Study on Calculation of Flue Gas Temperature at the Exit of Heating Furnace of Oil and Gas Field

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Abstract. It is of significance to ascertain the flue gas temperature at the exit of heating furnace, which lays the foundation of thermodynamic calculation of boiler and its design. This study analyses some normal calculation formulas of the flue gas temperature at the exit of heating furnace of oil and gas field, and makes comparisons of different calculation methods via examples. Appropriate parameters are presented, so as to give guide to the design and calculation of heating furnace of oil and gas field.

1. Introduction
In petroleum industry, heating furnaces are widely used in heating of crude oil, natural gas and well products in the oil-gas gathering and transportation systems, so as to realize the processes of transportation, sedimentation, separation, dehydration and initial processing. With the adjustment of energy consumption policy and the enhancement of environmental protection, the heating furnace of oil and gas field has been developed rapidly in recent years. However, there is no unified standard for the thermodynamic calculation of the furnace in the gas oil field.

The thermodynamic calculation of boiler is important, of which the crucial one is the heat transfer calculation of furnace radiation. To ascertain the flue gas temperature at the exit of heating furnace is the main task. This study gives some calculation formulas and makes comparisons via examples.

2. Common Calculation Methods

2.1 Union of Soviet Socialist of Thermal Standard method for Boiler Units
As for heat calculation for boiler, most designers followed the joint standards drawn up by the former Soviet Union’s Thermal Research Institute and the Central Boiler Steam Turbine Research Institute, which had a solid foundation in both theory and experimental verification, with certain authority. The calculation formula for the flue temperature of the furnace in the Soviet version in the 1973th "Thermal Standard Method of Boiler Units" [1, 2]:

\[
\theta_{11}'' = T_{11} / \left[ M (\delta_0 \varphi_{pj} F_1 T_{11}^3 / \phi Bj V_{cpj})^{0.6} + 1 \right] - 273
\]

(1)

Where: \(T_{11}\) is theoretical combustion temperature, K;
\(\delta_0\) is blackbody radiation constant, \(5.67 \times 10^{-11}\) KW/(M\(^2\)K\(^4\));
\(F_1\) is radiation heating area of furnace, m\(^2\);
\(\varphi_{pj}\) is average thermal efficiency coefficient in furnace;
\[ \alpha_{1} \] is systematic emissivity of furnace;  
\[ \phi \] is heat preservation coefficient;  
\[ B_j \] is calculation of combustion consumption, kg/s;  
\[ V_{cp,j} \] is average specific heat capacity of combustion products, kJ/kg·K;  
\[ M \] is fudge factor

This formula is based on the heat transfer model of chamber combustion furnace, applying the "similarity theory" amid the process. However, special attention should be paid to the physical meaning and calculation of the following parameters when applying this formula to horizontal internal combustion gas boiler.

1. Average thermal efficiency coefficient \( \varphi_{pj} \)

\[ \varphi_{pj} = \varepsilon \times \pi \]

Where: \( x \) is fractional cold of furnace;  
\( \xi \) is slagging factor, gas fuel, \( \xi = 0.65 \)

2. Systematic blackness of furnace \( \alpha_{1} \)

The radiation heat transfer between the flame and the furnace can be regarded as the radiation heat transfer between the closed systems of the cavity and inner convex object. It can be illustrated the relation by \( \alpha_{1} \) as follows:

\[ \alpha_{1} = \alpha_{by} / [ \alpha_{by} + \varphi_{pj} (1-\alpha_{by}) ] \]

Where: \( \alpha_{by} \) is flame blackness;  
\( \alpha_{fg} \) is luminous flame blackness (carbon black particle);  
\( \alpha_{g} \) is non-luminous flame blackness (Triatomic gas);  
\( m \) is the proportion of luminous flame, depends on heat load of furnace

For gas fuels, when \( q_v \leq 400 \text{kw/m}^3 \), \( m = 0.1 \), and when \( q_v \geq 1200 \text{kw/m}^3 \), \( m = 0.6 \), linear interpolation method can be used to determine the relationship between the two.

