Study on Dynamic Heat Transfer Process of Waste Gas in Coke Oven Riser Coking Cycle

Haiqing Huang, Shenghua Zou
School of Civil Engineering, Hunan University of Science and Technology, 411201, Xiangtan, China

Abstract. Waste heat recovery of waste gas in rising tube is a complex heat transfer process, and this paper analyses and studies the heat transfer problem of the coke hoist heat exchanger in 1 coking cycle by theoretical derivation and numerical calculation. Based on the thermal balance equation, the heat transfer differential equation of the gas flow of the rising tube is derived, the mathematical model of heat transfer for waste gas waste heat recovery is established, and the heat transfer and heat transfer coefficient of the coke oven rising tube heat exchanger in 1 coking cycle are obtained. In 1 coking cycle, the heat transfer of waste gas fluctuates in 1 coking cycle, and the heat transfer of waste gas in the rising tube is 19 to 26 kW, with an average heat transfer coefficient of 30 to 36 W/(m²·K). In the late coking, with the decrease of waste gas flow and the decrease of heat transfer, it will cause the temperature of the rising tube wall to change, and the gas flow should be maintained in the late stage of coking to prevent the phenomenon of sudden change of the inner wall temperature; In the actual production can be several coke ovens in parallel production, and the flow and temperature of waste gas timely monitoring, so that the flow of waste gas control at 800m³/h, improve the efficiency of waste gas waste heat recovery.

Keywords: riser, coal oven gas, heat-transfer process, coking period.

1. Introduction
China is a large producer of coke, in general, for every ton of coke produced, about 360 cubic meters of waste gas, China produces about 70 billion cubic meters of waste gas per year, and COG is considered to be a potential production of methanol raw materials[1]. Recovery and utilization of residual heat provides an important opportunity for the global steel industry to reduce energy consumption and improve energy efficiency [2]. The study found that no matter what method is used, the recycling of waste heat resources plays an important role in energy conservation and emission reduction, some scholars have put forward the theory of energy ladder utilization, but the energy ladder utilization efficiency of China's steel industry is only about 30% [3]. Waste gas produced by the coking process can directly reduce the block iron ore, not only to reduce production costs, but also to reduce energy consumption and CO2 emissions [5]. Coke production has a high energy consumption, accounting for about 10% of the steel industry's energy demand. During the coking process, a large amount of heat energy is lost in the coke production process due to the discharge of flue exhaust gas and the heat loss on the surface of the coke oven furnace. [6]. Chen Guanghui et al analysed the progress of waste gas
waste heat recovery in China, and put forward a new direction of waste gas waste heat recovery [7].

R. Viskanta introduced the solution method of the radiation gas model and the radiation transfer equation. [9]. Ezeddine Sediki et al. studied the interaction between radiation and convective gas flow in a vertical tube. The temperature field and velocity field of the flow gas were analysed by using the global absorption distribution function model. [10]. In solving the velocity field and energy balance equation, Chengyi Li et al. proposed a computational fluid dynamics method to simulate the flow process of high temperature waste gas in the furnace. The reforming process of multi-component mixture waste gas was simulated by the combination of chemical reaction and hydrodynamics. [11]. Wei Lin et al. established a two-dimensional transient model of coal carbonation process and simulated the heat transfer process in coking process and coking chamber. Application of multiple independent parallel reaction model to predict the formation of reactants [12]. The heat transfer and pressure drop equations of double tube heat exchanger are studied by Prabhata K et al. The system is optimized by using these equations, and the optimal values of inner diameter, outer diameter and flow rate of double tube heat exchanger with a given length are given. [13].

The above research mainly analyses the carbonation process of coal, the catalytic conversion of waste gas, the formation of reactants and the flow heat transfer process of waste gas, and simulates the heat transfer process of coking process and coking chamber, but the dynamic heat transfer coefficient of waste gas and the factors affecting the heat transfer efficiency of waste gas in a coking cycle are not analyzed. In this paper, taking the coke oven riser of a steel plant as the research object, according to the variation law of waste gas flow rate and temperature, the dynamic heat transfer coefficient of waste gas in a coking cycle is calculated, and the factors affecting the heat transfer coefficient are discussed, which provides the theoretical basis for the design of riser heat exchanger and the improvement of waste heat recovery efficiency, and puts forward some suggestions for waste heat recovery technology of waste gas in the future.

