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Heat transfer characteristics of straight-fin-tube heat exchanger for calcined petroleum coke waste heat recovery[1]

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Abstract. This paper reports the results of heat transfer characteristics of straight-fin-tube heat exchanger for calcined petroleum coke waste heat recovery. The model of straight-fin-tube heat exchanger was set up. The model has been used to investigate the effects of fin height (34 mm to 46 mm) and fin width (3 mm to 6 mm). The calculated values of calcined petroleum coke temperature showed good agreement with the corresponding available experimental data. The temperature distribution of calcined petroleum coke, the distribution of fin temperature and heat flux, the calcined petroleum coke temperature at heat exchanger outlet, the average heat transfer coefficient and the heat recovery efficiency were studied. With the increase of the fin height or fin width, the average temperature and the maximum temperature of the calcined petroleum coke decreases at the heat exchanger outlet, the heat recovery efficiency increases. The effects of the fin height is greater than the fin width. It can also be used in deriving much needed data for heat exchanger designs when employed in industry.

Key words. Calcined petroleum coke, heat transfer, waste heat, straight-fin-tube, temperature distribution.

1. Introduction

The total solid particle capacity with high temperature is about 10 billion tons annually in the world. If the waste heat of high temperature solid particle is recovered completely, which is equivalent to saving 400 million tons of standard coal. However,

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there is only few waste heat in solid particles with high temperature to be recycled. Hence, there is a good promising to recover the waste heat in solid particles with high temperature. At present, the recovery by direct heat transfer is the most effective way to recover the waste heat in solid particles with high temperature [1]. The recovery by direct heat transfer means that solid particles exchange heat with heat exchanger to recover waste heat when the high temperature particles flow through a special heat exchanger, which can be used to produce the steam immediately.

Waste heat reutilization of the solid particle has been studied in some field. Barati et al. [2] introduced some methods of recovering waste heat from high temperature steel slag. Fabian et al. [3] researched the heat transfer coefficient between the moving material layer and the wall of bed. In the experiment, the effects of the operational parameters, the moving speed of material layer and the depth of buried material on heat transfer coefficient were studied. Kashiwaya et al. [4–5] concluded that the waste heat of the high temperature steel slag can be utilized by rotary cylinder atomizing method and air nozzle method. Theodoros et al. [6] simulated the movement of irregularly arranged particle near the wall with CFD. Sundaresan et al. [7] researched the axial heat transfer characteristics in circulating fluidized bed, and analyzed surface heat transfer coefficient of several vertical pipes. The results showed that the length and the location of the tube affected heat transfer coefficient. Nomura and Kashiwaya [8–9] studied the generation of fuels based on the utilization of the slag thermal energy in endothermic reactions. Guo et al. [10] simulated the heat transfer in the gas-solid fluidized bed with Euler-Euler method, and obtained the effects of Reynolds number and porosity on heat transfer.

However, there is a lack of the investigations on the reutilization of calcined petroleum coke waste heat. In this paper, the straight-fin-tube heat exchanger of direct heat exchange mode was invented, and the heat transfer characteristics of straight-fin-tube heat exchanger for calcined petroleum coke waste heat recovery were studied.

2. Physical and mathematical description of the problem

The waste heat of calcined petroleum coke is recovered by a straight-fin-tube heat exchanger. The heat exchanger of calcined petroleum coke includes an internal heat exchanger and an external heat exchanger. The straight-fins are welded in the tubes. Its structure is shown in Fig. 1.

The calculated model of calcined petroleum coke heat exchanger is equal to the experimental heat exchanger model in scale. The calculation model is appropriately simplified. The calculated model includes two external heat exchanger tubes, one internal heat exchanger tube, and the region between the tubes and thermal barriers. The heat loss of the heat exchanger lateral is ignored. The calcined petroleum coke particles and the gas among them are regarded as homogeneous continuum. The lengths of X and Y axis are 78 mm and 262 mm. The height of the model is 1550 mm. It is showed as Fig. 2.

