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Research Article

Heat Transfer Characteristics of Calcined Petroleum Coke in Waste Heat Recovery Process

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This paper reports the results of heat transfer characteristics of calcined petroleum coke in waste heat recovery process. The model of heat exchanger was set up. The model has been used to investigate the effects of porosity (0.58 to 0.79), equivalent heat conductivity coefficient (0.9 to 1.1), and equivalent specific heat (0.9 to 1.1). 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 calcined petroleum coke temperature at heat exchanger outlet, the average heat transfer coefficient, and the heat recovery efficiency were studied. It can also be used in deriving much needed data for heat exchanger designs when employed in industry.

1. Introduction

With the rapid development of economy in China, energy consumption has been increasing on a vast scale in recent years. The equivalent coal consumption of China was 3.75 billion tons in 2013 [1]. To solve this problem, it is widely believed that energy recycle is an effective measure to decrease energy consumption. In China's industrial production, waste heat resource is rich and various, such as waste heat from high temperature gas, coke slag, and other solid particles [2]. The researches on waste heat utilization of high temperature gas and liquid are relatively wide, and technology of waste heat recovery is relatively mature. However, the researches and technology of waste heat utilization of high temperature solid are not inadequate.

Calcined petroleum coke is one of the important basic raw materials. It is widely used in producing anode of aluminum electrolytic, graphite electrode, recarburizer, industrial silicon, and other carbon products. The production capacity of calcined petroleum coke in China is the largest in the world, over 70% of which is produced in tank calcined furnaces. When calcined petroleum coke is discharged from tank calcined furnaces, the temperature is 1000°C. The heat of high temperature calcined petroleum coke is about 33.5% of the total heat of calcination process [3]. The waste heat of it has high possibility to be utilized.

Waste heat reutilization of the solid particle has been studied in some field. Cai and Ding [4, 5] summarized the current energy consumption condition of steel industry and distribution of waste heat resource of steel production process. Wang et al. [6] analyzed the thermal equilibrium of molten slag heat recovery system and discussed the relationship between waste heat utilization efficiency and the amount of cooling air. The cooling process of steel slag particles in the moving bed was analyzed. Chen [7] simulated the waste heat recovery system of high temperature slag with fluent software, analyzed the flow field and temperature field of steel slag, and researched the change of temperature of air at outlet and heat recovery efficiency when the wind speed and air temperature at inlet are varied. Liu [8] proposed a new technology of fluidized bed. The waste heat of slag can be efficiently used with this technology. The flow and heat transfer process were simulated in fluidized bed with CFD software. Herz et al. [9] researched the heat transfer coefficient between moving material layer and the wall of bed through experiment. The effects of operational parameters, moving speed of material layer, and depth of buried material on heat transfer coefficient were studied. Atmakidis and

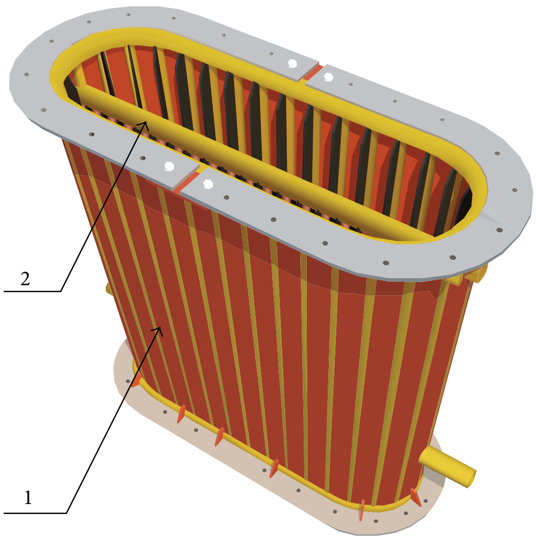

FIGURE 1: The structure of heat exchanger ((1) the external heat exchanger and (2) the internal heat exchanger).

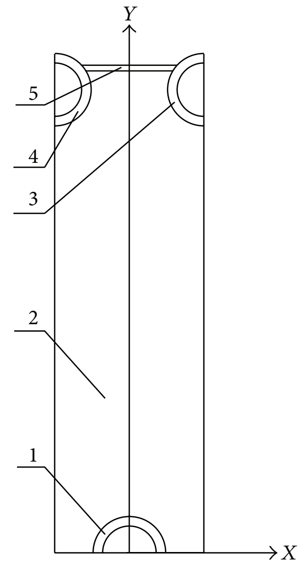

FIGURE 2: Simplified calculation model ((1) the internal heat exchange tube, (2) the calcined petroleum coke, (3) the 1st external heat exchange tube, (4) the 2nd external heat exchange tube, and (5) the diaphragm wall).

Kenig [10] simulated the movement of irregularly arranged particle near the wall with CFD. Sundaresan and Kolar [11] 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 location of the tube affected the heat transfer coefficient. Guo et al. [12] simulated the heat transfer in gas-solid fluidized bed with Euler-Euler method and obtained the effects of Reynolds number and porosity on heat transfer.

The investigations on the reutilization of calcined petroleum coke waste heat are lacking. In this paper, heat transfer characteristics of calcined petroleum coke in waste heat recovery process were studied.

