Analysis of flow wear characteristics of particle Material around the heat exchanger

Gao Zhaoqiang, Liu Yongqi, Sun Peng

Abstract—**In order to study the particle flow characteristics in heat exchanger, the numerical calculation model of heat exchanger was established by discrete element method, the particle flow process in heat exchanger was simulated, and the wear position and strength of particles in heat exchanger were analyzed. Shear layer position and critical blocking state of the bypass heat exchanger and its influencing factors. The flow characteristics analysis results show that the tube bundle has obvious influence on the particle flow, and the particle flow uniformity between the heat exchanges is good; the flow area is 3 to 5 times the particle size on both sides of the tube bundle, and the heat exchanger spacing should be 1.5 ~ 2.0 times of pipe diameter, the wear particle flow wears less on the heat exchanger; as the ratio of the heat exchanger spacing value to the pipe diameter increases, the wear position is gradually reduced from -45° to 45° to -20° to 20°, and wear The intensity is gradually weakened and the flow uniformity is greatly improved.**

Index Terms—**heat exchanger discrete element method wear flow characteristics**

I. INTRODUCTION

High temperature solid waste heat materials are produced in various fields of industrial production, such as high temperature red heat cement clinker and lime clinker in building materials industry. Red coke, sinter, blast furnace slag, steel slag, etc. Nonferrous industry from the rotary kiln hot clinker, calcined bauxite, nonferrous metallurgical slag, etc. Therefore, energy conservation and emission reduction has become a basic national policy of China and a major strategic guarantee for China to achieve sustainable development. Industrial energy consumption accounts for more than 70% of the total energy consumption, of which at least 50% can be converted into other forms of heat energy and used to make part of the waste heat can be used; However, the recovery rate of industrial waste heat resources in China is only about 30%, and the utilization efficiency of waste heat energy is generally low. The residual heat of solid materials in iron and steel enterprises accounts for 48% of the residual heat of the whole industry. The excess heat recovered by the cement industry every year is equivalent to about 85 million tons of standard coal [1]. In China, the total amount of solid high-temperature materials generated in the process of industrial production can reach more than 5 billion tons per year, ranking the first in the world. Among them, vanadium slag occupies a high proportion in industrial production in China. Vanadium slag high temperature residue is a general term for vanadium oxide obtained by oxidation blowing of vanadium containing iron in the process of vanadium extraction or vanadium containing iron concentrate obtained by wet vanadium extraction. The waste heat resources of vanadium slag are very rich, China is a big country of vanadium resources, most of vanadium slag came into being, and a large number of waste heat resources have not been utilized. Today is more reasonable and efficient waste heat recovery in urgent need of the development, including carbon waste heat recycling method is worth reference, LAN carbon more areas of waste heat recovery exchanger [2-3] by the method of dry quenched, carbon for waste heat recovery, according to the experience of vanadium slag particles by adopting the method of dry quenching cooling on high temperature vanadium particles, using the waste heat to produce steam at the same time, a large amount of waste heat energy has been effectively reuse, improve the quality of the vanadium slag material heat to reuse a lot of heat energy at the same time. A large number of literature studies show that the flow characteristics of granular materials have a great impact on the contact mode and heat transfer mode. How to better recover the waste heat of high temperature solid materials? This has become a hot topic at present, and heat exchange tube wear research is also more and more popular. More and more researchers have discussed the wear of particles and heat transfer wall surface by means of experiment, numerical simulation or modeling, and obtained certain results.

Through the modeling method: Fan jian-ren [4] established a model and studied and analyzed the wear of the buried pipe when the particles fell. Oka et al. [5] designed and built wear models with different particle sizes and entry velocities from different angles, and concluded that the larger the particle size, the more severe the wear on the pipe, and the greater the particle entry velocity, the more severe the wear on the pipe. Zhang benzhao et al. [6] concluded through numerical simulation that the particle size had no effect on the collision position. However, the size of particle size has an effect on the amount of wear, and the larger the particle size, the greater the amount of wear. Wang yinghui et al. [7] concluded that the number of collisions between large particle size and wall surface is less than that between small particle size through numerical simulation of the wear characteristics of flue gas transverse spiral groove tube bundles. The object simulated by wang zeli et al. [8] is the abrasion caused by particles on the in-line embedded pipe,

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and the following conclusion is drawn that the first row of embedded pipe is generally the most frequently hit by material particles. Ketterhagen et al. [9] carried out numerical simulation analysis on the wear caused by particles on the pipe wall, indicating that the main factors affecting the wear are the surface roughness of the pipe, the injection velocity of particles, particle diameter, particle injection Angle, etc. Meng et al. [10] carried out a numerical simulation study on particle rotation, indicating that when the particle injection Angle is small, the pointed particle rotation has a greater impact on the wear of the tube wall.