3. Fudge factor \( M \)

\( M \) is the key coefficient to ascertain the flue gas temperature at the exit of heating furnace. It is a semi-empirical conversion coefficient in the thermodynamic calculation of the furnace, which fully takes into account the structure of the furnace, the arrangement of the burner and the fuel composition. The radiation heat transfer of furnace has the characteristics of uniform radial direction and one-dimensional linear distribution along the furnace, so the expression of coefficient \( m \) adopts linear function relation:

\[ M = a-bX_d \]

Where: \( a \) and \( b \) is coefficient 1.01 and 0.49, respectively.

\[ M = 1.01-0.49X_d \]

After the correction of this coefficient, the outlet smoke temperature calculated by this method is consistent with the actual one. Therefore, this paper uses the above formula as the standard of calculation to investigate the accuracy of other formulas.
The Calculation Method in Theoretical Analysis and Calculation of Heat Transfer in Boiler Tank of Shell Oil and Gas Boiler

Bu Yinkun puts forward the calculation formula 7 [3] in Theoretical Analysis and Calculation of Heat Transfer in Boiler Tank of Shell Oil and Gas Boiler. This formula is derived on the basis of thermal radiation theory, which reflects the quartic temperature difference relationship of radiation heat exchange, which is reliable.

\[ Q_{12}^{cr} = 5.67 \times 10^{-11} \times A(\varepsilon_{1y}^{-4}T_{y} - \varepsilon_{1w}^{-4}T_{w})/(1+0.042) \times \varepsilon_{1y} \times \varepsilon_{1w} \] (7)

Where: \( Q_{12}^{cr} \) transfers heat via radiation heat transfer object 1 to object, KW;
A is the internal surface area of bellows furnace, m²;
\( \varepsilon_{1y} \) is object 1, the blackness of flue gas at the average thermodynamic temperature in the furnace tank;
\( T_{y} \) is average thermodynamic temperature of flue gas with high temperature in furnace K;
\( \varepsilon_{1w} \) is object 1, the blackness of smoke on the heating surface of furnace at thermodynamic temperature on the inner surface of soot;
\( T_{w} \) is thermodynamic temperature of smoke and soot on heating surface of furnace tank, K.

Calculation Method of Oil- and Gas-Fired Boiler

Zhao Qinxin and Hui Shi’en give a simplified calculation formula 8 [4] in their book of Oil- and Gas-Fired Boiler. The theoretical basis is still the basic equation of radiation heat transfer, which reflects the quartic temperature difference relationship of radiation heat exchange. The parameters are few and easy to obtain.

\[ Q = C \times H_{f} \times \left[ \left( \frac{T_{by}}{100} \right)^{4} - \left( \frac{T_{b}}{100} \right)^{4} \right] / B_{j} \] (8)

Where: \( Q \) is radiation heat exchange, kJ/kg, kJ/m³;
C is radiation heat transfer coefficient, kW/(m²·K), \( C = 11 \sim 15 \) is recommended in the book;
\( H_{f} \) is effective radiation heating area, m² ;
\( T_{by} \) is average temperature of the flame in the furnace, K;
\( T_{b} \) is temperature of inner surface wall of furnace, K;
\( B_{j} \) is calculated fuel consumption, kg/s, m³/s.
It is crucial to calculate \( T_{by} \), the average temperature of the flame and \( T_{b} \), the temperature of inner surface wall of furnace. Generally speaking, \( T_{b} \) can be calculated by the formula of \( T_{b} = T_{gb} + 90 \), while \( T_{by} \) can be calculated by the following methods:

1. Arithmetic interpolation method
\[ T_{by} = T^{11}_{1l} + \frac{1}{4} (T^{11}_{1l} - T^{11}_{11}) \] K (9)

Where: \( T^{11}_{1l} \) is outlet temperature of furnace assumed in design and calculation;
\( T^{11}_{11} \) is theoretical combustion temperature determined by incoming heat

