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To cite this article: Tao Zhang and Jizheng Chu 2018 J. Phys.: Conf. Ser. 1060 012092

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A Simplified Simulation Model of Steady Temperature for Tubular Furnace

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Abstract. To solve the problems of complex radiative, convective heat transfer and difficult parameter correction in tubular furnaces, a simplified model of a new tubular heating furnace was proposed, which coupling each pipe heat transfer to a whole pipe and simplified the radiation heat transfer formula parameters of each pipe to a whole single heat transfer parameter. In addition, the simplified method takes the flue gas generated by combustion as the sole heat source, each section of the pipe wall acts as the intermediate medium to receive the heat of the burning flue gas and heat the fluid. The results shows that the new model was effective and accurate.

1. Introduction

As the most important heating equipment, the reheating furnace plays an important role in the process of industrial production. As the second largest energy consuming equipment in China, it is next to thermal power generation, but its average combustion efficiency is about 30%, which is far lower than that of 50% in other developed countries [1]. As the important heating equipment in oil refineries and petrochemical plants, tubular reheating furnace plays an indispensable role in oil production and catalytic refining. In a refinery, the tubular furnace with multi pipes and multi burners is often used to heat the crude oil. It can improve the heat transfer efficiency and reduce the possibility of coking [2]. Therefore, simulating its combustion and heat transfer process can provide a reliable basis for its production and processing.

The structure of tube heating furnace started as a Heap-type furnace, which based on the principle of kettle type steamer. The tube bundles were used as an endothermic surface and the elbow of each tube was in the furnace. The burner was installed under the tube bundle, each tube was heated unevenly, it was easy to burn and fire at the elbow [3]. After that, the structure of tube furnace was adjusted to be a pure convective furnace, but it still had uneven heating phenomenon. To solve this problem, people designed a tubular heating furnace with a radiation chamber and a convection chamber, such as box furnace.

In the 1950s, researchers began to study furnace simulation models. SiddallRG and Selcuk [4] simplified the whole heat transfer model as a gas, a heating surface and a reflector by Lobo-Evens method, but it was too simple to get the surface temperature of radiation chamber and furnace tube temperature. Hottel [5] proposed a regional method to calculate heat transfer in the furnace, but it has a large amount of calculation and need a computer for numerical calculation. Howell [6] proposed a Monte-Carlo method to divide the radiation energy into several parts, calculated the radiative heat transfer of different regions by statistical method and got temperature and heat flux distribution.
Costik [7] based on statistical method, studied a two-dimensional radiation model. Fitzgerald et al. [8] studied a three-dimensional radiative heat transfer model. Spalding et al. [9] developed a turbulent combustion model, and then the model of reheating furnace began to take into turbulence and combustion. Yuan J et al. Wei-jun Zhang, Zhi Yi et al [10] proposed an zonal method to simplified the two-dimensional heat transfer model of a multi-zone reheating furnace. NC Mehta, DD Shukla, P K and oliya [11] had done a heat transfer analysis of induction furnace wall made of zirconia using explicit finite difference method. Gupta A K et al. [12] studied the relationship between flame volume, air preheat temperature and oxygen concentration by PDF combustion model and regional radiation model. Prins et al. [13] simulated flow field and pressure field in cracking furnace by complete unstructured grid partition scheme. Stefanidis et al. [14] used detailed combustion models in cracking furnace simulation to get a suitable combustion model. Habibi et al. [15] studied the effect of different radiation model included DOM, P-1, and Rosseland on flow field, temperature, and flame shape. The simulation results provides a basis for the simulation of the heating furnace model.

Due to complexity of the heat and energy transfer process, the calculation speed will become very slow [10]. In this paper, according to the actual production needs, a simplified model was developed by using single heat transfer parameter to simplify radiation and convection formula. This model can get the flue gas, the wall of each pipe and the heating oil temperature quickly and effectively, which are the important parameters of oil production.

2. Simplified model of reheating furnace and methodology

The tubular furnace investigated in this paper is from Shengli Oil Refinery of Qilu Petrochemical Corp. It consists of four parts, which are radiation chamber, convection chamber, chimney and residual heat recovery system. The bottom of the radiation chamber is equipped with burners, convection chamber and radiation chamber have heating pipes. The chimney is equipped with a flue baffle, and the flue gas pipeline is connected with residual heat recovery system.

The fuel oil or fuel gas is mixed with the incoming air at the bottom of radiation chamber through nozzles. The flue gas generated by combustion is used as a radiation source to heat tubes in the form of thermal radiation. Then it enters convection chamber and heat the tubes, after that enters the air preheater to heat air, finally enters the atmosphere through chimney. The radiation chamber tubes absorbs most of heat in the whole heat transfer process about 70% [16]. Figure 1 is the simplified schematic diagram of tubular heating furnace.