The unsteady model is used for calculation. The mass, momentum and energy conservation equations are showed as follows. The mass conservation equation reads

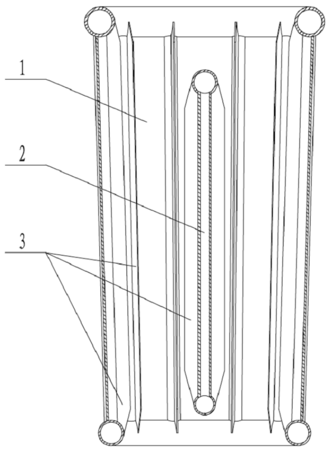

Fig. 1. Structure of heat exchanger: 1–external heat exchanger, 2–internal heat exchanger, 3–straight-fin

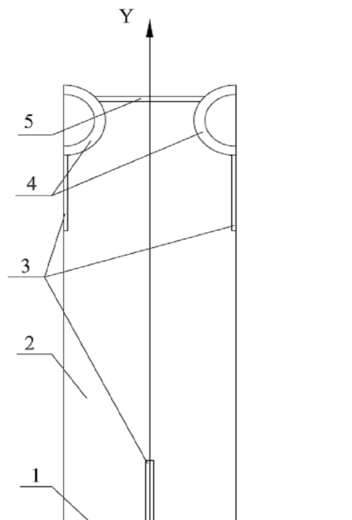

Fig. 2. Simplified calculation model: 1–internal heat exchange tube, 2–calcined petroleum coke, 3–straight-fin, 4–external heat exchange tube, 5–diaphragm wall

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho w)}{\partial z} = 0\,, \tag{1}$$

where ρ is the density, t is the time, u, v, w are the velocity components in the x, y and z axes, respectively.

The momentum conservation equations in components are given in the form

$$\frac{\partial(\rho u)}{\partial t}+\text{div }(\rho uV)=-\frac{\partial p}{\partial x}+\frac{\partial\tau_{xx}}{\partial x}+\frac{\partial\tau_{yx}}{\partial y}+\frac{\partial\tau_{zx}}{\partial z}+F_x\,, \tag{2}$$

$$\frac{\partial(\rho v)}{\partial t}+\text{div }(\rho vV)=-\frac{\partial p}{\partial y}+\frac{\partial\tau_{xy}}{\partial x}+\frac{\partial\tau_{yy}}{\partial y}+\frac{\partial\tau_{zy}}{\partial z}+F_y\,, \tag{3}$$

$$\frac{\partial(\rho w)}{\partial t}+\text{div }(\rho wV)=-\frac{\partial p}{\partial z}+\frac{\partial\tau_{xz}}{\partial x}+\frac{\partial\tau_{yz}}{\partial y}+\frac{\partial\tau_{zz}}{\partial z}+F_z\,. \tag{4}$$

Here, p is the pressure, τ_{xx}, τ_{xy}, τ_{xz}, etc., are component of the stress tensor τ caused by molecular viscosity, F_x, F_y, and F_z are the body forces, and V is the module of the velocity vector.

The energy conservation equation reads:

$$\frac{\partial(\rho T)}{\partial t}+\frac{\partial(\rho Tu)}{\partial x}+\frac{\partial(\rho Tv)}{\partial y}+\frac{\partial(\rho Tw)}{\partial z}=$$

$$=\frac{\partial}{\partial x}\left(\frac{k}{c_{\mathrm{p}}}\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{k}{c_{\mathrm{p}}}\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\frac{k}{c_{\mathrm{p}}}\frac{\partial T}{\partial z}\right)+S_{\mathrm{T}}\,. \tag{5}$$

Here, c_{p} is the specific heat of water at a constant pressure, k is the effective heat transfer coefficient, T is the temperature of fluid, and S_{T} is the viscous dissipation term.

The equations of the flow model in the pipe follow.

Turbulence intensity:

$$I=0.16\times\mathrm{Re}^{-0.125}\,. \tag{6}$$

Turbulent kinetic energy:

$$k=\frac{3}{2}\cdot(\overline{\boldsymbol{u}}\times\boldsymbol{I})^2\,. \tag{7}$$

Turbulence kinetic energy dissipation rate:

$$\varepsilon=C_{\mathrm{u}}^{0.75}k^{1.5}/l\,. \tag{8}$$

In the above three formulas, $\boldsymbol{I}$ is the turbulence intensity, Re is the Reynolds number of fluid, $\overline{\boldsymbol{u}}$ is the average fluid turbulent velocity, C_{u} is an empirical constant (0.09), and l is the characteristic length.

According to the simplified model, the heat transfer of the calcined petroleum coke in the heat exchanger mainly includes the heat transfer among calcined petroleum coke particles and heat transfer between calcined petroleum coke and the wall of the heat exchanger. The heat transfer process is unsteady with no internal heat source, so the heat conduction differential equation is

$$\rho c\frac{\partial T}{\partial\tau}=\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right)\,, \tag{9}$$

where ρ is the density, c is the specific heat, T is the temperature, and λ is the coefficient of heat conductivity.