By means of experimental methods, Tahakoff et al. [11] carried out wear experimental measurements on the impact pipes of coal ash particles, which showed that the wear of many steel pipes was plastic. Tao he, zhong wenqi et al. [12] used the multi-particle model to construct three non-spherical particles to calculate their contact characteristics. Zhao yongzhi, cheng yi, jin yong [13] analyzed the unstable flow of fluidized bed by considering rolling friction. Jenike [14] derived a theory to describe the inner stress of silos, which was mainly applied to the hopper part.

In summary, the particle material is affected by the physical property of the material itself, the heat exchanger structure and the friction coefficient between the material and the structure, so as to change the flow path of the material, explore the contact characteristics and flow between the material and the heat transfer structure, and obtain a reasonable structure arrangement and optimize to improve the heat transfer efficiency of waste heat.

II. PHYSICAL MODEL AND MATHEMATICAL DESCRIPTION

The selection of calculation model is based on different material characteristics. DEM discrete element analysis software provides multi-possibility calculation model to calculate different material characteristics. HertzMlidlin non-slip contact model is a conventional particle calculation model for materials that are not wet materials, and there is no obvious bonding and agglomeration between the particles due to electrostatic force and wet water, etc. Vanadium particles have very low moisture content in the heat exchanger, which is used for this model. This model is demarcated as an independent unit module. According to the interaction between the units and Newton's law of motion, the dynamic relaxation method and other iterative calculation methods are adopted to determine the force and displacement within each time step and update the unit position. See literature [15] for the detailed calculation process of the model. Particle motion is applicable to Newton's second law, and the formula is:

$$\begin{cases} m_i \dfrac{\partial \boldsymbol{v}_i}{\partial t} = \sum \boldsymbol{F} + m_i \boldsymbol{g} \\ \boldsymbol{I}_i \dfrac{\partial \boldsymbol{w}_i}{\partial t} = \sum \boldsymbol{T} \end{cases} \quad (1)$$

Where, m_i is the mass of particle i, $\boldsymbol{I}_i$is the moment of inertia of particle i, $\boldsymbol{v}_i$ is the velocity vector of particle i, $\boldsymbol{\omega}$i is the angular velocity vector of particle i, F is the contact force of particle i, T is the torque of particle i, and $\boldsymbol{g}$ is the acceleration of gravity. The hertz-mindlin non-slip model was adopted for the contact model. The calculation methods of the normal contact force, normal damping force and tangential damping force, normal stiffness and torque between particle i and particle j were as follows:

$$\boldsymbol{F}_n^t = \frac{4}{3} E^* \left(R^*\right)^{\frac{1}{2}} \boldsymbol{\delta}_{\boldsymbol{n}}^{\frac{3}{2}} \quad (2)$$

$$\boldsymbol{F}_n^d = -2\sqrt{\frac{5}{6}} \beta \sqrt{S^n m^*} v_n^{rel} \quad (3)$$

$$\boldsymbol{S}^t = 8G^* \sqrt{R^* \partial_n}$$
$$S^n = 2E^* \sqrt{R^* \partial_n} \quad (4)$$

$$\boldsymbol{F}_t^d = -2\sqrt{\frac{5}{6}} \beta \sqrt{S^t m^*} v_t^{rel} \quad (5)$$

$$\boldsymbol{T}_i = -\mu_r \boldsymbol{F}_i \ \boldsymbol{R}_i \boldsymbol{w}_i \quad (6)$$

