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Orthogonal Optimization Experiment of Steam and Semi-coke Heat Recovery Process

Xiaoyi Song, Peng Sun, Yanxia Wang, Yongqi Liu

***Abstract*— The material particle diameter, bed height, steam flow is the main factors in affecting steam for the semi-coke waste heat recycled. In order to study the effect of these factors on the recovery of residual heat and steam energy increased, a gas-solid heat transfer experimental system was established. The three factors were optimized to improve the waste heat recovery of the semi-coke, and the optimal combination of these factors was approved by orthogonal experimental method. The results showed that reduce the average particle size, improve the steam flow rate, increased the thickness of the material layer is beneficial to the increase of waste heat recycled. The optimum combination of factors is 7.5kg·h-1 of steam flow, the average particle size of particles is 0.009m, and the thickness of the material layer is 0.6m. The influence degree of the waste heat recovery is particle size, steam flow and layer thickness in turn.**

***Index Terms*— semi-coke; heat recovery; particle size; bed height; steam flow**

I. Introduction

Semi-coke is a kind of solid carbon product, which is obtained by high volatile coal with no caking property or weak caking property. According to the difference of pyrolysis temperature, it can be divided into three types: low temperature semi-coke, medium temperature semi-coke and high temperature semi-coke. It is a product of deep processing of coal. Semi-coke can replace general coke in ferrosilicon, calcium carbide, chemical and other industries. Semi-coke has great potential in the metallurgical fuel, adsorption materials, synthesis gas fields[1-2]. At present, China's coke production scale has exceeded 100 million tons, coke furnace equipment and technology is relatively mature, but the production process is widely used in water quenching method for cooling coke, the heat have not been fully utilized, resulting in a huge waste of energy. Research on gas-solid heat transfer characteristics in semi-coke heat exchanger is conducive to the improvement of energy using efficiency.

Many scholars have studied the gas-solid heat transfer and achieved fruitful results. Jian Yang et al. studied the gas-solid heat transfer coefficient by circular and elliptical bearing steel[3-4]. Wu J et al. studied the influence of several factors on the heat transfer coefficient in the moving bed, such as the contact time, the size of the contact surface between the particles[5]. The change trend of the equivalent thermal conductivity coefficient is studied by using different particle diameter steel beads to simulate the heat transfer experiment[6]. Abdulmohsin et al. measured the effective heat transfer coefficient and radial distribution of the convection in the sphere filled bed[7]. Wu J studied the change rule of the effective heat transfer coefficient between the heating pipe wall and the material layer in the indirect heating tube type rotary dryer[8]. In the field of waste heat utilization of sinter, many scholars have studied the methods to improve the utilization of waste heat in sinter[9-12]. Kong N et al. summarized the research status and development trend of heat transfer process in the dry quenching furnace[13]. Hu G et al. established a physical mathematical model to study the distribution of gas-solid temperature in the particle layer of the bed in different circumstances[14]. Du J et al. analyzed the cooling process of the fixed bed with internal heat source porous media[15]. To sum up, domestic and foreign scholars have researched little on the heat transfer characteristics of steam and semi-coke in the cooling process of semi-coke. Some important operating factors (such as steam flow rate, etc.) and particle characteristics factors (such as size, material thickness, etc.) on the influence of the gas-solid heat transfer characteristics in semi-coke stove is not entirely clear.

In order to further understand the heat transfer characteristics between steam and semi-coke, this paper established the steam carbon heat transfer experiment system to study the effect of various factors on the recycled waste heat. Provides the theoretical basis for waste heat utilization, energy conservation and emissions reduction.

II. Experiment

A. *Principle and Operation*

In the production process of semi-coke, semi-coke top-down moved slowly, discharged at the bottom of furnace after coke quenching. In the process of the coke quenching, steam upward moved from the bottom to strengthen the heat transfer. Because of semi-coke move slowly down, the velocity of movement is about 20cm/h, it can be ignored compared with the vapor velocity. So in this experiment, the static coal is heated to 600℃, then the steam is passed through the bottom, and studied the convection heat transfer characteristics.