2. Numerical calculation model

2.1. Physical model

The physical model of riser studied in this paper is shown in Fig. 1. The inner wall diameter is D and the height is H. When the temperature is \( T_{gi} \) (\( T_{gi} > T_w \)), the waste gas enters the riser from the bottom of the riser and carries out heat transfer with the inner wall of the riser. Through the heat conduction of the inner wall, the heat is transferred to the molten salt in the feed water jacket, and the heat transfer is carried out between the molten salt and the water jacket wrapped in the inner wall of the riser. The physical parameters of waste gas are assumed to be uniform in the whole pipeline, the inner wall of the pipe is considered to be overflowing ash surface, the waste gas is cooled when it flows through the riser, and the outlet temperature after heat exchange with the riser is \( T_{ge} \).

Table 1. Geometric parameters of riser heat exchanger mm

| Model parameter | Height | Inner wall diameter | Inner wall thickness | Water jacket spacing | Outer cylinder diameter |
|------------------|--------|---------------------|---------------------|---------------------|------------------------|
| Numerical number | 3000   | 500                 | 25                  | 70                  | 690                    |
2.2. Riser control equation

2.2.1. Energy balance equation of riser. In order to obtain the differential equations needed for the calculation, the following assumptions are made: the waste gas is an incompressible gas, the axial heat transfer of the waste gas can be ignored, and the inner wall of the riser is a diffused ash surface. As shown in Fig. 1, the temperature of the high temperature waste gas enters from the bottom of the riser, and the temperature changes when the waste gas and the riser heat transfer. Using the idea of microelement, the part of the riser is divided into countless microelements of length dx. In this microelement, the temperature of the waste gas and the inner wall of the riser can be considered to be isothermic and can be regarded as a constant. For cylindrical volumes of length dx and diameter D, the convective heat transfer between waste gas and riser $Q_h$ is [4]

$$Q_h = h(T_w(Z) - T_g(Z))\pi D dz$$  \hspace{1cm} (1)

In the formula, $h$ is the convective heat transfer coefficient between the raw gas and the inner wall of the riser, $T_w(Z)$ is the temperature of the riser wall, $T_g(Z)$ is the temperature of the riser gas, and D is the diameter of the inner wall of the riser. For any microelement in the riser, the radiation heat emitted from the surface of the microelement is composed of the direct emission radiation and the reflection of the incident radiation. The radiative heat reaching the surface of a microelement in the riser is $q_i$. Thus, for a microelement on the inner wall of the riser, the energy balance can be written as follows [4].

$$q + q_i = q_o + h(T_w(Z) - T_g(Z))$$  \hspace{1cm} (2)

In the formula, $q$ is the cooling amount of the water jacket side to the waste coal gas side, $q_i$ is the radiation heat input from the inner wall of the riser. $q_o$ is the radiative heat output from the inner wall of the riser. The last item is the convective heat transfer between the waste gas and the inner wall of the riser. $T_w(Z) - T_g(Z)$ is the difference between the wall temperature of the riser and the temperature of the waste gas. $q$ and the convective heat transfer coefficient $h$ are independent of the axial position. The radiation heat flux $q_o$ is the radiation heat which leaves the surface element of the riser, which is composed of direct radiation heat and reflected radiation heat, where the reflected radiation is $1-\varepsilon$ times of the incident radiation, thus, the radiation heat flux $q_o$ is obtained.[4]

$$q_o = \varepsilon \sigma T_{w,i}^4 + (1-\varepsilon)q_i$$  \hspace{1cm} (3)

The incident radiation heat $q_i$ consists of two parts: the radiation heat from both ends of the riser and the radiative heat from other microelements on the surface of the riser inner pipe. These two parts are divided into two parts. [4]:

$$q_i = \sigma T_{r,i}^4 F(z) + \sigma T_{r,e}^4 F(l-z) + \int_0^z q_o(\delta)K(z-\delta)d\delta + \int_z^l q_o(\delta)K(\delta-z)d\delta$$  \hspace{1cm} (4)
In order to obtain the relationship between $T_w$ and $T_g$, a heat balance equation about the waste gas is added. The heat transferred from the waste gas to the riser comes from the convective heat transfer with the inner wall of the riser. The variation of internal energy per unit volume of waste gas is $\Delta I$. [4]

$$I_1 - I_2 = \Delta I = -u_m \frac{\pi D^2}{4} \rho C_p \frac{dT_g(z)}{dz} dz$$  \hspace{1cm} (5)