Type, $\boldsymbol{E}^*$ as the young's modulus, $\boldsymbol{R}^*$ as the equivalent radius, $\boldsymbol{\delta}^n$, $\boldsymbol{\delta}^t$ for as the unit normal vector, unit tangent vector, **β**as the damping ratio, $\boldsymbol{S}^n$, $\boldsymbol{S}^t$ as the normal stiffness and tangential stiffness, **m*** as the to overlap equivalent mass, v_n^{rel},v_t^{rel} is the normal component of relative velocity and the tangential component of relative velocity respectively, $\boldsymbol{G}^*$ as the equivalent shear modulus, for the simulation of rolling friction is also very important reference factor as the coefficient of rolling friction, as the center of mass to the vector length of the contact point, for the particle unit angular velocity vector at the contact point. The relation between displacement and force is obtained by solving polynomial, and the solution of unknown parameter is obtained by iterative operation. According to the physical parameters and calculation criteria, the iteration time step is $2*10^6$s. Physical parameters are shown in table 1

类别	物性设置	数值
particles	particles density /(kg·m^{-3})	1650
	Poisson's ratio	0.28
	Shear modulus /GPa	$1.4×10^8$
	particles diameter /mm	0.5
wall	Wall density/(kg·m^{-3})	7800
	Poisson's ratio	0.3
	Shear modulus /GPa	$7×10^{10}$
Particle--Particles	Coefficient of static friction	0.45
	Coefficient of rolling friction	0.035
	Coefficient of restitution	0.5
Particle --Wall	Coefficient of static friction	0.42
	Coefficient of rolling friction	0.026
	Coefficient of restitution	0.48

Table 1 Mechanical parameters of the model

The discrete element method adopts a certain simplified treatment in the discussion model establishment, and the cycle boundary is set in the X and Y directions. The waste heat recovery system is divided into storage area and heat exchange area, in which three rows and three rows of heat exchangers are arranged in the heat extraction area. In order to study the influence of vanadium particles on heat exchange pipe bundles along the flow direction, heat exchangers of different diameters were selected and the distance between pipe diameters was treated with dimensionless treatment, $N=L/D_1$, in which the distance between two heat exchange pipes and the OD_1 (outer diameter of D_1),ID_0 (inter diameter of D_0),heat exchange pipe were treated with dimensionless quantities N=0.25, 0.5, 1, 1.5, 2, and the diameter of heat exchange pipe was shown in table 2.

ID_0 (mm)	OD1 (mm)	length (mm)
15	21.3	201
20	26.8	201
25	33.5	201

Table 2 Heat exchange tube diameter

After the dry distillation treatment, the granular material enters the heat exchanger and flows slowly under the action of internal gravity. Particles in the heat exchanger and the material static pile up in the bin, when the working condition of simulated with parallel plate at the bottom of the material at a constant velocity 0.01 (m./s) uniform motion, the model of grain diameter size is simplified to a diameter of 0.5 mm round ball particles, particles according to different dimensionless number N values, the heat exchange tube for inquiry model with symmetric distribution characteristics, therefore, to establish the model can be further simplified processing, X and Y direction set cycle boundary conditions. According to the different values of dimensionless number N, the specific model sizes under different working conditions were established. The DEM model of the created heat exchanger is shown in figure 2.