2. Physical and Mathematical Description of the Problem

The waste heat of calcined petroleum coke is recovered by a heat exchanger. The heat exchanger of calcined petroleum coke includes an internal heat exchanger and an external heat exchanger. Its structure is shown in Figure 1. The external heat exchanger consists of tubes and a diaphragm wall, and the ends of tubes are held together by two ring pipes. Similarly the internal heat exchanger also consists of tubes, with the ends of tubes held together by a straight pipe. The calcined petroleum coke flows from top to bottom in the heat exchanger surrounded by tubes and diaphragm walls, and the water flows from bottom to top in the tubes. The temperature of calcined petroleum coke is high; the water temperature is low; so the heat is transferred to water from calcined petroleum coke.

In this paper, the calculated model of calcined petroleum coke heat exchanger is equal to the experimental heat exchanger model in scale. Considering the structure characteristic of the heat exchanger, the calculation model is appropriately simplified.

(1) The lower ring pipe and the upper ring pipe of the internal heat exchanger and the external heat exchanger will not be calculated.

(2) The calculated model includes two external heat exchanger tubes, one internal heat exchanger tube, and the region between the tubes and thermal barriers.

(3) The tube pitch is equal from top to bottom. Additionally the symmetry plane of calculation model is the plane where the short axis of the oval heat exchanger exists.

(4) The calcined petroleum coke particles of high temperature 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.

(5) Considering the thermal insulation layer outside the heat exchanger, it is assumed that there is no heat loss from the heat exchanger lateral.

According to the simplification above, the model has been set up by Gambit. The lengths of x and y axis are 78 mm and 262 mm. The height of the model is 1550 mm. It is shown as Figure 2.

When heat exchanges between the high temperature calcined petroleum coke and water, the mass, momentum, and energy conservation exist. In this paper, the unsteady model is used for calculation. The mass, momentum, and energy conservation equations are shown as follows.

The mass conservation equation is as follows:

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

where ρ is density, kg/m^3, t is time, s, and u, v, and w are the velocity vectors in x, y, and z coordinate directions, m/s.

The momentum conservation equation is as follows:

$$\begin{aligned}\frac{\partial(\rho u)}{\partial t}+\operatorname{div}(\rho u V)&=-\frac{\partial p}{\partial x}+\frac{\partial \tau_{xx}}{\partial x}+\frac{\partial \tau_{yx}}{\partial y}+\frac{\partial \tau_{zx}}{\partial z}+F_x,\\ \frac{\partial(\rho v)}{\partial t}+\operatorname{div}(\rho v V)&=-\frac{\partial p}{\partial y}+\frac{\partial \tau_{xy}}{\partial x}+\frac{\partial \tau_{yy}}{\partial y}+\frac{\partial \tau_{zy}}{\partial z}+F_y,\\ \frac{\partial(\rho w)}{\partial t}+\operatorname{div}(\rho w V)&=-\frac{\partial p}{\partial z}+\frac{\partial \tau_{xz}}{\partial x}+\frac{\partial \tau_{yz}}{\partial y}+\frac{\partial \tau_{zz}}{\partial z}+F_z,\end{aligned} \tag{2}$$

where p is pressure on the infinitesimal body, Pa, τ_{xx}, τ_{xy}, and τ_{xz} are stick stress component of τ on the infinitesimal body caused by molecular viscosity, N/m^2, F_x, F_y, and F_z are body forces, N/m^3, and V is velocity vector quantity, m/s.

The energy conservation equation is as follows:

$$\begin{aligned}&\frac{\partial(\rho T)}{\partial t}+\frac{\partial(\rho T u)}{\partial x}+\frac{\partial(\rho T v)}{\partial y}+\frac{\partial(\rho T w)}{\partial z}\\ &\quad=\frac{\partial}{\partial x}\left(\frac{k}{c_p}\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{k}{c_p}\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\frac{k}{c_p}\frac{\partial T}{\partial z}\right)\\ &\quad+S_T,\end{aligned} \tag{3}$$

where c_p is specific heat of water, J/(kg·K), k is effective heat transfer coefficient, W/(m·K), T is temperature of fluid, K, and S_T is viscous dissipation term.

The equations of the flow model in the pipe are as follows.

Turbulence intensity is

$$I=0.16\times R_e^{-0.125}. \tag{4}$$

Turbulent kinetic energy is

$$k=\frac{3}{2}\times(\overline{u}\times I)^2. \tag{5}$$

Turbulence kinetic energy dissipation rate is

$$\varepsilon=\frac{C_u{}^{3/4}k^{3/2}}{l}, \tag{6}$$

where I is turbulence intensity, R_e is Reynolds number of fluid, $\overline{u}$ is average fluid turbulent velocity, m/s, C_u is empirical constant, 0.09, and l is characteristic length, m.

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 the heat transfer between calcined petroleum coke and the wall of the heat exchanger. The heat transfer process in this paper is steady with no inner heat source, so the heat conduction differential equation is as follows:

$$\rho c\frac{\partial T}{\partial \tau}=\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right), \tag{7}$$

where ρ is density, kg/m^3, c is specific heat, J/(kg·K), T is temperature, K, and λ is coefficient of heat conductivity, W/(m·K).