The above quantities are calculated at the discrete points. The implicit format of the unsteady heat conduction equation is used to solve problems in this paper.

$$\frac{T_n^{(i+1)} - T_n^{(i)}}{\Delta\tau} = a\frac{T_{n+1}^{(i+1)} - 2T_n^{(i+1)} + T_{n-1}^{(i+1)}}{\Delta x^2}\,, \tag{10}$$

where $\Delta\tau$ is the time step, n is the index of the node, i is the index of time level, a is the thermal diffusivity and Δx is the distance between two adjacent nodes.

The heat transfer equation of calcined petroleum coke and the wall of heat exchanger is

$$q = k \cdot A \cdot \Delta T_{\mathrm{m}} \tag{11}$$

where q is the heat flux, k is the heat transmission coefficient, A is the heat exchange area, and ΔT_{m} is the average temperature difference.

The calcined petroleum coke velocity, water velocity in the tube and calcined petroleum coke temperature in the heat exchange inlet are constant. The velocity of water in tube is 1 m/s, the inlet temperature of water is 300 K, the inlet temperature of calcined petroleum coke is 1173 K, the velocity of calcined petroleum coke in the heat exchanger is 6×10^{-5} m/s. The calcined petroleum coke particles and the gas among them are regarded as homogenous continuum. The physical parameters of calculation model are calculated as the porosity of calcined petroleum coke. The effective heat conductivity coefficient of homogenous continuum is calculated by the equation [11]

$$\lambda_{\mathrm{e}} = \phi\lambda_{\mathrm{f}} + (1-\phi)\,\lambda_{\mathrm{s}}\,, \tag{12}$$

where λ_{e} is the effective thermal conductivity coefficient, Φ is the porosity, λ_{f} is the thermal conductivity coefficient of gas, and λ_{s} is the thermal conductivity coefficient of solid.

The effective specific heat of homogenous continuum is calculated by the equation

$$C_{\mathrm{pe}} = \phi C_{\mathrm{pf}} + (1-\phi)\,C_{\mathrm{ps}}\,, \tag{13}$$

where C_{pe} is the effective specific heat, C_{pf} is the specific heat of gas, and C_{ps} is the specific heat of solid.

Table 1. Comparison results of different meshing schemes

	Grid quantity	The maximum temperature of calcined petroleum coke at outlet (K)	Relative change (% relative to the former scheme)
Scheme 1	270167	486.74	-
Scheme 2	383383	491.44	0.966
Scheme 3	492896	493.05	0.327
Scheme 4	766650	499.36	1.279

When the heat exchanger model is meshed, the internal boundary is refined locally. The test of grid independence is completed, The calculation results are showed as Table 1. Based on the comparison results, the scheme 2 from the Table 1 is adopted.

The heat recovery efficiency is calculated by the equation

$$\eta = \frac{q_1 \cdot (h_{1\text{out}} - h_{1\text{in}}) + q_2 \cdot (h_{2\text{out}} - h_{2\text{in}})}{c \cdot q_3 \cdot (T - 300)} \times 100\,, \tag{14}$$

where η is the heat recovery efficiency, q_1 is the water flow mass of external heat exchange tube, $h_{1\text{out}}$ is the enthalpy value of water in the tube outlet, $h_{1\text{in}}$ is the enthalpy value of water in the tube inlet, q_2 is the water flow mass of internal heat exchange tube, $h_{2\text{out}}$ is the enthalpy value of water in internal heat exchange tube outlet, $h_{2\text{in}}$ is the enthalpy value of water in internal heat exchange tube inlet, c is the specific heat capacity, q_3 is the calcined petroleum coke flow mass, and T is the temperature of calcined petroleum coke when it flows into the heat exchanger.

3. Experimental system

The experimental system of waste heat utilization exchanger was built in Weifang Lianxing New Materials Technology Co., Ltd. The heat transfer experiments were carried out by the experimental system (see Fig. 3). The experimental system is composed of the waste heat exchanger, the calcined petroleum coke supply system, the water circulation system and the measurement system.