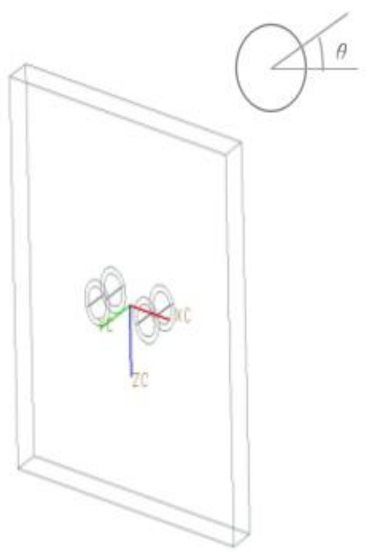

Fig1 schematic diagram of heart exchanger structure

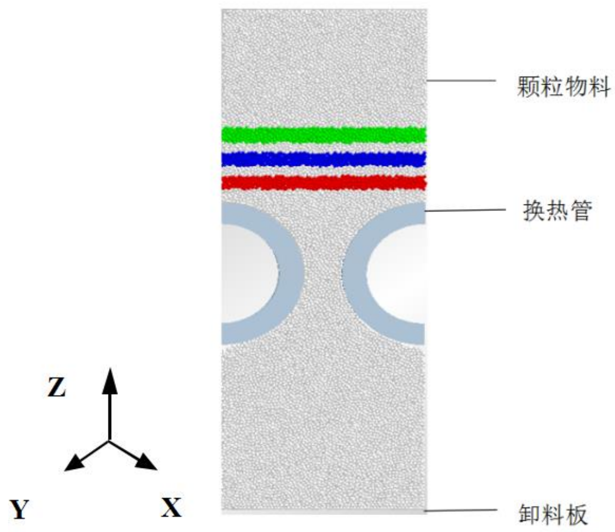

Fig.2 Heat exchanger and DEM model

III. RESULT

When the particles flow around the heat exchanger, the heat exchanger will cause an important blocking effect on the particle flow, according to the particle flow pattern can be divided into two categories: integral flow and funnel flow. Global flow means that the particles can maintain the same height and roughly the same speed in the same height layer. The flow area of the funnel powder layer is shaped like a funnel, which makes the order of the material flow disordered. Some of the powder even remains motionless, resulting in the flow of the material added first and then out. At the initial moment of the flow, the particles in each marker layer are at the same height. With the continuous movement, the marker layer begins to contact the heat exchanger and has a significant effect on the particle flow pattern. At the central position of the particle flow, the particle velocity is larger and is less affected by the blocking flow. At the central position of the marked particle layer, the elevation layer is basically unchanged. The particles near the heat exchanger tube are affected by the friction force on the wall of the heat exchanger tube, so the particle velocity near the wall is slightly lower than that at the central position. The flow pattern is shown in figure 3.

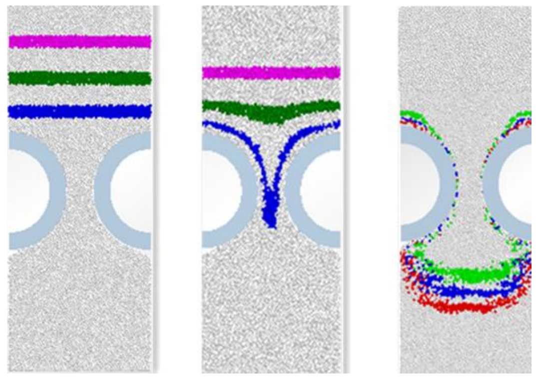

Fig.3 Flow patterns of particles

In the flow pattern diagram, it can be clearly seen that the particle layer at the center can maintain the same height, and the flow around the wall of the heat exchange tube is obvious. When the heat exchange tube θ=90°, there can be subsequent force chain analysis to obtain that there will be a little particle accumulation on its surface. In order to accurately judge the flow pattern, the flow index MFI is often used to judge the flow pattern. It is defined as the ratio of the particle velocity at the wall surface to the particle velocity at the center.

$$MFI = \frac{V_{wall}}{V_{center}} \qquad (7)$$

In formula (7), V_{wall} refers to the velocity at the wall surface, unit m/s; V_{center} is the particle at the center, m/s. The larger the MFI value, the more uniform the particle flow. Jenike and Johanson take MFI = 0.3 as the boundary value to distinguish the particle flow type, and when MFI > 0.3, the flow type is the overall flow. The calculated width of the center spacing of the heat exchange tube is 2d, and the calculated width of the tube wall is d, and d is the particle diameter. The inner diameter and size of heat exchanger tubes were selected as shown in table 2. The influence of heat exchanger on particle flow was explored under different values of N.

