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Research Article

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Effect of Particle Aspect Ratio on the Internal Heat Flux of a Single Stationary Particle

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Abstract A large number of high temperature solid particles are produced in the industrial production process, and waste heat resources are abundant. In order to better recover waste heat, it is very important to explore the internal heat transfer of particles. In this paper, high-temperature solid particles with an equivalent diameter of 16mm are taken as the research object, and particle heat transfer model are established to study the influence of particle aspect ratio on the internal longitudinal heat flux of particles. The results show that the particle longitudinal heat flux increases of the particles, and he particle longitudinal heat flux shows an exponential growth trend in the range of the aspect ratio of the particles studied.

Keywords Packed bed, Particle heat transfer, Particle aspect ratio, heat flux

1. Introduction

According to the data of the National Bureau of Statistics, the total energy consumption of various industries in China in 2019 was 4.87 billion tons of standard coal, an increase of about 3.2 % compared with the consumption of standard coal in 2018 [1]. At present, China 's industrial sector consumes a lot of energy, and more than half of the energy is wasted [2]. If we can make full use of these energy, we can greatly reduce the use of fossil energy, thus greatly ease the problem of energy shortage and environmental pollution. In order to utilize the waste heat of high temperature solid particles more effectively, it is very important to study the heat transfer characteristics of solid particles.

Scholars have made many explorations on the heat transfer characteristics of high temperature solid particles and the flow and heat transfer of non-spherical particles. Monghaddam et al, Govender et al, Yang et al, Wang et al, Xu et al studied the effects of stacking pattern, particle shape and physical parameters on particle heat transfer [4-7]. In this paper, the influence of particle aspect ratio on the internal longitudinal heat flux of particles is discussed by theoretical analysis and numerical simulation. It is hoped that the above research can enrich the theory of particle heat transfer.

2. Numerical model and Mathematical description

2.1. Numerical model

In the actual industrial production, the particle surface is rough and the particle size distribution is uneven. The shape and contact characteristics of the particles during the accumulation process are also too complicated. Therefore, in order to better summarize the heat transfer characteristics of the particle pile, the heat transfer model is simplified as follows: In order to eliminate the influence of particle surface roughness on heat transfer, the surface of particles is defined as smooth. The particle pile is in a static accumulation state, and ignore the movement of gas. Ignoring the convective heat transfer in the heat transfer model, the calculation model only considers the heat conduction [3].

2.2. Mathematical description

According to the simplification of the above physical model, the mathematical description equation of heat transfer can be obtained.

$$\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right)=0 \quad (1)$$

Where T is temperature, K; λ is the thermal conductivity, W/(m·K).

The particle material used in the numerical simulation is carbon structural steel, and its related physical parameters are as follows:

Table 1: Physical parameters table

Parameter Name	Parameter Value
density	7840 $kg\cdot m^{-3}$
air density	1.23 $kg\cdot m^{-3}$
air specific heat capacity	1.006$kJ\cdot kg^{-1}\cdot K^{-1}$
air thermal conductivity	0.024 $W\cdot m^{-1}\cdot K^{-1}$
high temperature surface temperature of particles	125℃
particle low temperature surface temperature	25℃
initial particle	25℃
Length-width ratio of adiabatic surface	2:1
relationship between specific heat capacity and temperature [3]	C_S=450.41+0.25T-0.02T^2+4.83×10^{-6} T^3-5.36×10^{-6} T^4
relationship between thermal conductivity and temperature [3]	λ_s= 56.44-0.02T-1.51×10^{-5} T^2+8.47×10^{-9} T^3

2.3. Initial condition and Boundary condition

Fig 1 shows a simplified numerical simulation model and a schematic diagram of the computational boundary. The simplified numerical simulation model includes an air computational domain around the high-temperature solid particles and a high-temperature solid particle computational domain, a high-temperature wall surface (125 ℃), a low-temperature wall surface (25 ℃), a gas-solid coupling surface in contact with the high-temperature solid domain, and an adiabatic surface around the air domain. According to the relevant literature, the ratio of the particle contact area to the maximum cross-sectional area of the particle is about 5 %, and the heat transfer cross-sectional area remains unchanged, which is the corresponding area of the particles with different aspect ratios. The part of the particles removed at both ends is in contact with the high and low temperature wall, and the contact part is the constant temperature wall.