2. Geometric mean method
\[ T_{by} = 0.9T_{L_{n}} T_{11}^{n} \] K (10)

For oil- and gas-fired boiler, \( n=0.5 \)

3. Parametric method
\[ T_{by} = \tau T_{L} \] K (11)
(4) Geometric parameter method

\[ T_{by} = T_{11}^{11} \left( \tau(1-x_{\max}) \right)^{0.25} \text{ K} \]  

Where: parameter \( \tau = \left[ 0.44 \times \theta^4 + 0.14 (\theta^2 + \theta + 1) \right]^{0.25} \), \( \theta = 1 + \frac{1}{3} \left( \frac{T_{11}''}{T_{11}} - 1 \right) \)

Taking a 350 KW heating furnace as an example, the average flue gas temperature is calculated according to the above four methods. The results of it are as follows: For arithmetic interpolation method and geometric mean method, \( T_{by} \) are 1290.05 k and 1329.04 k, respectively; that of parametric method and geometric parameter method are 1270.29 k and 940.2548 k, respectively. The calculation error of \( T_{by} \) via the above three methods is small, except for geometric parameter method. The arithmetic interpolation method is used in the calculation of this study.

3. Calculation Examples by Various Calculation Methods

3.1 Union of Soviet Socialist of Thermal Standard method for Boiler Units

The calculation results of the flue gas temperature at the exit of heating furnace with 350 KW of oil and gas field is showed in Table 1.

| Order number | Name | Symbol | Unit | Formula or data source | Result |
|--------------|------|--------|------|-------------------------|--------|
| 1            | flue gas temperature at the exit of heating furnace | \( \theta'_{1} \) | °C | \( \theta'_{1} = \frac{T_{ij}}{M(\sigma\varphi A_{ij}T_{ij}^{1.8})^{1.6} + 1 - 273} \) | 704.93 |
| 2            | Calculation error | \( \Delta \) | °C | <100°C meets the requirements | -0.00073 |

By applies the above methods, the flue gas temperature at the exit of heating furnace of other series of heating furnace can be calculated as follows: the temperature of 350 KW and 820 KW heating furnace is 705 °C and 70 °C, respectively; that of 1,250 KW and 1,600 KW furnace at 715 °C and 710 °C, respectively; that of 2,800 KW and 4,000 KW at 720 °C and 880 °C, respectively.

As the actual temperature of flue gas at the exit of heating furnace is close to the above calculated one, the above data are used as the standard for the calculation of following formula.

3.2 The Calculation Method in Theoretical Analysis and Calculation of Heat Transfer in Boiler Tank of Shell Oil and Gas Boiler

The calculation results of the flue gas temperature at the exit of heating furnace with different power of oil and gas field is showed in Table 2.
Table 2. The calculation data based on the formula in Theoretical Analysis and Calculation of Heat Transfer in Boiler Tank of Shell Oil and Gas Boiler

| Order number | Name                    | Symbol | Unit       | Calculation Result |
|--------------|-------------------------|--------|------------|--------------------|
|              |                         |        | 350 KW     | 820 KW             | 1250 KW             | 1600 KW             | 2800 KW             | 4000 KW             |
| 1            | Flue gas heat transfer  | Qcr    | KJ/Nm³     | 24505             | 28461              | 23702              | 24911              | 28152              | 24812              |
| 2            | Calculation error       | Δ      | %          | -4.98             | -21.06             | -2.90              | -4.41              | -17.59             | -18.40              |

3.3 The Calculation Method in Oil- and Gas-Fired Boiler

The calculation results of the flue gas temperature at the exit of heating furnace with different power of oil and gas field is showed in Table 3.

