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Numerical Investigation on Optimizing the Performance of Heat Transfer in Vertical Packed Bed at the Particle Scale

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Abstract

Enhancing the heat transfer efficiency in the vertical packed bed is deemed as significant focus issue and strategy. Heat transfer process in the vertical packed bed, granular flow profiles have obviously positive effect on the dynamics of heat transport between gas and solid matter. It is quite important to know the mechanism of various granular flow pattern related to these performances of heat transfer phenomena. In this study, discrete element numerical models coupled with continuous fluid are developed and proposed to optimize the effect of uniformity of granular flow on performance of heat transfer process. The coefficient of variation is introduced as quantitative measure of the uniformity of granular flow layer. The relation between granular flow profiles and the performance of heat transfer is verified by a combined numerical approach. The increase of uniformity of granular layer has a positive effect on improving of the efficient inter-phase heat transfer. The study also quantitative unfolds the efficient inter-phase heat transfer greatly enhanced by structural modification. The quantitative analysis for contribution of structural and operational modification to improve the efficient heat transfer is also performed.

Keywords

Combined Approach, Heat Transfer, Granular Flow

1. Introduction

The vertical packed bed is typical heat transport equipment which composed of a cylindrical silo as and a tapered hopper. Granular have been filled from top of pre-chamber and gradually falling through the cooling chamber which combines heat transfer with a jet cold air from bottom of bed. This process is essential to improve the granular flow profiles and uniformity of granular velocity distribution, to optimize the inter-phase heat transfer process, as well as to enhance the efficiency of heat recovery in equipment. Numerical algorithm is used to present the dynamics of granular flow in random structural packed bed. However, experimentally it is not possible to reveal the detail information for microscopic structural of granular flow behaviour.

Direct numerical simulation coupled with two-fluid model and discrete element model is presented to investigate the multi-scale fluid-particles flow behaviour, such as fluid-particle flow profiles, momentum and heat transfer coefficients [1]. An effective acknowledge proposes an approach to integrate continuous method with discrete element applied to analysis continuum flow and heat transfer [2]. A combined CFD-DEM method is established to describe the mechanism of discrete granular and gas fluid [3]. Discrete element approach is used to resolve the effect of non-spherical granular with complex shapes on granular dynamics [4]. The smoothed profile method combined with high order spatial discretization is established to determine the effect of influence factors on the thermal diffusivity and kinematic viscosity of the mixture [5]. The effect of gas-solid flow characteristics on the performance of grain matter heat transfer in fluidized bed [6]. Two-fluid-model and the Lagrange-Euler model are widely used to describe the properties of inter-phase flow and heat transfer [7]. In the previous research, the variation of granular flow profiles influence on inter-phase heat transfer process and critical issue on optimizing the dynamics of heat transport in vertical equipment are not adequately resolved with continuous approach.

In this study, a combined continuum model with discrete element approach is established which can be applied to predict the performance of inter-phase heat transfer under different conditions of granular flow profiles. In addition, the mathematical model has been programmed for exploring the effect of uniformity of granular flow on improving the performance of inter-phase heat transfer process.

2. Numerical Strategy

2.1. Discrete Element Algorithm

Discrete element method is used to describe the characteristics of collision and contact motion for multi-scale particles and particles and wall [8]. Numerical simulation based on the various operational parameter and particle properties in the measurement. All the modes of granular movement and governing equation are summarized in **Table 1**. The physical properties and contact parameters for granular collision and contact model are listed in **Table 2**.

2.2. Inter-Phase Heat Transfer Model

A combined continuous model and discrete element method are applied to perform the momentum and heat transfer inter-phase [9] [10] [11] in **Table 3**.

Table 1. Inter-particles movement and collisions model.