Where, $I_1 - I_2$ is the internal energy change of the raw gas, $\rho$ is the density of the raw gas, $C_p$ is the specific heat of the raw gas, $u_m$ is the average speed of the raw gas, and $\sigma$ is the Stefan-Boltzmann constant, $5.67 \times 10^{-8}$ W/(m$^2$·K$^4$).

Assuming that the average velocity of waste gas is constant, the simultaneous equations (1) and (9) of kinetic energy change of waste gas are ignored, and the equations of $T_w$ and $T_g$ are obtained. [4]

$$\frac{dT_g(z)}{dz} = \frac{4h}{u_m\rho C_p} [T_w(z) - T_g(z)]$$  \hspace{1cm} (6)

$St = \frac{4h}{u_m\rho C_p}$, $St$ is the Stanton number of waste gas, $z$ is dimensionless length, $z = Z/D$.

### 2.3. Boundary condition

Equation (6) is a first order differential equation. A boundary condition is needed to solve the equation. The temperature value of the inner wall of the waste gas and the riser at the inlet of the riser is taken as the boundary condition, that is, at the entrance $z=0$.

$$t_g = t_{g,i}$$ \hspace{1cm} (7)

$$t_w = t_{w,i}$$ \hspace{1cm} (8)

The simultaneous equation (4) (5) (6) (7) takes into account the variation of the inner wall temperature of the riser along the axis of the riser, and the curves of wall temperature and waste gas temperature of the riser can be obtained by replacing the boundary conditions with the equation.

### 2.4. Physical parameters

Finally, the temperature variation curve of the riser wall and the average heat transfer coefficient of the waste gas are obtained. The physical parameters of the riser and the waste gas related to the calculation are shown in Table 2. The inner and outer cylinder of the riser is made of 2Cr13 steel, in which the inlet temperature and flow rate of the waste gas are obtained according to the output of the waste gas in one coking cycle.

| materials | Density/(kg·m$^{-3}$) | Thermal conductivity/(W·m$^{-1}$·K$^{-1}$) | Specific heat capacity/(J·kg$^{-1}$·K$^{-1}$) | Kinetic viscosity/(kg·m$^{-1}$·s$^{-1}$) |
|-----------|---------------------|---------------------------------|----------------------------------------|-----------------------------------|
| COG       | 0.468               | 0.173                           | 3765                                   | $2.32 \times 10^{-5}$             |
| 2Cr13     | 7750                | 25.6                            | 532                                    | —                                 |
| water     | 998.3               | 0.63                            | 4184                                   | $7.26 \times 10^{-4}$             |

### 3. Calculation results and analysis

#### 3.1. Numerical calculation method

The equation (5) (6) is solved by matlab program. The numerical method is the fourth-order runge-kutta method, and the inner wall of the riser is considered to be a diffused gray surface. It is assumed that the convective heat transfer coefficient between the inner wall of the riser and the waste gas is constant, and the parameters related to the calculation are as follows: diameter of inner wall of riser $D=0.5$m, riser height $Z=3$m, heat transfer area $A=4.71$ m$^2$, COG density $\rho=0.468$ kg·m$^{-3}$, thermal conductivity $\lambda=0.173$ W·m$^{-1}$·K$^{-1}$, specific heat capacity $C_p=3765$ J·kg$^{-1}$·K$^{-1}$, kinetic viscosity $\mu=2.32 \times 10^{-5}$ kg·m$^{-1}$·s$^{-1}$. The
effects of radiation and convective heat transfer on the heat transfer efficiency of waste gas and the influence of radiation heat transfer on the outlet temperature of waste gas are obtained by numerical calculation.

The heat transfer of waste gas is calculated by formula (9):

\[ Q = C_p \cdot M_g \cdot (T_{gi} - T_{ge}) \]  

In the formula, Q is the heat transfer between the waste gas and the riser, W, \( M_g \) is the inlet and export temperature of the waste gas flowing through the riser, K.

