Heat transfer characteristics of activated coke in the moving bed for sulphur resource recovery

Gongpeng Wu, Rongsheng Tang, Yiyu Wang, Yan He*

College of Mechanical and Electrical Engineering, Qingdao University of Science and Technology, Qingdao, China

*Corresponding author e-mail: heyanqustjd@163.com

Abstract. A counter-flow moving bed and tube heat exchanger was designed and built for the heat transfer process of activated coke desorption, the heat transfer law between particles and tube wall surface in the moving bed was studied. The results show that with the increase of hot air inlet temperature and moving velocity of activated coke particles, the heat transfer coefficient inside the tube largely increases and then remains a small change. As the air velocity increases, the heat transfer coefficient inside the tube also shows increasing trend. In addition, with the increase of air temperature and particles moving velocity, total heat transfer coefficient of the moving bed and heat transfer coefficient outside tube increase first and then decrease. Finally, based on experimental data, the correlation coefficient of heat transfer coefficient outside the tube is obtained.

1. Introduction

With the rapid development of economy, the coal has been largely consumed as one of the primary energies. Hazardous substances such as sulfide and nitride released by coal combustion are making environment pollution get graveness. The SO₂ pollutant removal is the key process in the field of air pollution control. Thus, it is critical to explore and develop a technique with high desulfurization efficiency and low operating costs. Dry flue gas desulfurization is an advanced technology which can achieve sulphur resource recovery [1, 2]. As a novel adsorbent for dry desulfurization, powder activated coke has small high diffusion drag in comparison with columnar [3] activated coke, high mechanical strength and low manufacture cost. The regeneration progress of activated coke mainly occurs in shell-tube moving bed under the high temperature condition. The heat transfer efficiency of shell-tube moving bed directly affects the desorption rate of the activated coke [4, 5], and further affects the efficiency of the entire regeneration process. Therefore, the study on the heat transfer law of powdered activated coke in moving bed is significant and provide guidance for the sulphur resource recovery. Sun [6], Zhang [7] and Ding [8] analyzed the overall heat transfer mechanism of the traditional columnar activated coke in terms of theory and experiment. They established the total heat transfer resistance model from the tube wall to the activated coke particle and explored the effects of various heat transfer factors on the total heat transfer. Although there are many studies on the heat transfer characteristics of activated coke in moving bed, most of them only focus on the columnar active coke, rather than powder activated coke.

This paper aims to study the heat transfer characteristics of the sulfur resolution process in the moving bed. In experiment, we mainly considered the influence of the air velocity $u_a$ and air inlet temperature.
in the heat exchanger, and the moving velocity of particles $u_s$ in the moving bed, on the heat transfer law of powder coke in moving bed. Then, the theoretical analysis was conducted based on experimental data.

2. Experiment

2.1. Experiment material
The average particles size and bulking density are 74 µm, 0.728 g/cm$^3$, respectively. The specific heat capacity ($25^\circ$C) is 1.15 J/(g·K) and the thermal conductivity ($25^\circ$C) is 0.1448 W/(m·K).

2.2. Experiment apparatus

1-Air heater; 2-Circulation tube; 3-High temperature centrifugal fan; 5-Tee 7-Frequency converter control; 8,9-Thermocouple; 10-Vortex flowmeter; 11-Storage hopper; 12-Moving bed; 13-Heater casing; 14-Discharge valve; 15-Thermocouple on moving bed wall; 16-Thermocouple inside moving bed wall; 17-Data acquisition analyzer

**Figure 1.** Diagram of experimental device.

The experimental setup was shown in Fig1. The length of moving bed heat exchanger is 1440 mm. The diameter of internal tube is 89 mm and the diameter of external tube is 149 mm. The moving bed and the air circulation pipe were covered with insulation cotton to prevent heat loss. In experiment, air was first heated in air heater and the high-temperature centrifugal fan delivered hot air to the space formed the internal tube of moving bed and the external shell. The powder activated coke as moved down in the moving bed. The moving velocity was depended on twin screw extruder discharge valve. The hot air passed through the moving bed and then returned to the air heater through the circulating pipe. when the system stops heating, the tee was used to avoid deformation of the pipe caused by excessive vacuum due to excessive cooling.