Equations	
$m_i \frac{\mathrm{d}u_i}{\mathrm{d}t} = m_i g + F_p + \sum_{i=1}^{n} F_{c,ij}$	(1)
$I_i \frac{\mathrm{d}\omega_i}{\mathrm{d}t} = T_r + \sum_{i=1}^{n} T_{ij}$	(2)
$F_{c,ij} = F_{c,ij}^{n} + F_{c,ij}^{t} = \left(k_n \delta_{nij} n - \gamma_n v_{nij}\right) + \left(k_t \delta_{tij} t - \gamma_t v_{tij}\right)$	(3)
$k_n = \frac{4}{3} Y^* \sqrt{R^* \delta_n} k_t = 8G^* \sqrt{R^* \delta_n}$	(4)
$\Gamma_n = -2\sqrt{\frac{5}{6}} \zeta \sqrt{k_n m^*}$	(5)
$\gamma_t = -2\sqrt{\frac{5}{6}} \zeta \sqrt{k_t m^*}$	(6)
$\zeta = \frac{\ln(e)}{\sqrt{\ln^2(e) + \pi^2}}$	(7)

Table 2. Properties and parameters for contact model.

Parameter	Unit
Interaction force F_p	N
Contact force $F_{c,ij}$	N
Moment of inertia of particle I_i	$kg \cdot m^2$
Angular velocity vector ω_i	$rad \cdot s^{-1}$
Elastic constants k_n	$N \cdot m^{-1}$
Viscoelastic damping constant k_t	$N \cdot m^{-1}$
Normal deformation δ_{nij}	m
Tangential deformation δ_{tij}	m
Young's modulus Y^*	GPa
Shear modulus G^*	GPa
Damping coefficient ζ	-
Coefficient of restitution e	-

Momentum transfer coefficient is presented as a criterion to evaluate the momentum exchange between gas-solid, which can be determined by inter-phase drag models [12] [13] [14].

2.3. Validation

The accuracy of the numerical method is a quantitative granular velocity and comprehensive average temperature for packed bed, expressing the agreement between the value of the quantity to be calculated for numerical model and experiment results to be performed in **Figure 1**.

Table 3. Equations for granular-fluid coupled heat transfer model.

Equations	
$m_i c_{p,i}\dfrac{\mathrm{d}T_i}{\mathrm{d}t}=\sum_j Q_{i,j}+Q_{f,i}$	(8)
$\dfrac{\partial(\varepsilon\rho_f)}{\partial t}+\nabla\cdot(\varepsilon\rho_f u_f)=0$	(9)
$\dfrac{\partial}{\partial t}(\rho_f\varepsilon c_f T_f)+\nabla\cdot(\rho_f\varepsilon u_f c_f T_f)=-\nabla\cdot\left[-c_f\dfrac{\mu_f}{\sigma_T}\nabla T_f\right]+\sum_{i=1}^{n}Q_{f,I}$	(10)
$Q_{f,i}=h_{conv}A_i(T_f-T_i)$ heat transfer coefficient $h_{conv}=Nu_i\lambda_f/d_p$.	(11)
$Q_{i,j}=h_{i,j}(T_j-T_i)$	(12)
$h_{i,j}=2\lambda_p\left[\dfrac{3f_n r^*}{4E^*}\right]^{1/3}$	(13)
$f_{drag,i}=v_i\beta(u_f-u_s)/(1-\varepsilon)$ $\varepsilon=1-\dfrac{\sum_{i=1}^{n}V_i}{\Delta V}$	(14)
$\beta=\begin{cases}150\dfrac{(1-\varepsilon)^2}{\varepsilon^2 d_{p,i}^2}+\dfrac{1.75(1-\varepsilon)\rho_f}{\varepsilon d_{p,i}}\lvert u_f-u_s\rvert \\ \dfrac{3}{4}C_{Drag}\dfrac{(1-\varepsilon)\rho_f}{d_{p,i}}\lvert u_f-u_s\rvert\varepsilon^{-2.65}\end{cases}$	(15)
$Re_i<2\times10^4\,\varepsilon=0.26$ - 1 $Nu_{turb}=\left[0.037(Re_i/\varepsilon)^{0.8}Pr\right]/\left[1+2.443(Re_i/\varepsilon)^{-0.1}(Pr^{2/3}-1)\right]$	(16)

