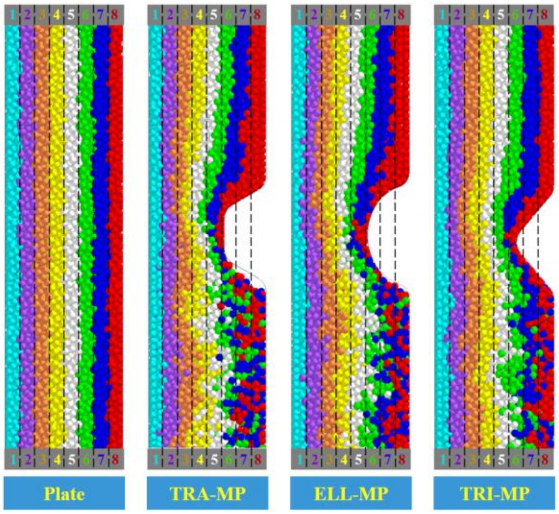


Fig. 2. The effect of the mixing part on particle flow with different color marks

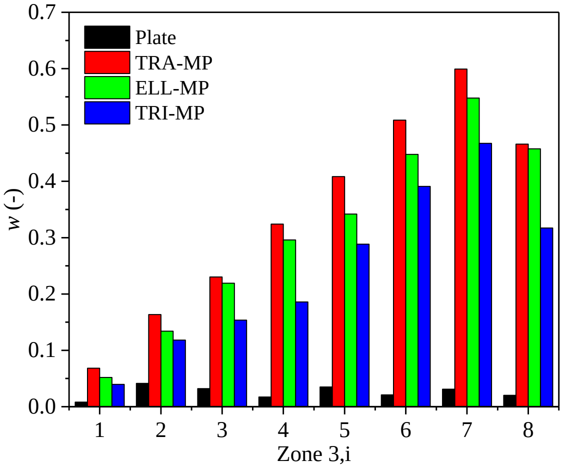


Fig. 3. Variations of the mixing ratio in different areas

$$w_{\mathrm{i}} = \left[\sum_{t_f \to t_f+40}^{\mathrm{Zone3,i}} \left(1 - \frac{N_{\mathrm{P_i}}}{N_{\mathrm{all}}} \right) \right] \Big/ 41 \qquad (1)$$

$$v_{\mathrm{f}} = \sum_{t_f \to t_f+40} \left(L \Big/ \left(\sum_{\substack{\text{channel outlet} \\ 0<x<1}} t_{\mathrm{c,p}} \Big/ N \right) \right) \Big/ 41 \qquad (2)$$

$$h = \frac{Q_{\mathrm{zone},t_f+40} - Q_{\mathrm{zone},t_f}}{40 A_{\mathrm{zone}} \left(T_{\mathrm{inlet}} - T_{\mathrm{constant}} \right)} \qquad (3)$$

The feature velocity (v_f) is defined as Eq. (2), where L is the length of the heat transfer surface and $t_{c,p}$ records that how long a particle has contacted with the heat transfer surface. The variations of v_f with outlet velocity are shown in Fig. 4. The feature velocity of particle flow along the plate is equal to v_{outlet}, while that of the plate with mixing parts are significantly larger than v_{outlet} due to the significant mixing in Zone3. Compared with the plate, the v_f of TRA-MP, ELL-MP and TRI-MP increase by an average of 123% ,108% and 82%. Compared with ELL-MP and TRI-MP, the mixing effect of TRA-MP is the best.