In the process of the experiment, it is necessary to ensure that the semi-coke can reach the working temperature and prevent the oxidation of the particles. This experiment adopted the way that discharged air from the experimental tube by adding nitrogen.

In this paper, designed and built up the steam and semi-coke heat transfer platform, experiment system as shown in figure 1. The system is composed by electric heater, temperature

Xiaoyi Song Graduated from Shandong University of Technology and got bachelor degree. Major in dynamics. He is researching on heat recovery.
Peng Sun Graduated from Xian Transport University and got doctor degree. Major in energy and power engineering.
Yanxia Wang Graduated from Shandong University, acquired master's degree in China Agricultural University. Major in dynamics.
Yongqi Liu Graduated from Shandong University, acquired master's degree in University of Shanghai for Science and Technology. Major in energy and power engineering.

collection device, flow recorder, steam generator, nitrogen tank, fixed support, experimental tube, stainless steel mesh, insulation layer and flue gas analyzer. Among them, 304 stainless steel is used as the whole material of the experiment table. The electric heating system consists of ceramic electric heating ring and the electric control box, the heating power is 11kw. Ceramic electric heating ring is closely attached to the outer wall of the experimental tube, the main function is to heat the semi-coke particles, and adding insulation layer on the outer layer. The temperature collection system is composed of the K thermocouple, USB temperature acquisition card and computer, which can be used to record the temperature of the steam and the bed in the experiment tube. The steam generator provides saturated steam for the experiment, the mass flow rate (kg/h) and the heat flux (kJ/h) of the inlet and outlet steam are measured by the flow recorder, the measurement accuracy is 0.001.

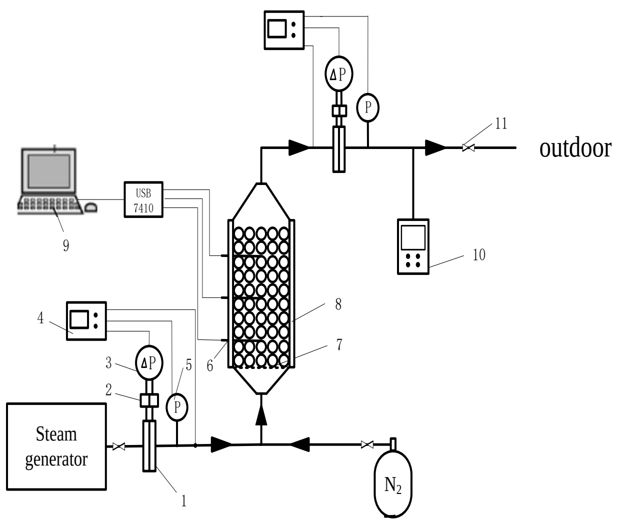

Fig.1. Schematic of the experimental system

1-Pore plate; 2-Condenser; 3-Differential pressure transmitter; 4-NHR-6600R Flow recorder; 5-Pressure transmitters; 6-Thermocouple; 7-Metal net; 8-Electric heating circle; 9-Computer ；10-Fluegas analyzer

The steam generator used in this experiment produced by Jiang Xin Boiler Factory, the type is LDRO.017-0.7, the maximum power is 4kw, the water storage volume is 8L, the weight is 63kg, the maximum rated out of steam quantity is 7.5kg/h, the temperature is 105℃, the pressure is 0.11MPa. The amount of steam can be adjusted by a voltage adjuster.

B. Materials

According to *Technical Conditions of Semi-coke Products* that were released by the People's Republic of China in 2010, screening three types of small particles, medium particles and large particles on the basis of particle sizes, the range of particle size were 6-13mm, 13-25mm, 25-50mm. Three test balls are installed in the axial direction of the cylinder, the average temperature of test balls is bed temperature. The test ball is made by inserting a thermocouple into the semi-coke particle. Before experiment, the location of the thermocouple should be adjusted, and the relative height (the ratio of the position *y* at the bottom of the distance material layer to the bed height *H*)should be adjusted to 0.1, 0.5, 0.9. The semi-coke physical parameters were listed in the table 1.