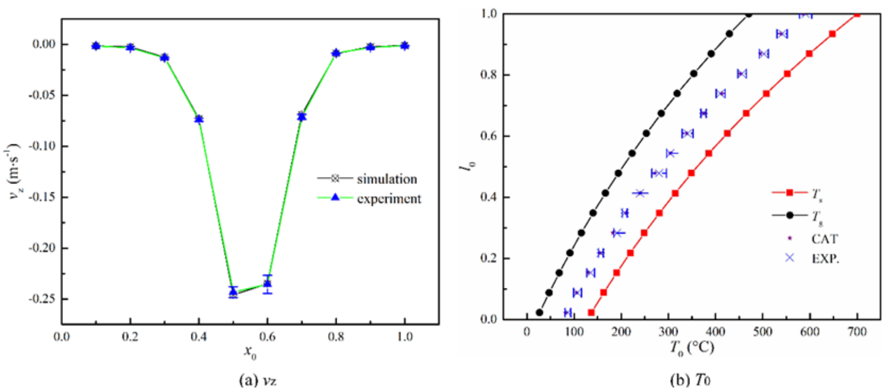

Figure 1. Validation for numerical model (a) vertical velocity (b) temperature distribution.

3. Optimizing Methods for Improving the Performance of Heat Transfer

3.1. Modification for Different Tapered Hopper Angles

Figure 2(a) show granular velocity profiles for different tapered hopper angles.

It can be seen from figure, the fluctuation of the curve of granular velocity distribution increase with an increase in hopper angle. While, the uniformity of granular layer at the same height decreases with the increase of hopper angle. The coefficient of variation is introduced as an indicative of quantitative characteristics of stability of granular flow layer. **Figure 2(b)** presents the CV (coefficient of variation) increases dramatically with an increase in hopper angle, which reveals the stability of granular layer is deeply reduced with increase of hopper angle.

Figure 3 demonstrates the granular temperature distribution and heat transfer efficient for different tapered hopper angles. **Figure 3(a)** shows the granular temperature distribution at same height of packed bed increase greatly with an increase in hopper angle, which expresses the performance of inter-phase heat transfer decrease with increase of hooper angle. **Figure 3(b)** presents the inter-phase heat transfer efficient and thermal gas outlet temperature monotonically down with an increase in hooper angle.

3.2. Modification Patterns

In this section, there are two different modification patterns are performed,

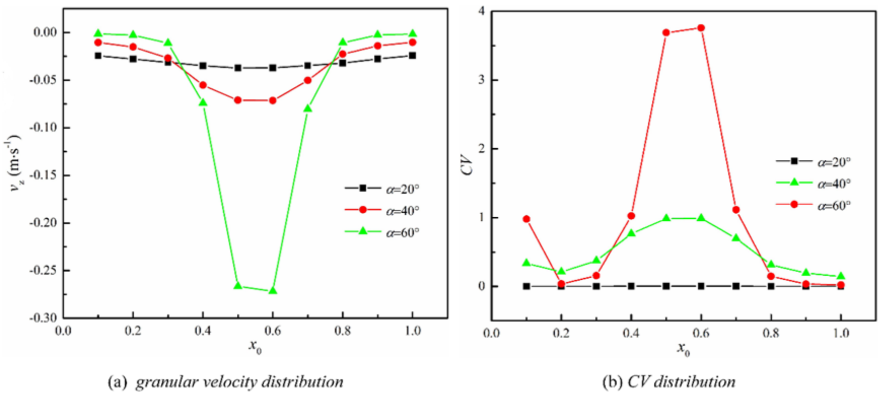

Figure 2. Granular flow profiles for different tapered hoppers (a) velocity distribution (b) CV distribution.

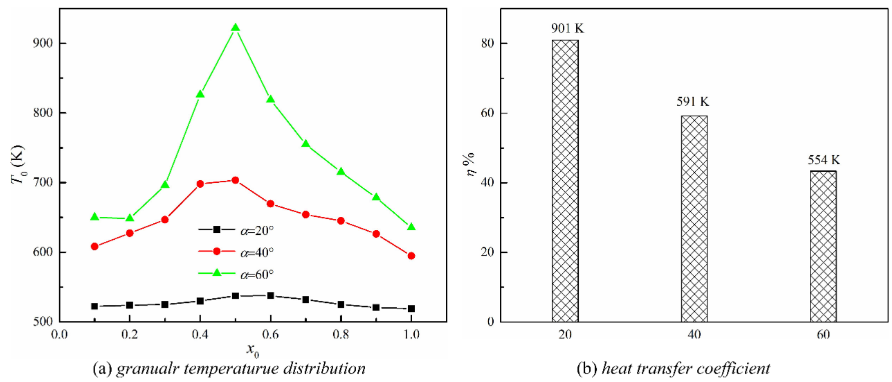

Figure 3. The performance heat transfer for inter-phase (a) granular temperature distribution (b) efficient heat transfer.