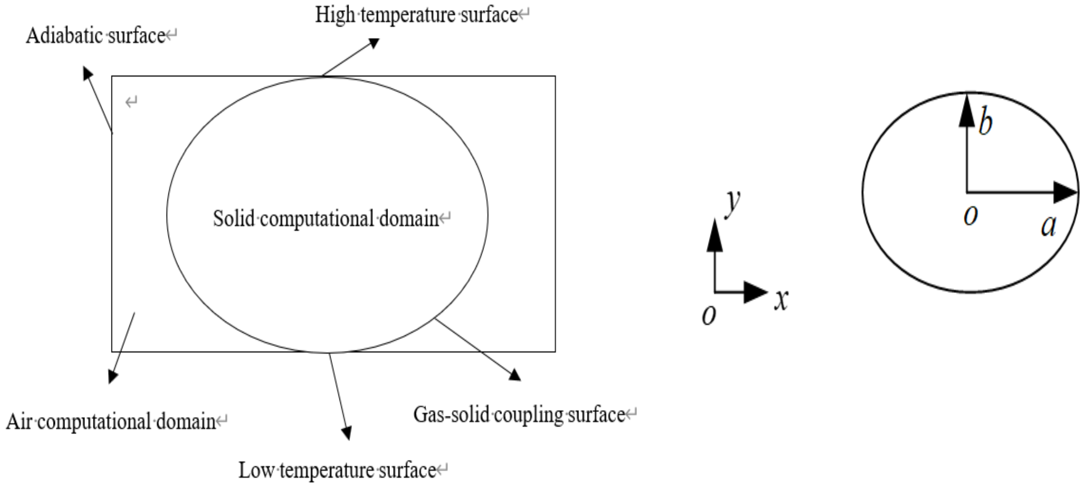
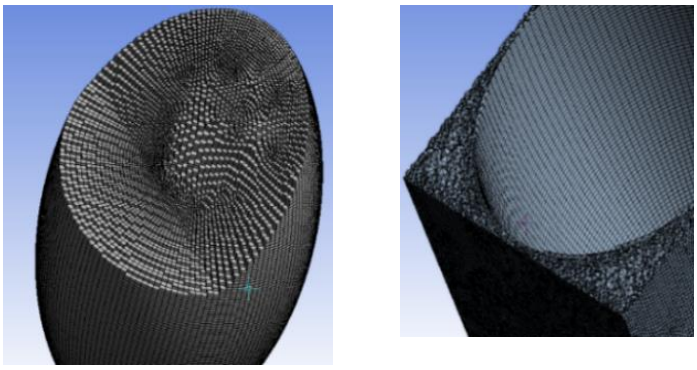


Figure 1: Simplified numerical simulation model diagram

2.4. Mesh division and main research parameters

Fig. 2 is the meshing model, which is divided into air domain and solid domain. Because the geometric structure of the solid domain is relatively regular, the solid domain and the air domain adopt unstructured hexahedral mesh and unstructured tetrahedral mesh respectively. In this paper, the particle aspect ratio is selected as the influencing factor of heat transfer research of solid particles, so as to explore the heat transfer behavior of solid particles at different levels. The particle aspect ratio is the ratio of the ellipsoid radius *a* perpendicular to the heat flow direction to the ellipsoid radius *b* along the heat flow direction, as shown in Fig.1.



(a) Particle area (b) Air region

Figure 2: Meshing model

Suppose that *a* is the ellipsoid radius in the direction perpendicular to the longitudinal heat flux, and *b* is the ellipsoid radius in the direction along the longitudinal heat flux. Seven groups of different aspect ratio levels are selected: 0.5, 0.75, 1, 1.25, 1.5, 1.75 and 2, so as to study the influence of aspect ratio on particle longitudinal heat flux.

3. Comparison of Simulated and Theoretical Longitudinal heat flux of Solid Particles

The maximum longitudinal section of solid particles satisfies the standard mathematical equation of ellipse. At the same time, the area of high and low temperature contact section and the longitudinal distance between high and low temperature section of solid particles under different aspect ratios have been calculated. Based on the above data, the theoretical numerical derivation of high and low temperature wall longitudinal heat flux of solid particles is carried out. The following assumptions are made:1) The thermal conductivity of solid particles is set to a constant value.2) The longitudinal heat flux from the high temperature surface to the low temperature surface is regarded as one-dimensional propagation in the spatial dimension. 3) The longitudinal heat flux of each transverse section inside the solid particles is the same. 4) Ignoring the impact of air, that solid particles around the wall is adiabatic.