The discrete points within the domain are solved. The implicit format of the unsteady heat conduction equation is used to solve problems in this paper:

$$\frac{T_n^{(i+1)}-T_n^{(i)}}{\Delta\tau}=a\frac{T_{n+1}^{(i+1)}-2T_n^{(i+1)}+T_{n-1}^{(i+1)}}{\Delta x^2}, \tag{8}$$

where $\Delta\tau$ is time step, s, T is temperature, K, n is the serial number of n node; i is the serial number of i temporal sequence; a is thermal diffusivity, m^2/s, and Δx is distance between two adjacent nodes, m.

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

$$q=k\cdot A\cdot\Delta T_m, \tag{9}$$

where q is heat flux, W, k is heat transmission coefficient, W/(m^2·K), A is heat exchange area, m^2, and ΔT_m is average temperature difference, K.

The calcined petroleum coke velocity, water velocity in the tube, and calcined petroleum coke temperature in the heat exchange inlet are constant. 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 using (10) [13]:

$$\lambda_e=\phi\lambda_f+(1-\phi)\lambda_s, \tag{10}$$

where λ_e is effective thermal conductivity coefficient, W/(m·K), ϕ is porosity, λ_f is thermal conductivity coefficient of gas, W/(m·K), and λ_s is thermal conductivity coefficient of solid, W/(m·K).

The effective specific heat of homogenous continuum is calculated using

$$C_{pe}=\phi C_{pf}+(1-\phi)C_{ps}, \tag{11}$$

where C_{pe} is effective specific heat, J/(kg·K), ϕ is porosity, C_{pf} is specific heat of gas, J/(kg·K), and C_{ps} is specific heat of solid, J/(kg·K).

When the heat exchanger model is meshed, the internal boundary is refined locally. The quantity and quality of the grid have a great influence on the calculation results. If the grids are much less, it cannot meet the precision request. If the grids are too dense, it will require sufficient computer memory. And the calculating time will increase. So it is critical to confirm the quantity of grids. The test of grid

Table 1: Comparison of the calculation 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	130442	647.8571	—
Scheme 2	215817	653.0132	0.796
Scheme 3	313721	657.2785	0.653
Scheme 4	467604	662.5237	0.798

independence has been widely used to solve this problem. There are four schemes for meshing. The quantity of grids is 130442, 215817, 313721, and 467604. When calculation is completed, the temperature of calcined petroleum coke at outlet is used as the evaluation standard. The calculation results are shown as in Table 1.

Table 1 showed that the relative change of Scheme 2 is within 2% compared to Scheme 1. There will be little influence on calculation results if grids are much dense. Therefore Scheme 2 not only reaches the calculation accuracy but also saves much time. So Scheme 2 was used for calculation.

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 1073 K, and the velocity of calcined petroleum coke in the heat exchanger is 6×10^{-5} m/s.

The heat recovery efficiency is calculated by

$$\eta = \frac{q_1 \cdot (h_{1\text{out}} - h_{1\text{in}}) + q_2 \cdot (h_{2\text{out}} - h_{2\text{in}}) + q_3 \cdot (h_{3\text{out}} - h_{3\text{in}})}{c \cdot q_4 \cdot T} \times 100\%, \quad (12)$$

where η is heat recovery efficiency, %, q_1 is water flow mass of 1st external heat exchange tube, kg·s^{-1}, $h_{1\text{out}}$ is enthalpy value of water in 1st tube outlet, kJ·kg^{-1}, $h_{1\text{in}}$ is enthalpy value of water in 1st tube inlet, kJ·kg^{-1}, q_2 is water flow mass of 2nd external heat exchange tube, kg·s^{-1}, $h_{2\text{out}}$ is enthalpy value of water in 2nd tube outlet, kJ·kg^{-1}, $h_{2\text{in}}$ is enthalpy value of water in 2nd tube inlet, kJ·kg^{-1}, q_3 is water flow mass of internal heat exchange tube, kg·s^{-1}, $h_{3\text{out}}$ is enthalpy value of water in internal heat exchange tube outlet, kJ·kg^{-1}, $h_{3\text{in}}$ is enthalpy value of water in internal heat exchange tube inlet, kJ·kg^{-1}, c is specific heat capacity, kJ·kg^{-1}·K^{-1}, q_4 is calcined petroleum coke flow mass, kg·s^{-1}, and T is temperature of calcined petroleum coke when it flows into the heat exchanger, K.

The definition of the equivalent heat conductivity coefficient is the ratio of the actual heat conductivity coefficient to the standard heat conductivity coefficient. The standard heat conductivity coefficient is the actual heat conductivity coefficient of the calcined petroleum coke porosity which is 0.7.

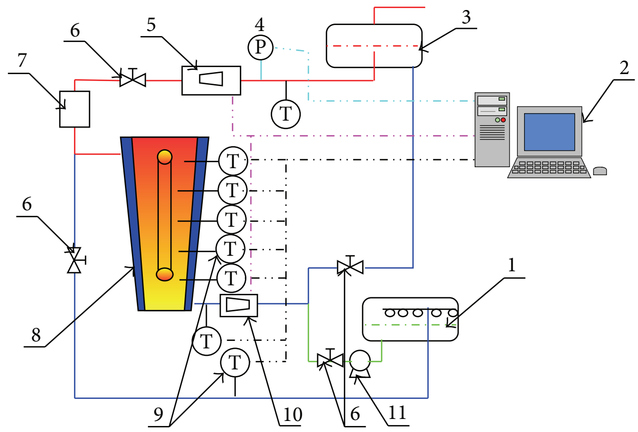

Figure 3: Schematic of experimental system ((1) the cooling pond; (2) the data acquisition system; (3) the drum; (4) the pressure sensor; (5) the two-phase flowmeter; (6) valve; (7) the sight glass; (8) the waste heat exchanger; (9) the temperature sensor; (10) the flowmeter; (11) the pump).