The total heat transfer coefficient \( h \) of the riser heat exchanger is obtained by the heat transfer Q, the heat transfer area and the average temperature difference of heat transfer \( \Delta t_m \):

\[ h = \frac{Q}{A \cdot \Delta t_m} \]

3.2. Variation of temperature and flow rate of waste Gas in one Coking cycle

Fig. 3 and fig. 4 show the variation of the flow rate and temperature of waste gas with coking time in one coking cycle, respectively. During the coking period, the flow rate and temperature of waste gas change periodically, the flow rate of waste gas fluctuates at 0~1180 m³/h, and the temperature of waste gas fluctuates at 1000~1200 K.

As can be seen from Figure 3 and Figure 4, 1 coking cycle can be divided into 3 stages, in the 0 to 8 h for the pre-coking, at this time the carbonization chamber temperature is the highest, the heat passed
to the waste gas, the temperature of waste gas gradually increased, the maximum temperature of waste gas can reach 1040 K; At this stage coal gradually to coke conversion, the temperature of waste gas is also rising, the maximum temperature can reach 1100 K, the flow rate is relatively stable, at 800 m$^3$/h fluctuations; In the 14-22 h for the late coking, at this time the coal is all converted into coke, the amount of waste gas produced is reduced until the waste gas flow is zero, at the same time at this stage the temperature of waste gas drops, the minimum temperature drops to 1010 K. In 1 coking cycle, the flow rate of waste gas is decreasing. In the study of waste heat recovery of waste gas, the temperature and flow rate of waste gas change in 1 cycle, which has a great influence on the heat transfer process of waste gas, and the heat transfer process of waste gas should be studied on 1 coking cycle.

3.3. Heat transfer change of waste Gas in Coking cycle

Figures 5 and 6 are the changes in heat transfer and heat transfer coefficient of waste gas with the coking time in 1 coking cycle. In the pre-coking period, with the increase of the import temperature of waste gas, the radiation heat transfer gradually increased, the flow of waste gas fluctuated less, and the total heat transfer fluctuated near 23.5 kW; In the middle of coking, with the decrease in the flow of waste gas, waste gas to the circulation of heat reduction, waste gas temperature is stable, radiation heat transfer is basically unchanged, the total heat transfer is about 22 kW; The radiation transfer heat changes little, the total heat transfer is about 21.5 kW. In the whole coking cycle, the total heat transfer fluctuates from 19 to 26 kW, and the late coking decreases with the reduction of the waste gas flow, and the heat on the circulation decreases, thus reducing the total heat transfer of waste gas. Maintaining the stability of the waste gas flow in the late stage of coking can improve the total heat transfer of the rising tube, so that the temperature of the inner wall of the rising tube will not change greatly, and improve the efficiency of waste gas waste heat recovery.

As can be seen from Figure 5 and Figure 6, the average heat transfer coefficient of waste gas transfer in 1 coking cycle fluctuates by 23 kW, the heat transfer coefficient is the largest in 11 to 16h, and the minimum value of the decrease is 19 kW in the late coking due to the reduction of the temperature and flow of waste gas. During 1 coking cycle, the average heat transfer coefficient of waste gas decreased, which was caused by the decrease in heat transfer temperature difference in the late coking period.

In 1 coking cycle, the heat transfer of waste gas is relatively stable in the early and medium period, in the late stage of coking, due to the reduction of the amount of waste gas, the reduction of heat to the circulation of heat, the decrease of the heat transfer coefficient of waste gas, indicating that the effect
on the total heat transfer of circulating heat is greater, appropriate increase in the flow of waste gas can improve the heat transfer coefficient of waste gas. From the above analysis can be obtained when the waste gas flow at 800 m$^3$/h heat transfer efficiency is high, in the actual production can be several coke ovens in parallel production, the flow and temperature of waste gas timely monitoring, so that the flow of waste gas control at 800 m$^3$/h, improve the efficiency of residual heat recovery.

4. Conclusion
The main purpose of this paper is to obtain the dynamic heat transfer coefficient change law of waste gas in 1 coking cycle according to the law of waste gas flow and temperature change, and to discuss the factors affecting heat transfer coefficient, to provide theoretical basis for the design of the rising tube heat exchanger and improve the efficiency of waste heat recovery.