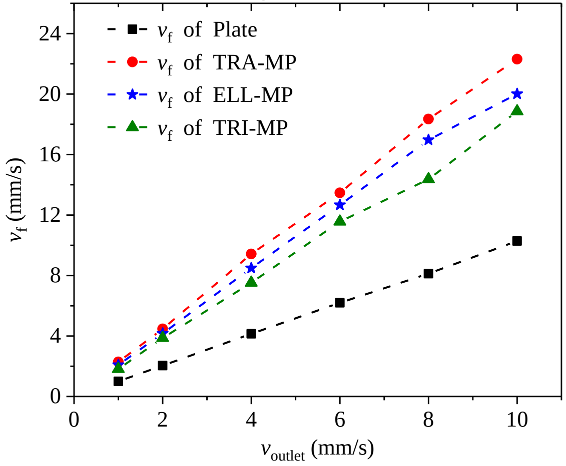


Fig. 4. Variations of the feature velocity (v_f)

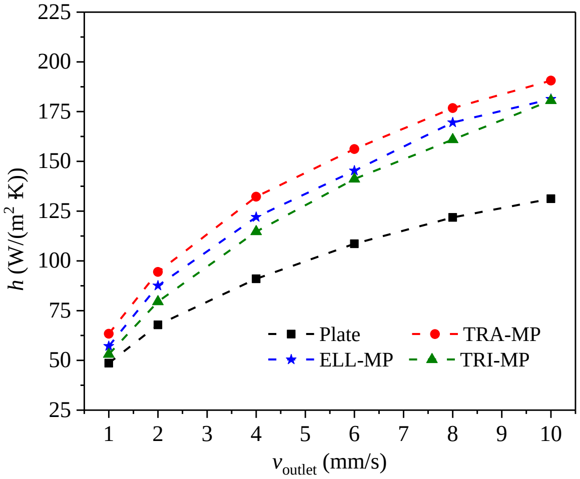


Fig. 5. Variations of the heat transfer coefficient (h) in Zone 3

The heat transfer coefficient (h) is defined as Eq. (3), where Q is the total heat transfer between particles and heat transfer surface and A_{zone} is the area of different zones. The variations of h with outlet velocity in Zone3 are shown in Fig. 5. Because the increase of v_{outlet} accelerates the renewal of particles, The h in Zone3 increases with the increasing of v_{outlet}. The h of the plate with mixing part are significantly larger than that of the plate. Compared with the plate, the h of TRA-MP, ELL-MP and TRI-MP increase by an average of 40% ,28% and 22%.

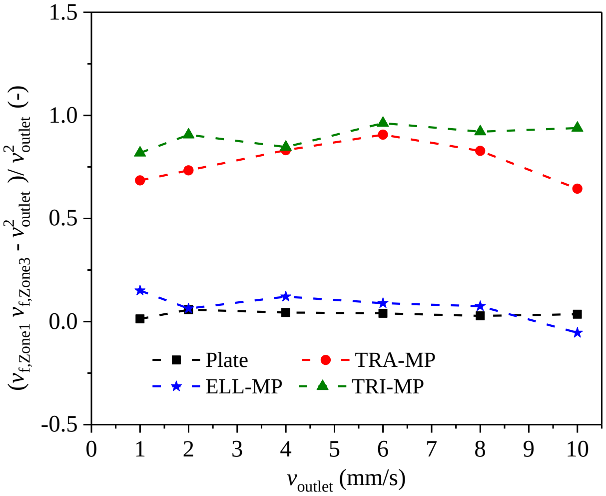


Fig. 6. Variations of the mixing efficiency

The variations of the mixing efficiency with outlet velocity are shown in Fig. 6. The mixing efficiency reflects the effect of mixing parts on the hindering of particles in the upstream region and the renewal of particles in the downstream region. The mixing efficiency of ELL-MP is the smallest, while that of the TRI-MP is the largest. The mixing efficiency of TRA-MP is slightly lower than that of TRI-MP. Considering the enhancement of heat transfer coefficient by mixing part, the flow and heat transfer performance of TRA-MP is the best.

4. CONCLUSIONS

To enhance heat transfer in particle flow for MPBHE, the heat transfer performance of plate with three different mixing parts are investigated in detail. The major findings are summarized as below:

1) There is strong mixing between particles after flowing through the mixing part.

2) Compared with ELL-MP and TRI-MP, the mixing ratio and feature velocity of TRA-MP are the largest.

3) The mixing parts can significantly improve the heat transfer performance, and TRA-MP is the best.

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