The experimental system is installed in the tank calcined furnace. The high temperature calcined petroleum coke is directly supplied from the tank calcined furnace. The water circulation system is composed of a cooling pond, pumps, valves, sight glass, drum and so on. There is a WSM-D two-phase flowmeter in the heat exchanger outlet, which is used to for measuring steam dryness and flow. There is a FLUXUS F601 ultrasonic flowmeter in the heat exchanger inlet, which is used to measure the water flow. Its measuring accuracy is $\pm 0.5\,\%$. Its measuring velocity range is from 0.01 m/s to 25 m/s. Its repeatability is 0.15 %. The temperature measuring points of calcined petroleum coke in the heat exchanger are shown in Fig. 4.

4. Results and discussions

4.1. Model validation

The experimental data were used to validate the developed model. Simulations were conducted for the same operational conditions as those employed in the experimental investigation. Fig. 5 shows temperatures of numerical and experimental results in different planes when the calcined petroleum coke porosity is 0.7, the fin height is 40 mm and width is 3 mm. The temperature difference of numerical and

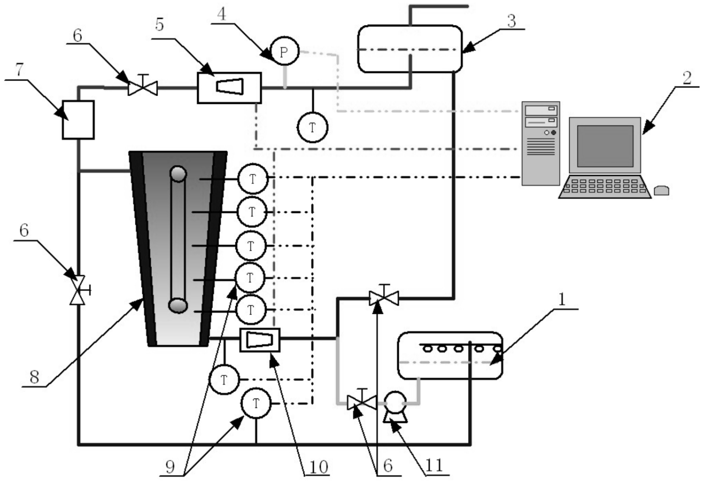

Fig. 3. Scheme of experimental system: 1–cooling pond, 2–data acquisition system, 3–drum, 4–pressure sensor, 5–two-phase flowmeter, 6–valve, 7–sight glass, 8–waste heat exchanger, 9–temperature sensor, 10–flowmeter, 11–pump

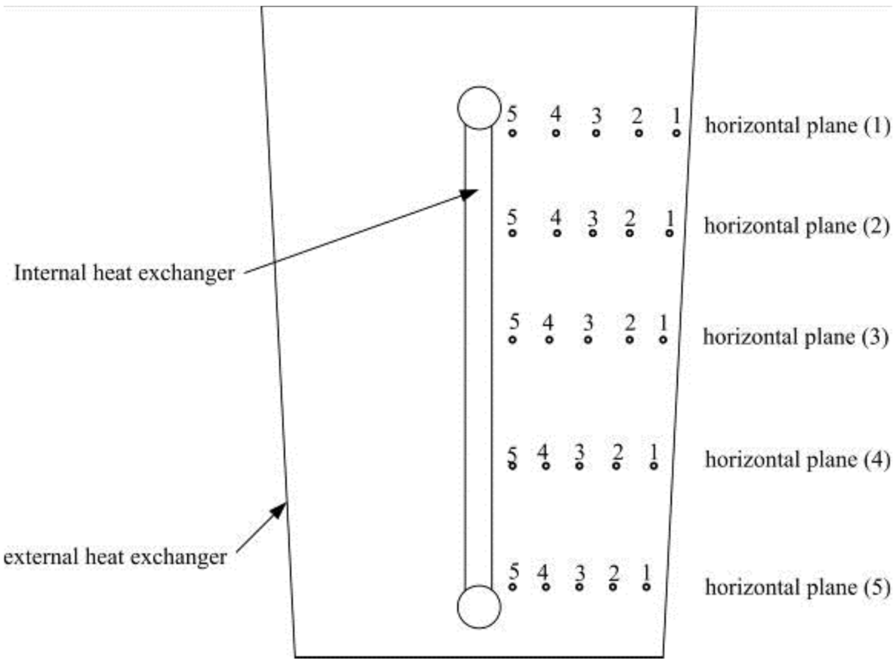

Fig. 4. Temperature measuring points of calcined petroleum coke in waste heat exchanger

experimental results is 19.2 K and the relative error is 4.54 %. The results are in good agreement with the experimental value obtained in the same conditions.