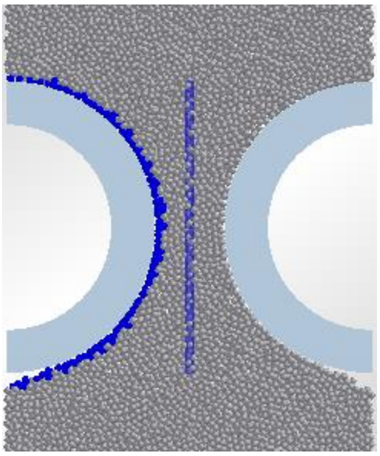

Fig.4 Average speed calculation area

When D_0 = 15 mm, N = 0.25, figure 5 (a) the MFI numerical distribution table, it can be seen that particles in through the heat exchange tube wall affected by the strong choke, the heat exchange tube spacing of 8 times the particle size, MFI = 0.21, near the particle flow heat exchanger by particle and wall friction role, unilateral effect range of 4 to 6 particle size range, blocking phenomenon in a heat exchanger. With the increase of N value in the same heat transfer pipe diameter, the flow blocking phenomenon disappeared and the flow uniformity was improved. The flow uniformity is greatly affected by the heat exchanger, but not enough to cause the flow to be blocked. In the heat exchange tube wall tube diameter 15 mm, N = 0.25, 0.5, 1.0, 1.5, 2.0, MFI will with larger tube spacing, as shown in figure 5 (b), with the increase of N values under the same diameter, MFI peak value is near the center value from 0.9 to 0.926, the increase of 2.8%, low peak near the wall is MFI value under the same N values, the value also gradually increased from 0.751 to 0.795, the increase of up to 5.4%

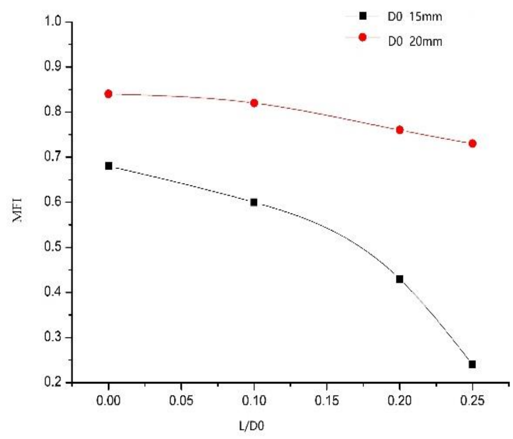

Fig.5 (a) Comparison of MFI values

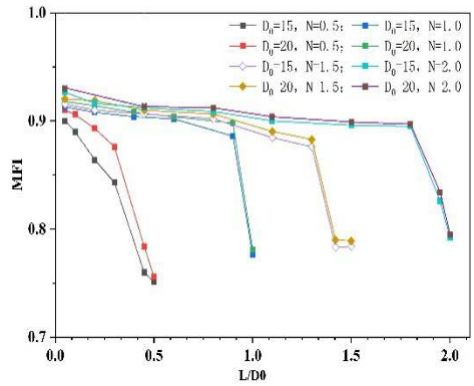

Fig.5 (b) Comparison of MFI values

In this paper, on the basis of EDEM software by record tracking particle position and by Tangential Cumulative Contact Energy accumulation (Tangential Contact can) to quantitative said heat exchange tube wall quantity in different position with different N values wear position and with the change of N values to change the flow around on the tube wall wear position and the changing rule of the scope of the effects of wear and tear strength. FIG. 6 (a), FIG. 6 (b), FIG. 6 (c), FIG. 6 (d), FIG. 6 (e) reveal some laws of its specific influence.

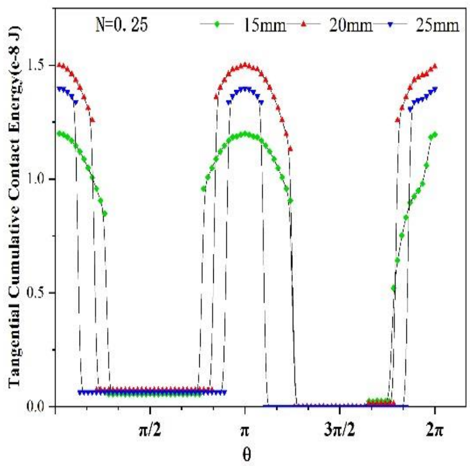

Fig.6(a) Numerical distribution of tangential cumulative contact energy at different positions of N=0.25

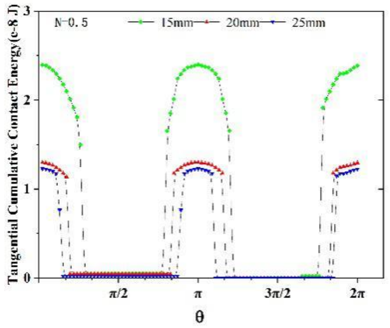

Fig.6 (b) Numerical distribution of tangential cumulative contact energy at different positions of N=0.5