The definition of the equivalent specific heat is the ratio of the actual specific heat to the standard specific heat. The standard specific heat is the actual specific heat of the calcined petroleum coke porosity which is 0.7.

3. Experimental System

The experimental system of the 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 (Figure 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 supplied directly from the tank calcined furnace. The water circulation system is composed of cooling pond, pumps, valves, sight glass, a drum, and so on. There is a WSM-D two-phase flowmeter in the heat exchanger outlet, which is used to measure 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 ±0.5%. Its measuring velocity range is from 0.01 m/s to 25 m/s. Its repeatability is 0.15%.

The measurement system is composed of a temperature sensor, a pressure sensor, and a piece of data acquisition instrument. The temperature sensor is used to measure the temperature of water in the heat exchanger inlet, the temperature of calcined petroleum coke in heat exchanger, the temperature of steam in the heat exchanger outlet, and so on. The pressure sensor is used to measure the water pressure and the steam pressure. The data acquisition instrument is used to record the data. The temperature measuring points of calcined petroleum coke in the heat exchanger are shown in Figure 4.

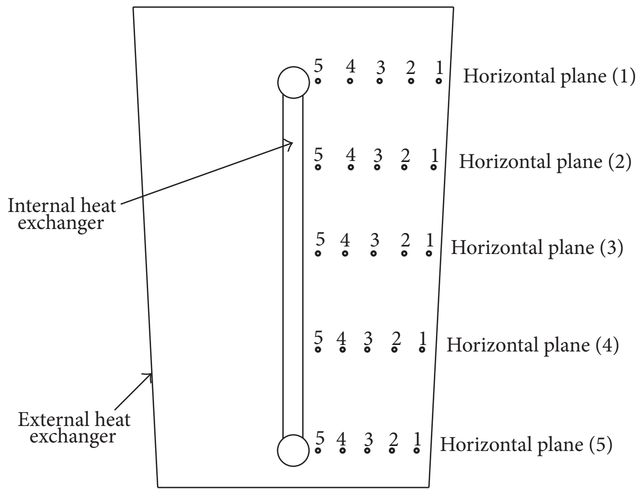

Figure 4: Temperature measuring points of calcined petroleum coke in the waste heat exchanger.

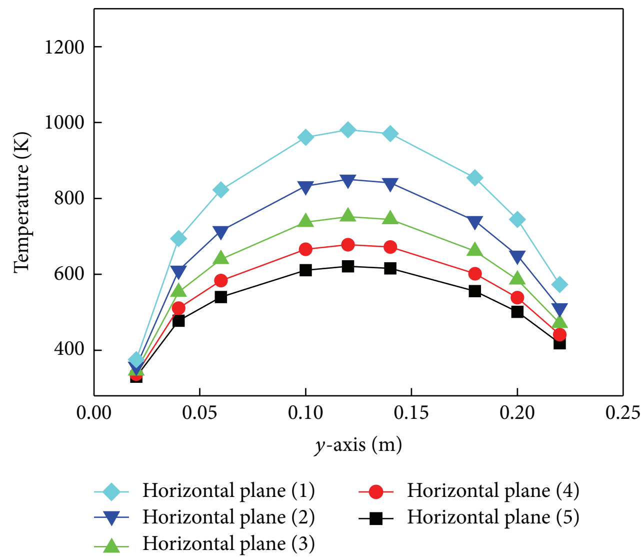

Figure 6: The temperature distribution of calcined petroleum coke.

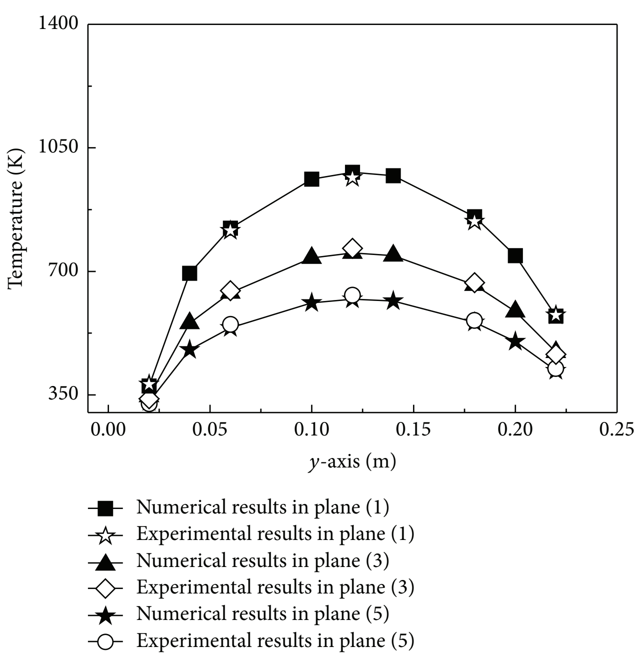

Figure 5: The temperatures of numerical and experimental result.

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. Figure 5 shows the temperatures of numerical and experimental results in different planes when the porosity is 0.7. The temperature difference of numerical and experimental results is 16 K and the relative error is 1.78%. The results are in good agreement with the experimental value obtained in the same conditions.