Ten thermocouple sensors were arranged on the moving bed heat exchanger. Five sensors lay on moving bed wall and the rest was inside the moving bed wall. The five measuring points are 120 mm, 370 mm, 620 mm, 870 mm and 1120 mm above the bottom of the heating section of the moving bed.

3. Data Processing

3.1. Heat transfer coefficient inside the tube
Heat transfer inside the tube (i.e., from tube wall to activated coke) is defined as follow:

$$h = \frac{\Phi_c}{A \Delta T_{mc}}$$  \hspace{1cm} (1)

Where, $\Phi_c$—Heat transfer capacity of powder activated coke; $\Delta T_{mc}$—Logarithmic mean temperature difference; $A$—Heat transfer area of moving bed.
3.2. Heat transfer coefficient outside the tube

The total heat transfer coefficient $K$ of the moving bed can be expressed as follows:

$$K = \frac{1}{d_o h_o} + \frac{d_o - d_i}{\lambda_o} + \frac{d_i}{d_m h_i}$$  \hspace{1cm} (2)

Thermal resistance of the tube wall of the moving bed can be neglected because the wall thickness between thermocouple and particles was small. Thus we thought that $d_o=d_i=d_m$, The heat transfer coefficient outside the tube can be obtained from Eq. (3):

$$h_o = \frac{1}{\frac{1}{K} - \frac{1}{h_i}}$$  \hspace{1cm} (3)

3.3. Total heat transfer coefficient

The formula for calculating the total heat transfer is as follows:

$$K = \frac{\Phi_a}{A \Delta T_{ma}}$$  \hspace{1cm} (4)

Where, $\Phi_a$—Heat transfer capacity of hot air; $\Delta T_{ma}$—Logarithmic mean temperature difference of moving bed.

4. Result and discussion

4.1. Variation of heat transfer coefficient in tube

![Figure 2. Relationship between inlet temperature of hot air and heat transfer coefficient.](image)

When the moving velocity of activated coke particles was 6.2 cm/min and the air velocity was 7.94 m/s, the effects of the air inlet temperature $T_a$ on the heat transfer performance of moving bed were shown in Fig. 2. With the increase of inlet temperature the heat transfer coefficient increases rapidly and then increase at $T_a = 220$ °C, heat transfer coefficient inside tube reaches maximum value. As the temperature of activated increases, the air inlet temperature has a increase. However, the specific heat capacity of activated coke particles was larger than that of air. Thus the temperature difference between particles and air in shell gradually increases. At the same time, activated coke particles can absorb additional heat and the heat transfer load increases. As can be seen from Fig. 2, the effect of inlet air temperature on total heat transfer coefficient was attenuated. When inlet temperature of air exceeds a certain value, the heat transfer coefficient inside the tube no longer increases significantly.
Figure 3. Relationship between particle moving velocity and heat transfer coefficient.

When the velocity of hot air was 7.26 m/s and the inlet temperature of air was 180 °C, experimental studies were carried out to investigate the effect of particle velocity on heat transfer coefficient. We can be seen from Fig. 3, the heat coefficient increases with the increase of moving speed of activated coke particles. When the moving velocity of particles increases from 3.8 cm/min to 6.5 cm/min, heat transfer coefficient increased from 12.08 W/(m²·°C) to 14.32 W/(m²·°C). This result indicates that the falling speed of activated coke particles has a great influence on heat transfer coefficient inside the tube. With the increases of the moving speed of particles, the temperature difference between the air and the particles inside the tube increases, enhancing heat effects. As the moving velocity of the particles rise to 6.5 cm/min, the heat transfer coefficient has a reduced tendency, because the large moving velocity of particles shortens heating time. Thus the incomplete heating occurs, leading to the reduction of heat transfer effect.