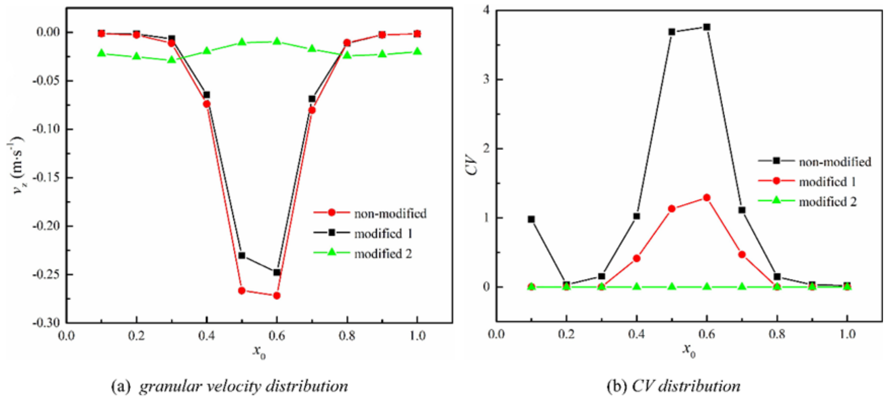

Figure 4. Granular flow profiles for different modification schemes (a) velocity distribution (b) CV distribution.

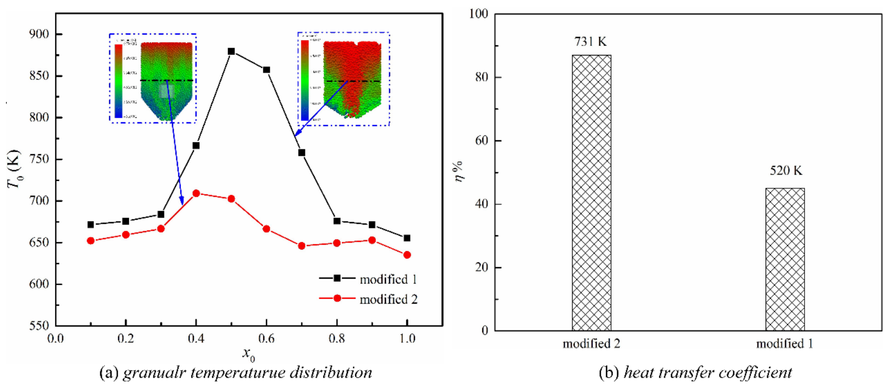

Figure 5. The performance of heat transfer inter-phase for different modification schemes (a) granular temperature (b) efficient heat transfer.

namely operational modification pattern (modified 1) and structural modification pattern (modified 2), respectively.

Figure 4 shows the variation of granular velocity distribution and CV distribution for different modification patterns. **Figure 4** illustrates the structural modification pattern (modified 2) has a positive effect on improving the uniformity of granular layer compared with operational modification pattern (modified 1) for granular velocity and coefficient of variation distribution.

Figure 5 demonstrates the granular temperature distribution and heat transfer efficient for different modification patterns. The figure unfolds a comparison of the granular temperature distribution for different modification patterns, which demonstrates the hot granular have more difficult to be cooled under the condition of modified 1 than that of modified 2. The inter-phase heat transfer efficient for modified 2 is approximately 1.5 folds that of modified 1. The figure of air outlet temperature of modified 2 is significantly greater than the corresponding of modified 1.

4. Conclusions

A combine method of continuous approach and discrete element algorithm is programmed to quantitative reveal the relationship between granular flow profiles and the performance of heat transfer process. The comparison in the performance of heat transfer for structural modification and operational modification. It is evident that the structural modification has more positive effect than operation modification for improving the inter-phase heat transfer and efficiency.

This study verified the relation between granular flow profiles and the performance of heat transfer by a combined numerical approach. The performance of heat transfer increase with an increase in uniformity of granular flow layer. The structural modification has a positive effect on improving of the efficient inter-phase heat transfer. This paper also quantitative unfolds a comparison of efficient inter-phase heat transfer between structural and operation modification. The figure of efficient inter-phase hat transfer for structural modification is 1.5 folds that of operation modification.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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