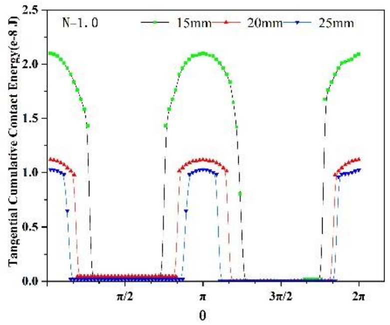

Fig.6 (c) Numerical distribution of tangential cumulative contact energy at different positions of N=1.0

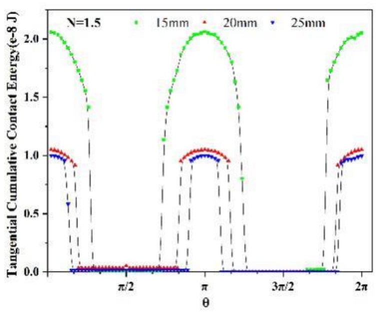

Fig.6(d) Numerical distribution of tangential cumulative contact energy at different positions of N=1.5

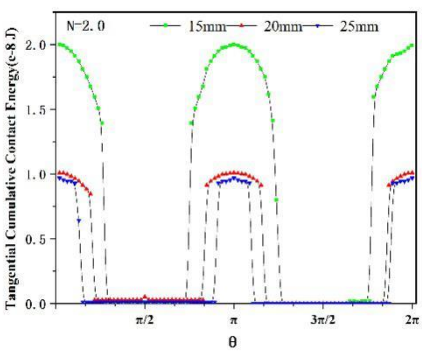

Fig.6(e) Numerical distribution of tangential cumulative contact energy at different positions of N=2.0

FIG. 6 shows that when N values are the same, the smaller the outer diameter of the pipe is, the wider the wear area is, and the corresponding wear intensity is larger than that of the large pipe. Special case happened in the N = 0.25, tube diameter is 15 mm, wear and tear strength maximum location tangential accumulated exposure to e-8 1.22 J, than the outer diameter 20 mm, 25 mm of tangential accumulated exposure to small for 35% and 20% respectively, this is because in the above mentioned when N = 0.25, tube diameter 15 mm, inside the heat exchanger with granular layer movement occur relatively obvious blocking phenomenon. When the inner diameter of the tube is 15mm, except when N=0.25, when N=0.5, 1.0, 1.5, and 2.0, the data analysis shows that the position of the heat exchange tube subjected to strong wear is 310°~50° and 130°~230°. When the inner diameter of the tube is 20mm, when N is 0.25, 0.5, 1.0, 1.5, and 2.0, the concentrated wear position of the heat exchange tube wall further decreases and is roughly distributed between 330°~30° and 150°~210°. When the inner diameter of the tube is 25mm, The concentrated wear position of heat exchanger tube wall is further reduced and roughly distributed between 340°~20° and 160°~200°.In the area around PI /2, the heat exchange tube concentrated wear is rare, most of the particles after the forward collision point domain and the intensity is very small. At the heat exchanger position, little shear energy is recorded in the area oscillating /3 from side to side. At the same time, when the value of N is distributed in 1.5~2.0, the peak value of concentrated wear intensity on the wall of heat exchange tube is basically the same, which provides a certain reference value for the transverse spacing of heat exchange tube. The excessive spacing distribution will not continue to reduce the wear intensity, but will reduce the heat recovery efficiency of the heat exchange pipe due to the unreasonable pipe distribution.

The distance between the wall of the heat exchanger and the heat exchanger also affects the particle flow. Too large spacing will lead to unreasonable heat exchange tube distribution position, too small spacing will also cause the wall and heat exchange tube between the blocking effect on waste heat recovery efficiency. FIG. 7 reveals the influence of heat exchanger spacing on the number of particle collisions.