In this paper, the flue gas produced by fuel combustion are simplified as a process that heat source to heat the tube wall. So the energy equation [17]:

\[
F_{g}h_{g} + F_{a}h_{a} + \sum_{i} Y_{k,i} F_{k} dH_{i} = F_{s}h_{s}
\]

(1)

Where \( F_{g}, F_{a}, F_{s} \) are the fuel gas, air and flue gas flow. \( h_{g}, h_{a} \) and \( h_{s} \) are the enthalpy of fuel, gas and air, \( dH_{i} \) is the combustion heat of each component in fuel gas.

\[
h_{i} = \sum_{k} Y_{k,i} h_{k,i} \quad (k = g,a,s)
\]

(2)

\( Y_{k,i} \) is the mass fraction of species \( i \) and \( h_{i} \) is defined as:

\[
h_{k,i} = \int_{1}^{T} C_{p,i} dT \quad (k = g,a,s)
\]

(3)

Where \( C_{p,i} \) is the constant pressure specific heat of species \( i \). The fuel gas composition and combustion heat as shown in table 1.

The flue gas transfers heat to the tube wall in radiation chamber and convection chamber, then each tube wall transfers heat to heated oil. This process follows the radiative and convective heat transfer formula. In this paper, multichannel tubes are heated at the same time. Figure 2 is the radiative heat transfer model.
Table 1. Fuel gas composition and combustion heat

| Component       | Volume content % | Combustion heat kJ/Nm³ |
|-----------------|------------------|------------------------|
| CO              | 1.84             | 12636                  |
| CO₂             | 0.38             | 0                      |
| H₂              | 13.34            | 11096                  |
| O₂ and N₂       | 9.19             | 0                      |
| CH₄             | 49.82            | 35902                  |
| C₂H₆            | 16.17            | 64397                  |
| C₃H₄            | 4.14             | 59477                  |
| C₃H₈            | 1.94             | 93240                  |
| C₄H₈            | 1.86             | 87667                  |
| iso-C₄H₁₀       | 0.02             | 122853                 |
| n-C₄H₁₀         | 0.42             | 123412                 |
| n-C₅H₁₂         | 0.46             | 123649                 |
| t-C₅H₁₂         | 0.07             | 112964                 |
| c-C₅H₁₂         | 0.05             | 112964                 |
| i-C₅H₁₂         | 0.07             | 134821                 |
| n-C₆H₁₂         | 0                | 156467                 |
| neo-C₅H₁₂       | 0                | 140375                 |
| C₆              | 0                | 176273                 |
| H₂S             | 0.23             | 23368                  |

For simplicity, analysis is carried out under the following assumptions:
1) The flue gas is mixed uniformly in radiation chamber and radiation chamber.
2) There is no heat transfer between the tube walls.
SI is the flue gas of entering radiation chamber, which is generated by the combustion of fuel and air in adiabatic condition. SO is the flue gas of leaving radiation chamber. TI and TO are the heated fluid of L road entering and leaving radiation chamber. W is the tube wall of L road.

By the radiative transfer equation, the heat release of flue gas to wall as:

$$Q_{s,l} = \alpha_{s,l} A_{s,l} \left( \overline{T}_S^4 - \overline{T}_W^4 \right) \quad (4)$$
$Q_{s,l}$ is the radiation quantity that flue gas to the wall of L road. $\alpha_{s,l}$ is the heat transfer coefficient, $A_{s,l}$ is the heated area of tube wall. $T_{SO}$ and $T_{W}$ are the temperature of flue gas and tube wall. Heat balance equation of heat transfer between flue gas and tube wall as:

$$Q_{s} = \sum_{l=1}^{L} Q_{s,l} = F_{SO}C_{p,SO}(\overline{T_{SO}} - T_{SO})$$  \hspace{1cm} (5)

$F_{SO}$ is the flow of the flue gas, $C_{p,SO}$ is the average specific heat of flue gas, $T_{SO}$ and $T_{SO}$ are the temperature at the inlet and outlet of radiation chamber. $L$ is the number of total heated pipes. To simplify the whole heat transfer process, $\lambda_{s,l}$, $\lambda_{s}, T_{W,av}$ can be as:

$$\lambda_{s,l} = \frac{F_{SO}C_{p,SO}}{\alpha_{s,l}A_{s,l}}$$  \hspace{1cm} (6)

$$\lambda_{s} = \frac{1}{\sum_{l=1}^{L} 1/\lambda_{s,l}}$$  \hspace{1cm} (7)

$$T_{W,av} = \left( \frac{\sum_{l=1}^{L} \overline{T_{Wl}} / \lambda_{s,l}}{\sum_{l=1}^{L} 1/\lambda_{s,l}} \right)^{\frac{1}{4}}$$  \hspace{1cm} (8)

From Eq. (4), Eq. (5) can be obtained:

$$\overline{T_{SO}}^{4} + \lambda_{s}T_{SO} = \lambda_{s}T_{sl} + T_{W,av}^{4}$$  \hspace{1cm} (9)

Where $T_{W,av}$ is the average temperature of all the tube walls.