4.2. Temperature Distribution Characteristics in the Heat Exchanger. Figure 6 shows the temperature distribution of calcined petroleum coke in the heat exchanger for the porosity which is 0.7. Figure 6 indicates that the temperature of calcined petroleum coke is low near the wall of the heat exchanger tube and the temperature differences are small in different planes. The temperature difference of the first plane and the fifth plane is only 19 K, while, in the center of the internal and external heat exchangers, the temperature of calcined petroleum coke is high and the temperature differences of different planes are great. The temperature difference of the first plane and the fifth plane is 359 K. The main reason is that the coefficient of the heat conductivity of calcined petroleum coke is very low. The longer the distance of the heat transfer is, the bigger the heat resistance of calcined petroleum coke is and accordingly the higher the temperature is.

4.3. Effect of Calcined Petroleum Coke Porosity. Figure 7 shows the effects of porosity on calcined petroleum coke temperature at the outlet of the heat exchanger. Figure 7 shows that when the porosity increases from 0.58 to 0.79, the average temperature of calcined petroleum coke decreases from 541 K to 489 K and the maximum temperature decreases from 650 K to 582 K. The main reason is that, with the increase of porosity, the effective specific heat and the effective density decrease and the initial total heat quantity reduces, which make the temperature of calcined petroleum coke decrease at the heat exchanger outlet. However, with the increase of porosity, the effective heat conductivity coefficient decreases. So the ability of the heat conductivity decreases, which makes the temperature of calcined petroleum coke increase at the heat exchanger outlet. But the effect of the initial total heat quantity reduction is a major influence factor, so the calcined petroleum coke temperature decreases with the increase of porosity.

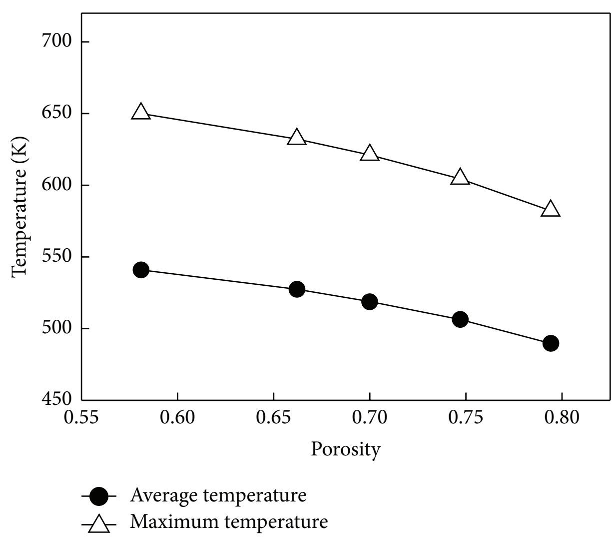

FIGURE 7: Variations of temperature at the heat exchanger outlet with different calcined petroleum coke velocity porosity.

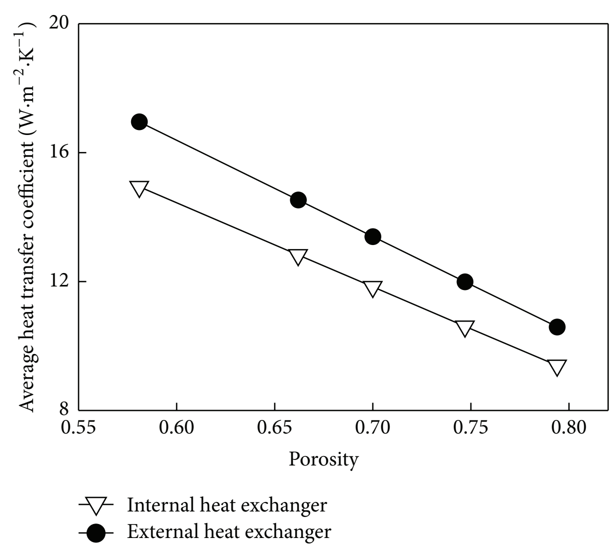

FIGURE 8: Variations of average heat transfer coefficient with different calcined petroleum coke velocity porosity.

Figure 8 shows the effects of porosity on average heat transfer coefficient. As can be seen from Figure 8, the average heat transfer coefficient of the internal heat exchanger is higher than the external heat exchanger. When the porosity increases from 0.58 to 0.79, the average heat transfer coefficients of the internal and the external heat exchanger decrease by 6.4 and 5.6 $W/(m^2{\cdot}K)$, respectively. The reason for this is that, with the increase of porosity, the effective specific heat and effective heat conductivity coefficient decrease and the average heat flux of the heat exchanger tube wall decreases. At the same time, with the decrease of the effective specific heat, the initial total heat quantity reduces while the cooling rate of calcined petroleum coke increases, so the average heat transfer temperature difference decreases. However, the effect

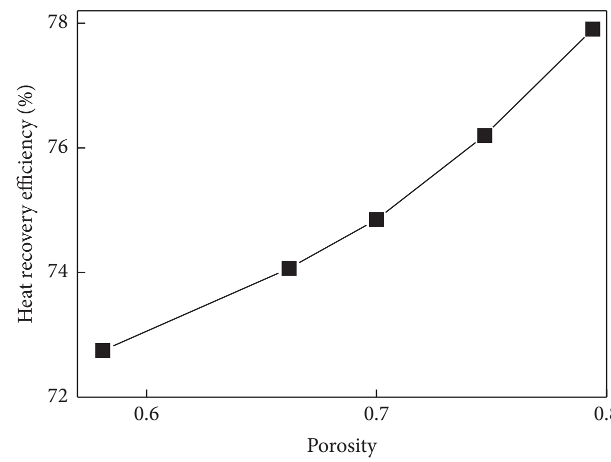

FIGURE 9: Variations of heat recovery efficiency with different calcined petroleum coke velocity porosity.

of heat exchanger tube average heat flux is a major influence factor, so the average heat transfer coefficient decreases with the increase of porosity.