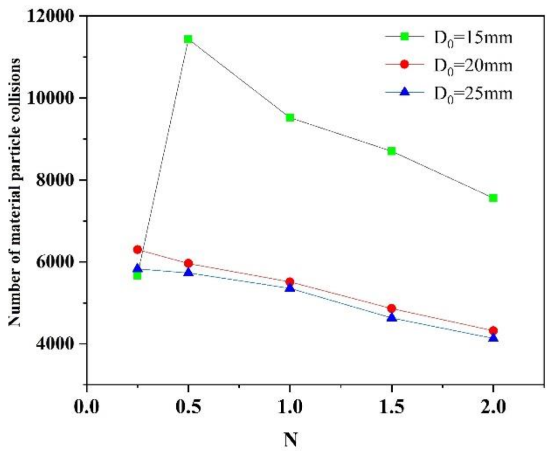

Fig.7 Number of material particle collisions

It can be concluded from FIG. 7 that with the change of the pipe diameter of the heat exchanger, the larger the value of N under the quantitative pipe diameter, the lower the number of effective particle collisions will be. However, when N=1.5~2.0, the reduction of the effective particle collisions will gradually decrease and finally almost close. When N=0.25, the number of particles will decrease sharply with the smaller diameter, indicating that the effective number of particle collisions is reduced due to the blocking phenomenon .At the same time, in order to consider the dimensionless quantity of particle size and distance ratio and the particle range acted on by the heat exchanger wall surface, the selected investigation area is as follows As shown in FIG. 8, the influence of dimensionless quantities of distance from the wall surface and particle diameter on void ratio is shown in FIG. 9.

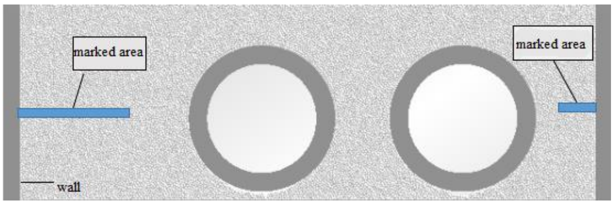

Fig.8 Marked area

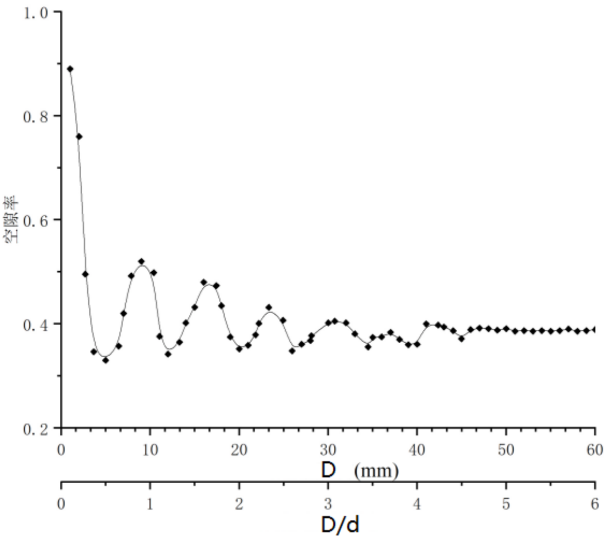

Fig.9 Wall effect

Void fraction gradually reduce with increase of depth from the surface, the scope of the heat exchanger wall effect on particles in 4 to 6 times the particle size range, it is because of the heat exchanger wall and particles in different radius of curvature, and as the flow continued heat exchanger wall will appear "hang wall" phenomenon, and as the population of the material flow and wall attachment of granular layer gradually thickening, ultimately affect the heat exchanger of waste heat recovery effect.

CONCLUSION

(1) The particle flow in the heat exchanger will be affected by the pipe diameter of the heat exchanger, the spacing of the heat exchanger and the distance from the heat exchanger wall. When the inner diameter of the heat exchanger tube is 15mm, blocking will occur when N=0.25, and the wall of the heat exchanger tube will affect the 3-5 times particle diameter range of the material. With the increase of the value of N, the particle fluidity in the heat exchanger is significantly improved.

(2) The large difference in curvature radius between the heat exchanger wall surface and the particles leads to the "hanging wall" phenomenon when the particles flow through the heat exchanger wall surface, and the heat exchanger wall surface affects 4-6 times the particle size range. The recovery efficiency of waste heat is reduced and the uniformity of particle flow is worsened.

(3) Particles will cause severe erosion and wear on the outer wall surface of heat exchanger tube when they flow through the heat exchanger tube. As the pipe diameter increases, the concentrated wear range of particles becomes smaller. When the pipe spacing is about 1.5-2.0 pipe diameter, the wear value peak value will basically no longer change, and the effective number of particle collisions will decrease with the increase of the area.

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