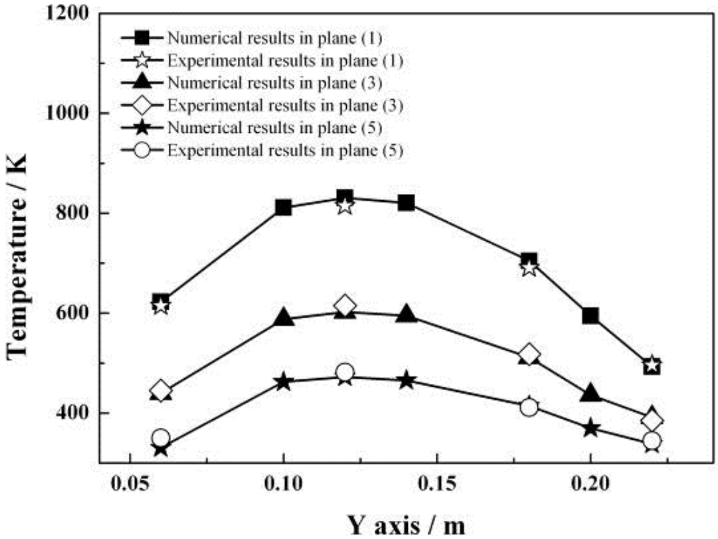

Fig. 5. Temperatures of numerical and experimental result

4.2. Characteristics of temperature distribution in heat exchanger

Figure 6 shows the temperature distribution of calcined petroleum coke in the fin-tube heat exchanger and the light-tube heat exchanger with the calcined petroleum coke porosity 0.7. The light-tube is a non-fin-tube. Figure 6 indicates that whether it is the fin-tube or the light-tube, the temperature of calcined petroleum coke is low near the wall of the heat exchanger tube and the temperature of calcined petroleum coke is high in the center of the internal and the external heat exchangers. The main reason is that the coefficient of the heat conductivity of calcined petroleum coke is very low. The longer the distance of heat transfer is, the bigger the heat resistance of calcined petroleum coke is, and thus the higher the temperature is.

At the same time, it can be seen form Fig. 6 that compared with the light-tube heat exchanger, the heat transfer performance of the fin-tube heat exchanger is better. The temperature of calcined petroleum coke in the heat exchanger decreases. The reason is that when the fin is equipped with a tube, the heat transfer area increases, and the heat transfer distance between the heat exchanger and the calcined petroleum coke increases. Thus, the heat transfer process is strengthened.

4.3. Characteristics of temperature and heat flux distribution in the fin

Figure 7 shows the temperature variations of the straight-fin surface along fin height direction when the calcined petroleum coke porosity is 0.7, the fin height is 40 mm and the fin width is 3 mm. Figure 7 shows that with the increase of fin height, the fin temperature increases slowly firstly. But when the fin height is greater than

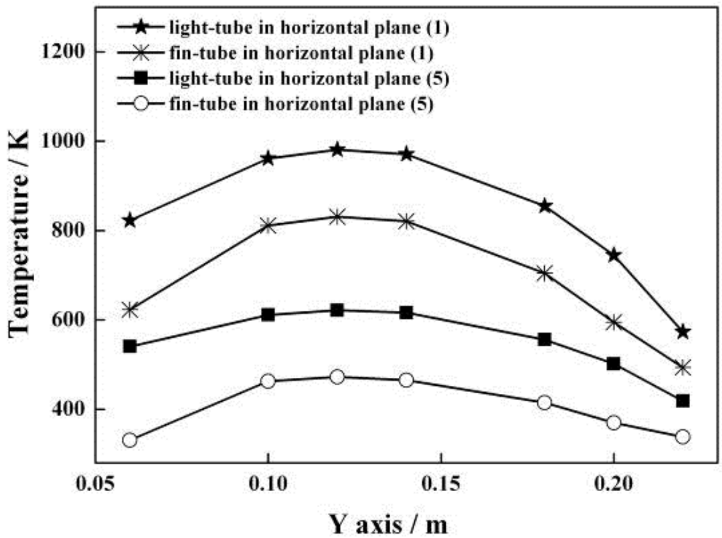

Fig. 6. Temperature distributions of calcined petroleum coke

39.5 mm, the fin temperature increases dramatically and the temperature difference is 162 K in the first horizontal plane. Figure 8 shows the total heat flux distributions in the fin. As can be seen from Fig. 8, the total heat flux increases in the same horizontal plane from the top of the fin top to the root. The total heat flux difference between the fin top and the fin root is 14867.9 W/m^2 in the first horizontal plane and 1791.7 W/m^2 in the fifth horizontal plane. Because the fin is a straight-fin, the heat gathers from two sides from the top of the fin to the root, the total heat flux accumulates gradually. Therefore the total heat flux rises to the maximum value in the fin root.