Heat transfer equation and heat balance equation between tube and wall as

$$Q_{o,l} = \alpha_{o,l}A_{o,l}(\overline{T_{Wl}} - \frac{T_{ro} + T_{rl}}{2}) = F_{RO}C_{p,RO}(\overline{T_{Tol}} - T_{rl})$$  \hspace{1cm} (10)

$Q_{o,l}$ is the contact heat transfer quantity of the tube wall to the heated oil. $T_{ro}, T_{rl}$ are the heated oil temperature at the inlet and outlet of radiation chamber. $F_{RO}$ is the flow of heated oil. $C_{p,SO}$ is the average specific heat of heated oil. So, $\overline{T_{ro}}$ can be obtained:

$$\overline{T_{ro}} = \frac{T_{ro} + T_{rl}}{0.5 + \lambda_{o,l}T_{rl}}$$  \hspace{1cm} (11)

$$\lambda_{o,l} = \frac{F_{RO}C_{p,RO}}{\alpha_{o,l}A_{o,l}}$$  \hspace{1cm} (12)

Energy balance equation of gas and oil as:

$$Q = \sum_{l=1}^{L} Q_{s,l} = F_{SO}C_{p,SO}(\overline{T_{SO}} - T_{SO}) = \lambda Q_{o} = \lambda \sum_{l=1}^{L} Q_{o,l} = \lambda F_{RO}C_{p,RO}(\overline{T_{Tol}} - T_{rl})$$  \hspace{1cm} (13)

$\lambda$ is the thermal efficiency with the range of 0 to 1. From Eq. (9), Eq. (10), Eq. (11) can be obtained
Thus, the heat transfer formula of every tube can be simplified. \( \lambda_{s,l} \) and \( \lambda_{o,l} \) above can be obtained through the steady state data of the industrial field. To solving the equation of higher degree, one way is using Newton method and Secant method.

In convective model, the convective heat transfer is the first square function about flue gas temperature and tube wall temperature. The other heat transfer equations of convection model are the same as radiation model that need not be detailed here. It is worth noting that the outlet temperature of flue gas obtained by radiation model was used as the input condition for convection model, and the outlet temperature of oil obtained by convection model was used as the input condition of radiation model. Therefore, in the process of coupling radiation model and convection model, the oil temperature at the inlet of radiation chamber need to be assumed in advance, and then solved the real oil temperature by Secant method. The main parameters about the heating furnace are in table 2.

In this paper, the parameters were corrected by a set of industrial data. Then using the parameters, this model predicts three sets of outlet temperature of oil and flue gas. Table 3 is prediction error of this model. In figure 3-4, 15 sets of data was obtained by changing the feed volume of fuel gas, and then draw the relationship between the combustion calorific value, flue gas temperature, oil temperature and wall temperature. In figure 5-6, when changing the feed amount of the heated oil, get the relationship between gas, tube temperature and oil flow.

\[
\lambda \hat{T}_w^4 + \frac{2 \lambda_{s,l} \hat{T}_w}{1 + 2 \lambda_{s,l}} \hat{T}_w = \lambda \hat{T}_{so}^4 + \frac{2 \lambda_{o,l} \hat{T}_{so}}{1 + 2 \lambda_{o,l}} \hat{T}_{so}
\]  

(14)

Figure 3. Relation diagram of combustion heat value and flue gas in the radiation chamber

Figure 4. Relation diagram of tube wall temperature and oil flow temperature

Figure 5. Relation diagram of oil flow and smoke temperature in radiation chamber

Figure 6. Relation diagram of smoke temperature and oil temperature in the convection chamber

Table 2. Parameter value of reheating furnace.
Parameter | Calibrated value
---|---
Fuel flow, Nm³/h | 5960.19
Combustion heat of fuel gas, kJ/Nm³ | 37309.25
Thermal load of Radiation chamber, GJ/h | 139.15
Thermal efficiency, % | 93.5
Surface area of convection tubes, m² | 1509
Thermal strength of convection tubes, W/m² | 8916.87
Surface area of radiation tubes, m² | 1577
Thermal strength of convection tubes, W/m² | 24510.32
Mass flow of radiation tubes, kg/h | 892256
Internal diameter of pipe, mm | 177.3
Number of tube passes | 6
Excess air factor | 1.08

**Table 3.** Prediction error of the simplified model.

|  | 1 | 2 | 3 |
|---|---|---|---|
| Prod. oil Tem, °C | 365.03 | 369.95 | 367.05 |
| Prediction oil Tem, °C | 369.8648 | 362.5119 | 363.6381 |
| Error | -4.8348 | 7.4381 | 3.4119 |
| Prod. Smoke Tem, °C | 309.5 | 314.9 | 312.6 |
| Prediction Smoke Tem, °C | 315.8064 | 310.6808 | 311.3591 |
| Error | -6.3064 | 4.2192 | 1.2409 |

**3. Conclusions**

By the research on simplified model of tubular furnace, the simulation results proved that using flue gas as the heat source is feasible and the single heat transfer parameter can simplify the transfer heat formula. Compared with the actual production data, it is obvious that the simplified model is effective and accurate. Therefore, it can simulate and predict the actual tubular furnace for production and research.

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