Figure 9 shows the effects of porosity on heat recovery efficiency. Figure 9 shows that the heat recovery efficiency increases by 5.2% when the porosity increases from 0.58 to 0.79. The main reason is that when the porosity increases, the initial total heat quantity and the heat recovery quantity reduce. But the reduce rate of the initial total heat quantity is higher than that of the reduce rate of heat recovery quantity, and thus the heat recovery efficiency increases.

4.4. Effect of Equivalent Heat Conductivity Coefficient. The normal value of heat conductivity coefficient is the effective heat conductivity coefficient when the calcined petroleum coke porosity is 0.7. The definition of the equivalent heat conductivity coefficient is a ratio of the objective heat conductivity coefficient and the normal value.

Figures 10–12 show the effects of equivalent heat conductivity coefficient at the calcined petroleum coke temperature at the heat exchanger outlet, the average heat transfer coefficient, and the heat recovery efficiency. As can be seen from Figures 10–12, when the equivalent heat conductivity coefficient increases from 0.9 to 1.1, the average temperature reduces by 35 K and the maximum temperature decreases by 50 K, the average heat transfer coefficient of the internal and external heat exchanger increases by 2.8 and 2.6 $W/(m^2{\cdot}K)$, respectively, and the heat recovery efficiency increases by 4.3%. The reason for this is that, with the increase of the equivalent heat conductivity coefficient, the heat resistance of calcined petroleum coke decreases, the heat transfer quantity in unit time increases, the temperatures at the heat exchanger outlet reduce, and the average heat transfer coefficient and the heat recovery efficiency increase.

4.5. Effect of Equivalent Specific Heat. The normal value of specific heat is the effective specific heat when the calcined petroleum coke porosity is 0.7. The definition of equivalent

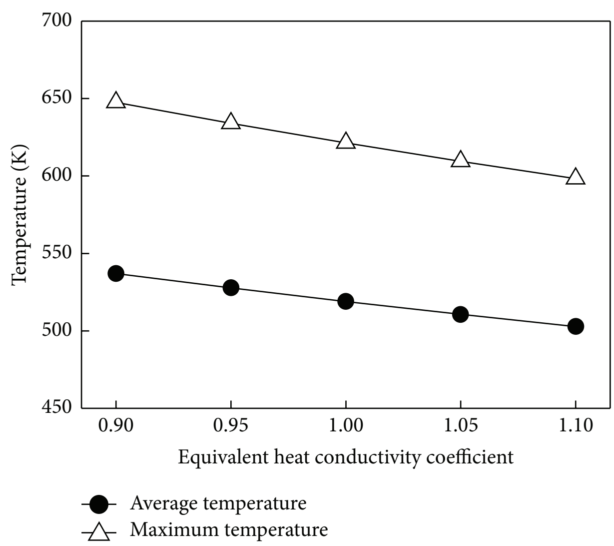

Figure 10: Variations of the temperature at the heat exchanger outlet with different equivalent heat conductivity coefficients.

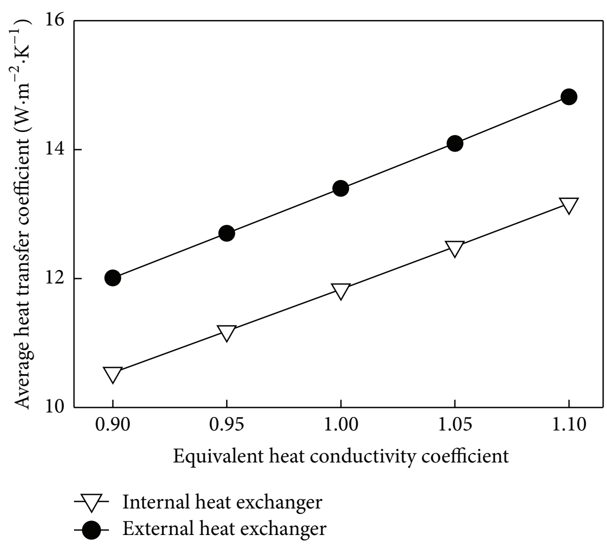

Figure 11: Variations of the average heat transfer coefficient with different equivalent heat conductivity coefficients.

specific heat is a ratio of the objective specific heat and the normal value.

Figure 13 shows the effects of equivalent specific heat on calcined petroleum coke temperature at the heat exchanger outlet. Figure 13 shows that when the equivalent specific heat increases from 0.9 to 1.1, the average temperature of calcined petroleum coke increases from 501 K to 535 K and the maximum temperature increases from 595 K to 644 K. The main reason is that when the equivalent specific heat increases, the initial total heat quantity heat increases and when the heat conductivity coefficient of calcined petroleum coke is a constant, the calcined petroleum coke temperature at the heat exchanger outlet increases.