Mathematical expression of fourier heat conduction law

$$\Phi = -A\lambda \frac{\mathrm{d}t}{\mathrm{d}x} \tag{2}$$

Where Φ is the longitudinal heat flux from the high-temperature wall to the low-temperature wall, W, A is the transverse cross-sectional area of the high-temperature solid particles, which changes with distance x, m^2, λ is the thermal conductivity of the high-temperature solid particles, which changes with temperature, W/(m·K). The calculation expression of the longitudinal heat flux of the cross section of the solid particles can be obtained by using the standard mathematical equation of the ellipse:

$$\Phi = \frac{\pi\lambda b^2 \Delta t}{a \ln\left(\frac{a+l}{a-l}\right)} \tag{3}$$

In the formula, Δt is the temperature difference between the high and low temperature walls, K, l is half of the distance between the high and low temperature walls, m.

Fig. 4 shows the comparison between the theoretical value and the simulated value of the particle longitudinal heat flux. It can be seen from Fig.4 that the cross-sectional longitudinal heat flux of the high-temperature solid particles decreases with the increase of the particle aspect ratio. When the particle aspect ratio increases from 0.5 to 2, the cross-sectional longitudinal heat flux of the high-temperature solid particles decreases from 8.9 W to 2.8 W. This is consistent with the trend of the numerical curve calculated by the longitudinal heat flux theory above. The cross-sectional longitudinal heat flux of high-temperature solid particles decreases exponentially with the particle aspect ratio, and the fitting relationship is Φ=3.57+20.43exp(0.196-0.4x),$x=a/b$. However, the increase of the simulated particle longitudinal heat flux value with the decrease of the particle aspect ratio is not as rapid as the theoretical calculation of the longitudinal heat flux. The theoretical calculation assumes that the heat transfer is one-dimensional heat transfer, which obviously has a large gap with the actual situation. In the calculation range, the error reaches 0.63, so the one-dimensional simplified calculation method cannot be used in the actual calculation. In the direction perpendicular to the longitudinal heat flux propagation, the larger the particle aspect ratio, the greater the longitudinal heat flux through the solid particles. When the particle aspect ratio changes from 2 to 0.5, the theoretical calculation value of longitudinal heat flux through the cross section of particles is always greater than the simulated value.

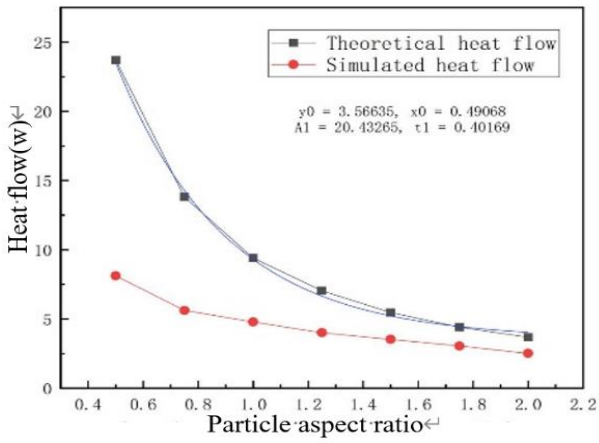


Figure 4: Comparison between theoretical and simulated values of particle heat flux

4. Effect of particle aspect ratio on internal temperature of particles

Fig. 5 shows the temperature distribution of the longitudinal section of particles with different aspect ratios under adiabatic conditions. It can be seen from fig. 5 that the isotherms are densely distributed near the high and low temperature walls of the particles, while the isotherms in the middle of the cloud are relatively sparse. Secondly, when the particle aspect ratio changes from large to small, the length of the particles in the direction of longitudinal heat flux propagation decreases, which indirectly leads to the shortening of the heat transfer path between the high and low temperature walls of the particles. The temperature difference between the high and low temperature walls of the particle with different aspect ratio is equal, and the shortening of the heat transfer path will naturally cause the decrease of the average spacing between the isotherms.

(a) aspect ratio:2 (b) aspect ratio:1.25

(c) aspect ratio:1 (d) aspect ratio:0.75

Fig. 5 Temperature distribution of longitudinal section of particles with different aspect ratios under adiabatic condition

5. CONCLUSION

In this paper, the simplified ellipsoidal high-temperature solid particles in the packed bed are taken as the research object, and the influence of the particle aspect ratio on the longitudinal heat flux of the particles is analyzed. It is concluded that under the premise that the equivalent diameter of the particles is constant, the longitudinal heat flux of the particles increases with the decrease of the particle aspect ratio, and shows an exponential decrease trend. The fitting relationship is Φ=3.57+20.43exp(0.196-0.4x), and the longitudinal heat flux changes from 2.80W to 8.89W. It provides a reference for the calculation of heat transfer of industrial particles.

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