4.4. Effect of fin height

Figure 9 shows the effects of fin height on calcined petroleum coke temperature at the outlet of heat exchanger. As is shown, when the fin height increases from 34 mm to 46 mm, the average temperature of calcined petroleum coke decreases from 415 K to 377 K, and the maximum temperature decreases from 499 K to 443 K. The main reason is that with the increase of fin height, the heat transfer distance between calcined petroleum coke in the heat exchanger center and the fin decreases, the heat transfer area as well as the total heat transfer quantity increases, and both the maximum temperature and the average temperature decrease.

Figure 10 shows the effects of fin height on average heat transfer coefficient. As can be seen from Fig. 10, when the fin height increases from 34 mm to 46 mm, the average heat transfer coefficient of the internal and the external heat exchangers increases by 12.5 % and 11.2 % respectively. The reason for this is that with the increases of fin height, the heat transfer distance between calcined petroleum coke in the heat exchanger center and the fin decreases, and so does the heat resistance

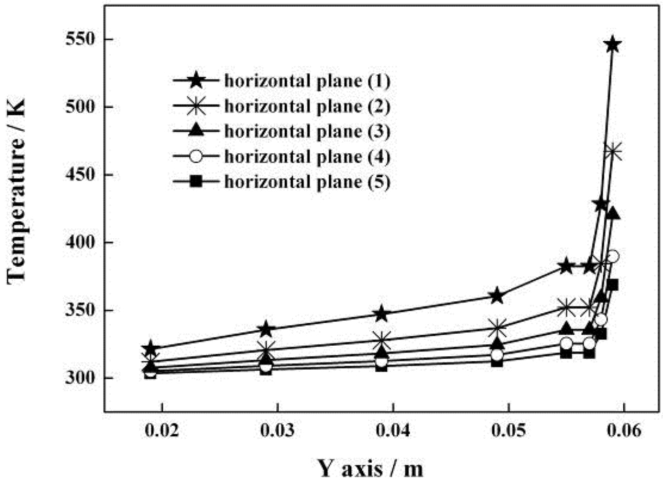

Fig. 7. Temperature distributions

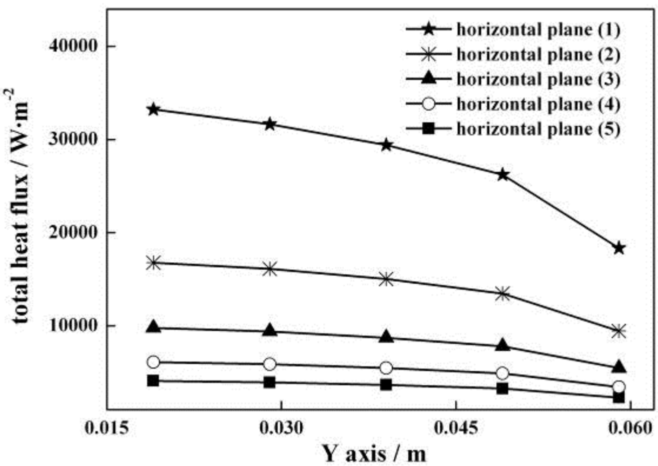

Fig. 8. Total heat flux distributions

while the average heat transfer coefficient increases.

Figure 11 shows the effects of fin height on heat recovery efficiency. It shows that the heat recovery efficiency increases by 4.1 % when the fin height increases from 34 mm to 46 mm. The main reason is that when the fin height increases, both the total heat quantity and the heat recovery efficiency increase.