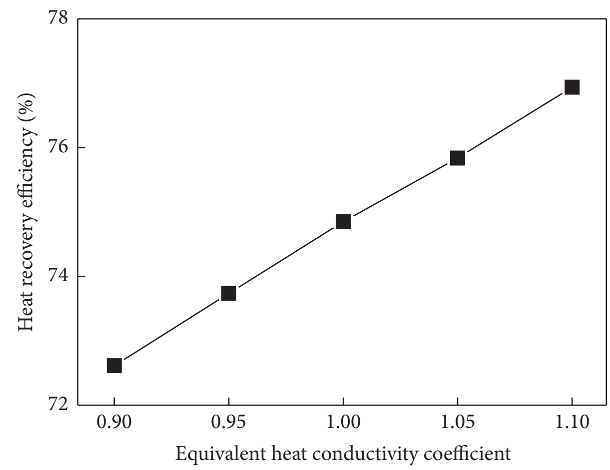

Figure 12: Variations of the heat recovery efficiency with different equivalent heat conductivity coefficients.

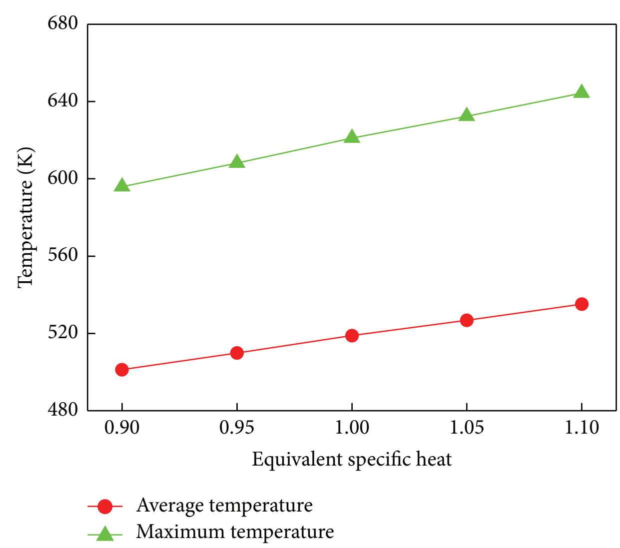

Figure 13: Variations of the temperature at heat exchanger outlet with different equivalent specific heat.

Figure 14 shows the effects of equivalent specific heat on average heat transfer coefficient. As can be seen from Figure 14, when the equivalent specific heat increases from 0.90 to 1.10, the average heat transfer coefficients of the internal and external heat exchanger decrease by 0.16 and 0.28 W/(m^2·K), respectively. In other words, the effect is very small.

Figure 15 shows the effects of the equivalent specific heat on heat recovery efficiency. Figure 15 shows that the heat recovery efficiency decreases by 4.1% when the equivalent specific heat increases from 0.90 to 1.10. The main reason is that when the heat transfer time is a constant, with the increase of equivalent specific heat, the initial total heat quantity heat increases, the heat transfer sufficiency decreases, and the heat recovery efficiency reduces.

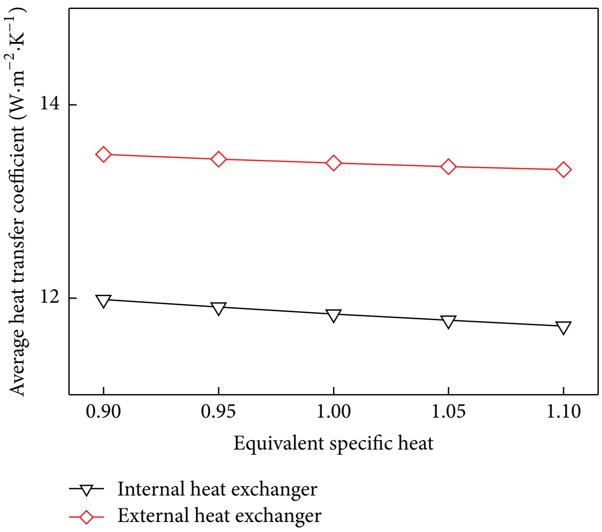

Figure 14: Variations of the average heat transfer coefficient with different equivalent specific heat.

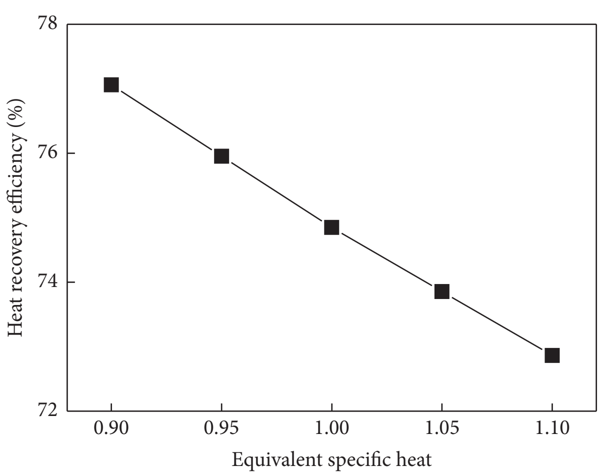

Figure 15: Variations of the heat recovery efficiency with different equivalent specific heat.