1) A new calculation method is proposed by constructing the heat transfer calculation model of the rising tube and the differential equation of heat transfer. In 1 coking cycle, the heat transfer and average heat transfer coefficient of waste gas will change with the temperature and flow rate of the waste gas, the total heat transfer is 19 to 26 kW, the average heat transfer coefficient is 30 to 36 W/(m$^2$·K).

2) In 1 coking cycle, the flow rate of waste gas shows a downward trend. In the study of waste heat recovery of waste gas, the temperature and flow rate of waste gas change in 1 cycle, which has a great influence on the heat transfer process of waste gas, and the heat transfer process of waste gas should be studied on 1 coking cycle.

3) The late coking with the reduction of the flow of waste gas, the circulation of heat reduction, thus reducing the total heat transfer of waste gas. Maintaining the stability of the waste gas flow in the late stage of coking can improve the total heat transfer of the rising tube, so that the temperature of the inner wall of the rising tube will not change greatly, and improve the efficiency of waste gas waste heat recovery.

4) The heat transfer efficiency of waste gas flow in 800 m$^3$/h is high, several coke ovens can be produced in parallel in actual production, the flow rate and temperature of waste gas can be monitored in time, so that the flow rate of waste gas can be controlled at 800 m$^3$/h, and the efficiency of waste heat recovery can be improved.

References
[1] Rauf Razzaq, Chunshan Li, Suojiang Zhang. Coke oven gas: Availability, properties, purification, and utilization in China [J]. Fuel, 2013, 113(5):287-299.
[2] Qi Zhang, Xiaoyu Zhao, Hongyou Lu et al. Waste energy recovery and energy efficiency improvement in China’s iron and steel industry [J]. Applied Energy, 2017, 191(1): 502-520.
[3] Lingen Chen, Bo Yang, Xun Shen et al. Thermodynamic optimization opportunities for the recovery and utilization of residual energy and heat in China’s iron and steel industry: A case study [J]. Applied Thermal Engineering, 2015, 86(1): 151-160.
[4] R. Siegel and M. Perlmutter, Convective and radiant heat transfer for flow of transparent gas in a tube with a gray wall [J]. Int. J. Heat Mass Transfer, 1962, 639-660.
[5] Elsayed Abdelhady Mousa, Alexander Babich, Dieter Senk. Utilization of Coke Oven Gas and Converter Gas in the Direct Reduction of Lump Iron Ore [J]. Metallurgical and Materials Transactions B, 2014, 45(2): 617-628.
[6] Shiyue Qin, Shiyuan Chang. Modeling, thermodynamic and techno-economic analysis of coke production process with waste heat recovery [J]. Energy, 2017, 141: 435-450.
[7] Chen Guanghui, Li Shengda, Tao Shaoxun, et al. Research Progress on the Comprehensive Use of Residual Heat in Coke Furnaces [J]. Progress in Chemical Industry, 2018, 37(10): 3799-3805.
[8] YUE Yifeng, ZHANG Zhongxiao, HU Guangtao, Study on physical parameters of coke oven waste gas [J]. Clean Coal Technology, 2012, 18(4): 61-64.
[9] R. Viskanta. Overview of Convection and Radiation in High Temperature Gas Flows [J]. Int. J. Engineering Science, 1998, 36:1667-1699.
[10] EzEddine Sediki, Anouar Soufiani, Mohamed Salah Sifaoui. Combined gas radiation and laminar mixed convection in vertical circular tubes [J]. Int. J.Heat and Fluid Flow, 2003, 24 (5): 736-746.

[11] Chengyi Li, Srinivas Appari, Ryota Tanaka, et al. A CFD study on the reacting flow of partially combusting hot coke oven gas in a bench-scale reformer [J]. Fuel, 2015, 590-598.

[12] Wei Lin, Yanhui Feng, Xin Xin Zhang. Numerical study of volatiles production, fluid flow and heat transfer in coke ovens [J]. Applied Thermal Engineering, 2015, 353-358.

[13] Prabhata K. Swamee, Nitin Aggarwal, Vijay Aggarwal. Optimum design of double pipe heat exchanger [J]. Heat and Mass Transfer, 2008, 2260-2266.