Table 1. Physical properties of semi-coke used in the experiment

Screening diamete /mm	6-13	13-25	25-50
Voidage	0.46	0.54	0.59
Mass percentage（%）	0.08	0.17	0.75
Average particle size (mm)	9.0	19.0	37.5

C. Assessment indicator

1) Heat recovery

The calculation formula of heat recovery in the experiment:

$$\Delta Q = Q_2 - Q_1 \tag{1}$$

Where ΔQ(kJ) is the amount of heat recovery. Q_1(kJ) and Q_2(kJ) are the total amount of inlet and outlet heat flow.

2) Steam energy increased

Steam energy values can be calculated by the following equation:

$$E = Q \times \Omega \tag{2}$$

Where *E*(kJ) is the energy value. Q(kJ) is heat. Ω is energy level.

Energy level calculation formula of variable temperature heat source[16]:

$$\Omega = 1 - \frac{T_{gi}}{T_{go} - T_{gi}} \times \ln \frac{T_{go}}{T_{gi}} \tag{3}$$

Where T_{gi}（℃）、T_{go}（℃）is the inlet and outlet temperature of gas.

III. RESULTS AND DISCUSSIONS

A. The effect of single factor on heat recovery.

Respectively different particle size, bed height, steam flow as a single factor condition, analysis of hot recycled and steam energy increases.

1) Choose the condition that the bed height is 500mm and the steam flow is 7.5kg/h to analyze. The average particle size is 9.0mm, 19.0mm and 37.5mm respectively. As shown in Figure 2.Due to the larger particle size, the greater voidage, the quality of semi-coke is smaller in the material layer, so the initial heat storage is lower under the condition of same bed height. The larger particles size, the effective heat transfer area of the material and the steam is smaller, so the heat recovery decrease.

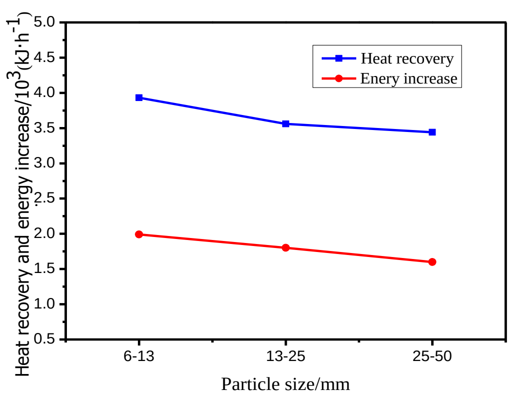

Fig.2. Effects of particle size on the amount of heat recovery and energy increase

2) Analyzed the bed temperature, the amount of heat recovery that the average particle size is 19.0 mm, the steam flow is 7.5 kg/h. The bed height is 400 mm, 500 mm, 600 mm respectively. As shown in Figure 3. At the same particle size and steam flow, the heat recovery increase with the increase of the bed height. This is because the higher the thickness of the bed, which leads to the increase of the initial heat storage capacity, and the longer the gas flow in the bed, the heat change more.

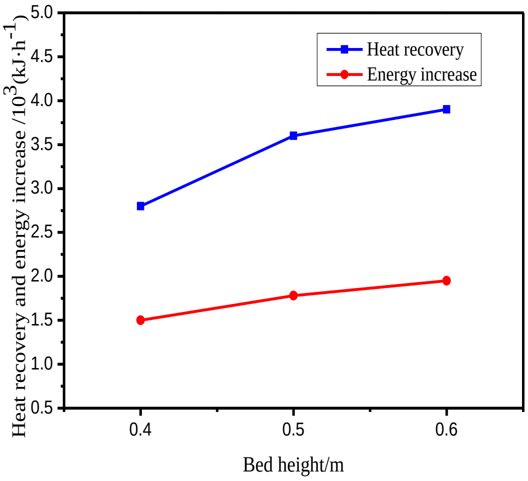

Fig.3. Effects of bed height on the amount of heat recovery and energy increase

3) Choose the conditions that the average particle size is 19.0mm, the bed height is 500mm to analyze. The steam flow is 4.5 kg/h, 6 kg/h, 7.5kg/h. As shown in Figure 4. The amount of heat recovery is 2.7×10^3kJ, 3.0×10^3kJ and 3.6×10^3kJ respectively during the whole heat transfer process. Because increased flow led to increased heat exchange, and the heat brought by gas increased.