5. Conclusions

The main conclusions of the present study are as follows.

(1) The temperature of calcined petroleum coke is low near the wall of the heat exchanger tube, and the temperature differences are small in different planes, while, in the center of the internal and external heat exchangers, the temperature of calcined petroleum coke is high and the temperature differences of different planes are great.

(2) When the porosity increases from 0.58 to 0.79, the average temperature of calcined petroleum coke at the outlet of the heat exchanger decreases from 541 K to 489 K and the maximum temperature decreases from 650 K to 582 K. The average heat transfer coefficients of the internal and external heat exchanger decrease by 6.4 and 5.6 W/(m^2·K), respectively. The heat recovery efficiency increases by 5.2%.

(3) With the increase of the equivalent heat conductivity coefficient (from 0.9 to 1.1), the average temperature reduces by 35 K and the maximum temperature decreases by 50 K, the average heat transfer coefficients of the internal and external heat exchanger increase by 2.8 and 2.6 W/(m^2·K), respectively, and the heat recovery efficiency increases by 4.3%.

(4) If the other conditions remain the same, when the equivalent specific heat increases from 0.9 to 1.1, the average temperature of calcined petroleum coke increases from 501 K to 535 K and the maximum temperature increases from 595 K to 644 K. The average heat transfer coefficient of the internal and external heat exchanger decreases by 0.16 and 0.28 W/(m^2·K), respectively. The heat recovery efficiency decreases by 4.1%.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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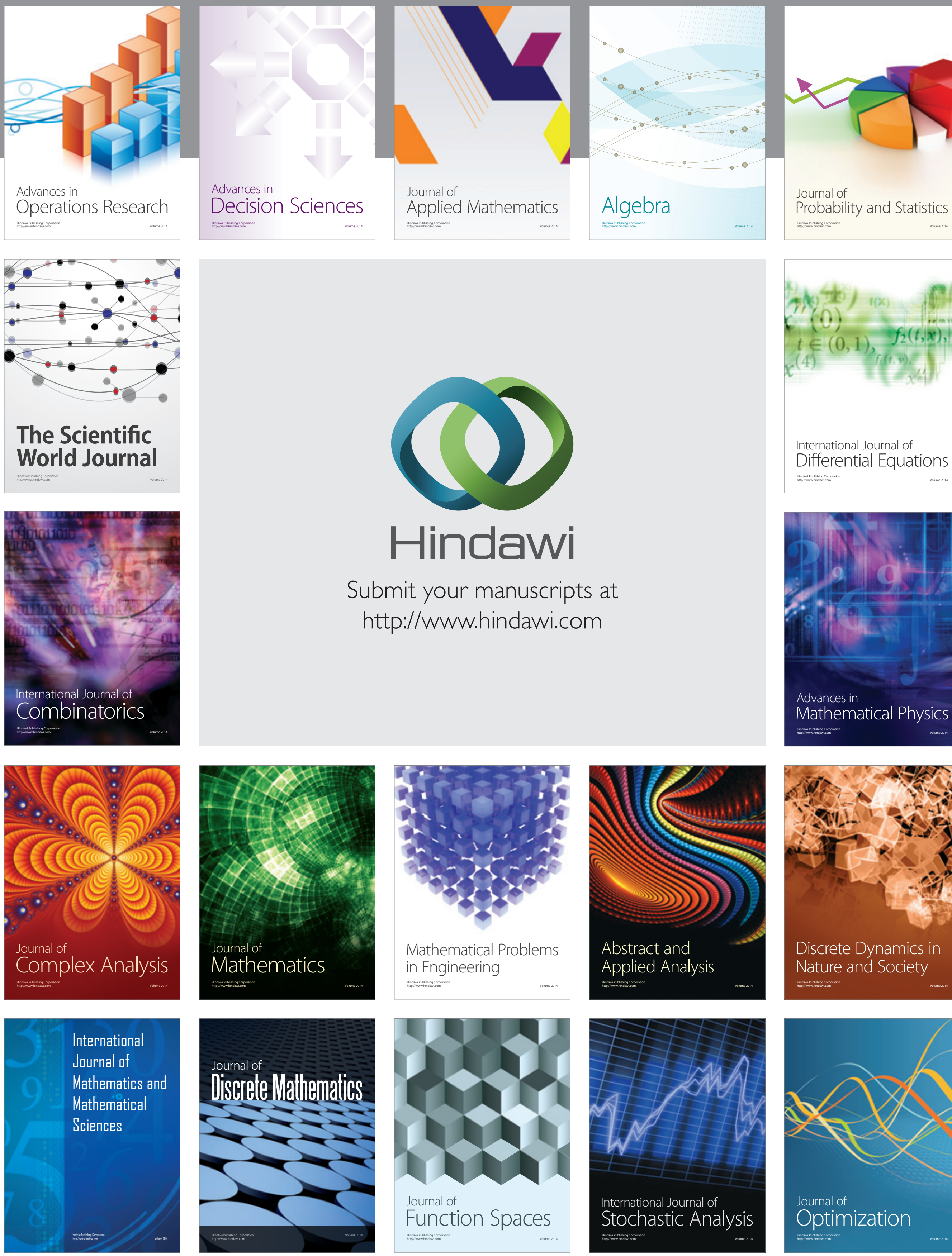
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