Figure 4. Relationship between air velocity and heat transfer coefficient.

When inlet temperature of hot air in shell side was 180 °C and moving velocity of particles was 6.2 cm/min, the influence of air velocity on heat transfer performance of moving bed was shown in Fig. 4. The results show that high air velocity results in a high heat transfer coefficient. The temperature of heat air remains a high level due to increasing air velocity. Caloric supplementation is rapid and the quality of heat absorbed by particles is limited, leading to high temperature difference between air and particle. Moreover the convective heat transfer coefficient between hot air and wall increases with the increasing air velocity. Therefore particle side can absorb more heat, and the heat transfer coefficient inside tube inevitably increases.
4.2. Total heat transfer coefficient and convection heat transfer coefficient outside the tube

Figure 5. Relationship between air temperature, particle moving velocity and heat transfer coefficient.

The variations of the total heat transfer coefficient and the heat transfer coefficient outside the tube under different conditions are shown in the Fig. 5. In Fig. 5, the total heat transfer coefficient and the heat transfer coefficient outside the tube both increase first and then decrease. The increase of the air temperature leads to an increase in the kinematic viscosity and thermal conductivity of the air. The increase of the air kinematic viscosity reduces the heat transfer coefficient between the air and the wall and the increase of the thermal conductivity enhances the heat transfer coefficient. In Fig. 5, the increase of air temperature leads to an increase in thermal conductivity of the air and the heat transfer coefficient outside the tube. When the temperature increases to a certain temperature, the influence of the kinematic viscosity on the heat transfer coefficient is enhanced, resulting in a tube. Therefore, the external heat transfer coefficient first increases and then decreases. Meanwhile the heat transfer coefficient outside the tube has a great influence on the total heat transfer coefficient. This induces the that total heat transfer coefficient also increases first and then decreases, as shown in Fig. 5. In Fig. 6, the increased air velocity enhances the convective heat transfer between the air and the tube. Thus the total heat transfer coefficient bed and the heat transfer coefficient outside the tube are significantly increase.

Figure 6. Relationship between air velocity and heat transfer coefficient

4.3. Correlation of convective heat transfer outside the tube

In the moving bed, air keeps a fully developed turbulence flow. Many scholars have put forward many empirical formulas of air convection heat transfer. Under different experimental conditions, the parameters in the empirical relationship also vary greatly. Generally, the calculation of convective heat transfer coefficient is related to Nusselt number and Prandtl number. According to the data obtained, the correlation of the convective heat transfer outside the tube can be obtained.

\[
\frac{Nu}{Pr^{1/3}} = \frac{C}{Pr} Re^n
\]  \hspace{1cm} (5)

\[
\lg \frac{Nu}{Pr^{1/3}} = \lg C + n \lg Re
\]  \hspace{1cm} (6)
According to the Eqs. (5)-(6), the linear fitting was carried out. The results of $C$ and $N$ are 0.0184 and 0.8126, respectively. For the turbulent heat transfer process outside the tube, the relationship is shown in Eq. 7.

$$\text{Nu} = 0.0184 \text{Pr}^{1/3} \text{Re}^{0.8126}$$

5. Conclusion

1. As the air velocity, air temperature and particle moving velocity increase, the heat transfer coefficient has a noticeable increase.

2. The overall coefficient of heat transfer and convective heat transfer coefficient outside the tube increase first and then decline with the increase of air inlet temperature and particle moving velocity. The total heat transfer coefficient of moving bed and the heat transfer coefficients outside the tube significantly increase as the air velocity increases.

3. According to the data association analysis, the correlation of the turbulent heat transfer outside the tube is obtained. Specifically, $\text{Nu} = 0.0184 \text{Pr}^{1/3} \text{Re}^{0.8126}$.

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