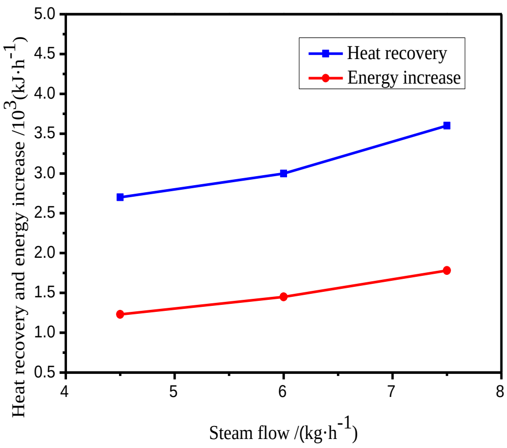

Fig.4. Effects of steam flow on the amount of heat recovery and energy increase

B. *Orthogonal optimization experiment*

1）Experimental design and results.

In this paper, the L9 (34) orthogonal table was used to design the experiment. The relationship between factors and levels is shown in table 2, and the orthogonal test table and results are shown in table 3.

Table 2. Relationship between factors and the corresponding levels

Level	Factor. A Steam flow/ (kg·h^{-1})	Factor. B Particle size /mm	Factor. C Bed height/m
Level 1	4.5	0.009	0.4
Level 2	6.0	0.019	0.5
Level 3	7.5	0.0375	0.6

In table 3, Ki and ki respectively represent the total value and average value of the experimental results under level i, the average value can be used to determine the optimal level and optimal combination of the column factors. R is the range, which is the difference between the best level and the worst level, and reflects the variation of the experimental results when the factor level of the column fluctuated. The larger R is, the greater influence of the factor on the experimental results, and vice versa.

Table 3. Orthogonal experimental table

Experimental number	Factor			Heat recovery/10^{3}kJ · h^{-1}
	A	B	C	
1	4.5	0.009	0.4	3.06
2	4.5	0.019	0.5	2.77
3	4.5	0.0375	0.6	2.40
4	6.0	0.009	0.5	3.64
5	6.0	0.019	0.6	3.49
6	6.0	0.0375	0.4	2.58
7	7.5	0.009	0.6	4.18
8	7.5	0.019	0.4	2.83
9	7.5	0.0375	0.5	3.44
K_1	8.23	10.88	8.47	
K_2	9.71	9.09	9.85	
K_3	10.45	8.42	10.08	
k_1	2.74	3.63	2.82	
k_2	3.24	3.03	3.28	
k_3	3.48	2.81	3.36	
Range R_i	0.74	0.82	0.54	
Order of primary and secondary	B>A >C			
Better level	A_3	B_1	C_3	
Optimal combination	$A_3B_1C_3$			

2) Influence of different levels of the same factor on the experimental results

As can be seen from table 3, for factor A, $k_3>k_2>k_1$, the steam flow 7.5 kg•h^{-1} is the optimal level under this factor. For factor B, $k_1>k_2>k_3$, the particle average particle size of 0.009m is the optimal level under this factor. For factor C, $k_3>k_2>k_1$, the bed height of 0.6m is the optimal level for this factor.

3) Influence of different factors on experimental results

In table 3, the order of the range is R2>R1>R3, so the influence of three factors on residual heat recovery is the average particle size, steam flow and bed height.

4) Optimization results

In table 3, the maximum value of heat recovery is 4.18×10^3 kJ / h^{-1}. In the range of this experiment, the best combination of factors is 7.5 kg / h^{-1} of steam flow, 0.009m of average particle size and 0.6m of bed height.

IV. CONCLUSION

(1) In the effect of the single factor on heat recovery, increase steam flow, reduce particle size, and increase bed height is beneficial to the increase of the heat recovery.

(2) In the orthogonal experiment, the optimum combination is 7.5 kg/h^{-1} of steam flow, the average particle size is 0.009m, and the thickness of the material layer is 0.6m. The average particle size of particle particles is the most important factor affecting heat recovery, followed by the steam flow and the thickness of the material layer.

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