Table 3. The calculation data based on the formula in Oil- and Gas-Fired Boiler

| Order number | Name                    | Symbol | Unit       | Calculation Result |
|--------------|-------------------------|--------|------------|--------------------|
|              |                         |        | 350 KW     | 820 KW             | 1250 KW             | 1600 KW             | 2800 KW             | 4000 KW             |
| 1            | Flue gas heat transfer  | Qcr    | KJ/Nm³     | 23334             | 23429              | 22935              | 23860              | 23979              | 20937              |
| 2            | Calculation error       | Δ      | %          | 0.034             | 0.345              | 0.426              | -0.00227           | -0.160             | 0.0924              |

Though the above formula, the calculation error may be large, if it is applied the formula C=11-17, which proves the recommended C value of this formula is not suitable to calculate the flue gas temperature at the exit of heating furnace of oil and gas field. This paper analyzed C value should adopt different power of various kinds of furnaces in order to reduce error.

Parameter C of 350 KW and 820 KW heating furnace are 5.1 and 8.9, respectively; that of 1,250 KW and 1,600 KW at 10.4 and 10.7, respectively; that of 2,800 KW and 4,000 KW at 11.5 and 8.8. The relationship between the thermal power of the heating furnace and the parameter C is drawn as a line, as shown in figure 1.
When the flue gas temperature at the exit of heating furnace is calculated by this formula, the recommended value of parameter C under the corresponding power can be found out from the fitting curves in figure 1, so that the calculation error can be reduced.

4. Analysis, Comparison and Conclusion

The flue gas temperature at the exit of heating furnace calculated by the method in formula 1 is in good agreement with the actual one. Although it is not reflected the difference of radiation heat exchange of quartic temperature difference, indeed, it is the combination of simultaneous heat exchange equation and heat balance equation. More importantly, all the factors affecting radiation heat exchange in this formula are expressed accurately. $Q_{pj}$, the effective coefficient of radiation heating surface, presents the structural factors of furnace and combustion chamber heating surface (guard fuel belt, dry back, wet back, etc.), especially the furnace blackness, which is calculated from the thickness of effective radiation layer reflected by furnace structure, until the positive pressure of furnace, luminous and non-luminous flame blackness, and then combined with the factors that affect the blackness. Coefficient M is a semi-empirical conversion coefficient in the calculation of furnace thermodynamic, which fully considers the furnace structure, burner arrangement, fuel composition and so on. Therefore, the flue gas temperature at the exit of heating furnace calculated by this formula can be in good agreement with the actual one, which is more accurate. And this formula is widely used in the industry of boiler with certain authority.

The heat transfer error calculated in formula 7 is based on formula 1. The heat transfer error of 350 KW and 820 KW heating furnace is 4.98% and 21.06%, respectively, that of 1,250KW and 1600 KW at 2.9% and 4.41%, respectively; that of 2,800 KW and 4,000 KW at 17.59% and 18.40%. Through the calculation, it can be seen that the design or checking calculation by this method is in accordance with the reality in most cases. The error of flue gas temperature is generally less than 100 ℃, and that of heat transfer is generally not more than 20%. Moreover, this method is simple, with few independent variables, fast operated and sufficient theoretical basis.

Formula 8 can only roughly determine the coefficient C, which is selected appropriately according to different conditions of radiation heat exchange. In fact, the variation range of this value is very large, which is difficult to select exactly. Therefore, the calculation is certainly not very accurate. When the flue gas temperature at the exit of heating furnace is calculated by this formula, the recommended C value under the corresponding power can be found out from figure 1, so that the calculation error is very small. The application of this formula is simple, with few parameters and relatively sufficient theoretical basis, which is a good method for calculating the flue gas temperature at the exit of heating furnace.
In conclusion, one of the three formulas can be selected in the calculation of heat transfer of heating furnace of gas and oil field, according to the specific situation. In fact, the theoretical basis of these three formulas is derived from the radiation heat transfer equation of flame and furnace wall, and the furnace heat balance equation, with same basic theory. Only formula 1 has more empirical components and required parameters. Formula 7 has a solid theoretical foundation, with fewer parameters to make it easy to calculate, but in some cases the error is larger than that of other methods. Formula 8 also has a solid theoretical foundation, with clear concept, few parameters, with is easy to obtain and more convenient to calculate. However, it is necessary to accumulate more basic data and make the corresponding c-value fitting curve, in order to obtain more accurate data which is suitable for the corresponding furnace design.

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