4.5. Effect of fin width

Figures 12–14 show the effects of the fin width on the calcined petroleum coke temperature at the heat exchanger outlet, the average heat transfer coefficient and

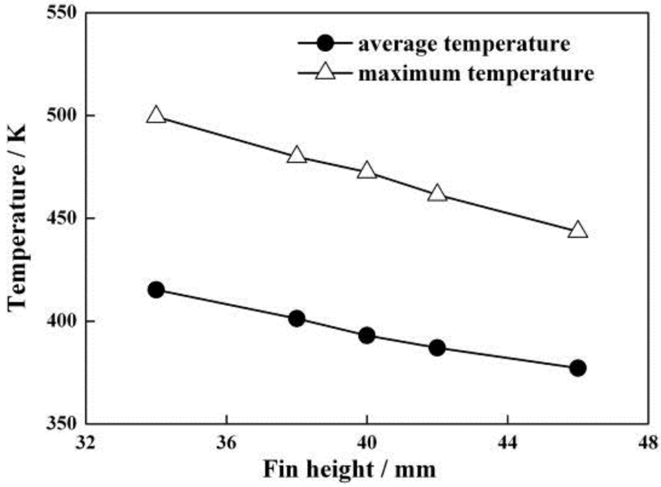

Fig. 9. Variations of temperature at heat exchanger outlet with different fin height

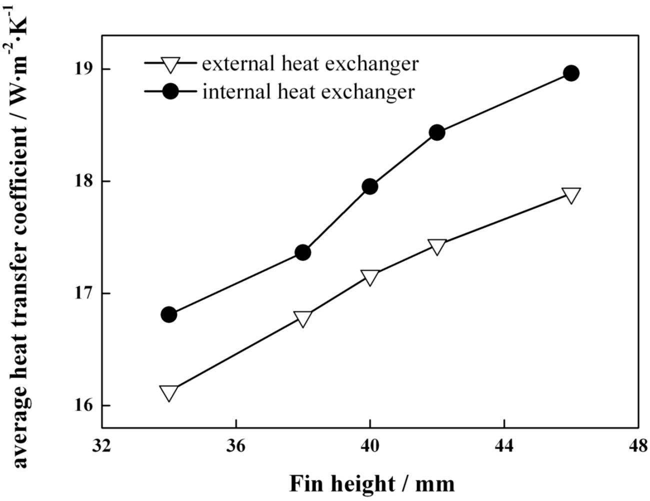

Fig. 10. Variations of average heat transfer coefficient with different fin height

the heat recovery efficiency respectively. As can be seen from Figs. 12–14, when the fin width increases from 3 mm to 6 mm, the average temperature reduces by 5.6 K and the maximum temperature decreases by 11.7 K; the average heat transfer coefficient of the internal and the external heat exchangers decreases by 2 % and 2.5 % respectively, and the heat recovery efficiency increases by 0.68 %. The reason for this is that the heat transfer distance between calcined petroleum coke in the heat exchanger center and the fin, the heat transfer area and the total heat transfer quantity are nearly constant. That is, the changes in the value of the calcined petroleum coke temperature at the heat exchanger outlet, the average heat transfer coefficient and the heat recovery efficiency are little. Thus, the effect of fin width is

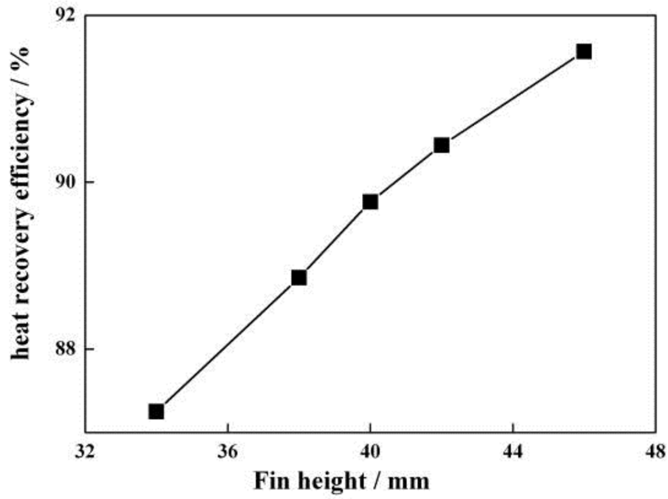

Fig. 11. Variations of heat recovery efficiency with different fin height

insignificant.

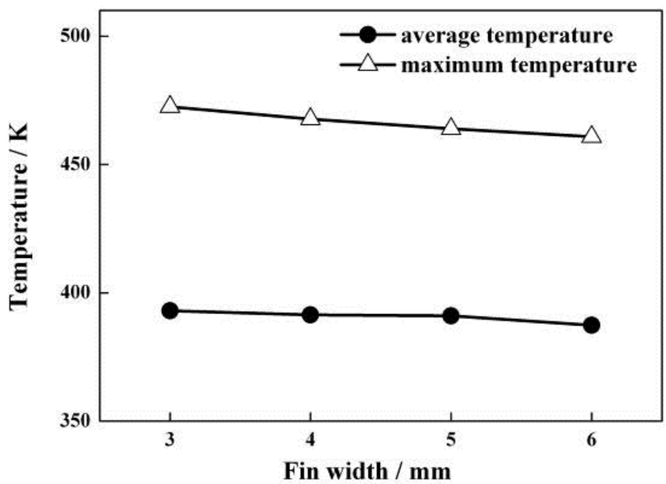

Fig. 12. Variations of temperature at the heat exchanger outlet with different fin widths

5. Conclusion

Whether it is the fin-tube or the light-tube, the temperature of the calcined petroleum coke is low, the wall of the heat exchanger tube and the temperature of the calcined petroleum coke is high in the center of the internal and the external

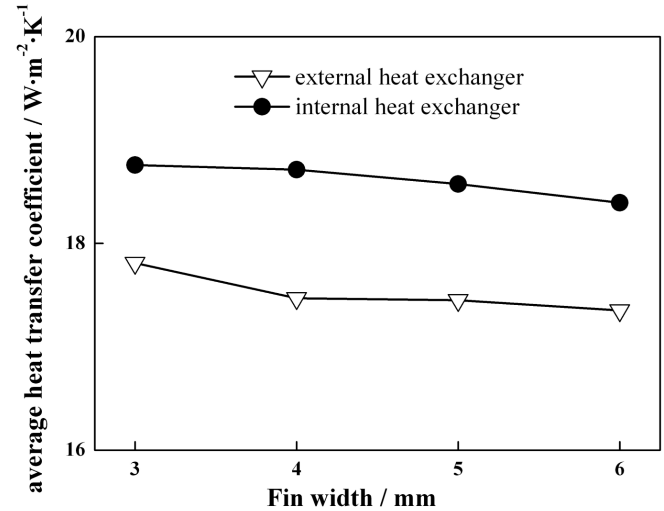

Fig. 13. Variations of average heat transfer coefficient with different fin widths

heat exchangers. Compared with the light-tube heat exchanger, the heat transfer performance of the straight-fin-tube heat exchanger is better. The temperatures of calcined petroleum coke in the straight-fin-tube heat exchanger decrease. With the increase of the fin height, the fin temperature increases slowly firstly. But the fin temperature increases dramatically when the fin height is greater than a critical value. The total heat flux increases from the fin top to the root in the same horizontal plane.

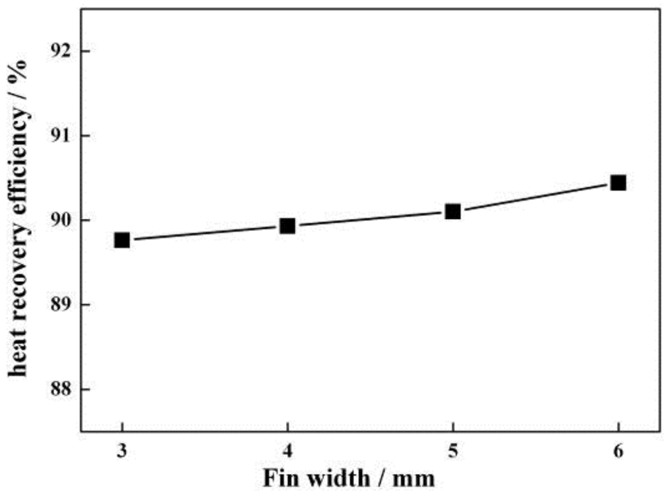

Fig. 14. Variations of heat recovery efficiency with different fin width

When the fin height increases from 34 mm to 46 mm, the average temperature of the calcined petroleum coke decreases from 415 K to 377 K, the maximum temperature decreases from 499 K to 443 K the average heat transfer coefficient of the internal and external heat exchangers increases by 12.5 % and 11.2 % respectively, and the heat recovery efficiency increases by 4.1 %. Therefore, the effect of the fin height is significant. When the fin width increases from 3 mm to 6 mm, the average temperature reduces by 5.6 K and the maximum temperature decreases by 11.7 K. The average heat transfer coefficient of the internal and the external heat exchangers decreases by 2 % and 2.5 %, respectively, and the heat recovery efficiency increases by 0.68 %. Thus, the effect of the fin width is small.

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