Research on Low Temperature Condensation of Flue Gas from Gas Industrial Boiler

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Abstract. The paper analyzed the heat transfer in the condensing section of condensing gas industrial boiler. As to the operation of boiler, the field test of the flue gas condensing section was carried out where the field test data was compared with the theoretical values to verify the calculation formula of the convective exothermic coefficient of the condensing section in the condensing boiler’s spiral rib.

1. Introduction
The energy available in the flue gas generated by the combustion of gas fuel is divided into two parts: the obvious heat of flue gas and the latent heat of water vapor in flue gas. The difference between condensing boiler and traditional boiler is that the latent heat of water vapor in flue gas is effectively utilized. For natural gas in northern Shaanxi, about 70% of the latent heat of water vapor in the flue gas can be utilized if the exhaust smoke temperature of the boiler is reduced to 40°C [2].

The higher temperature of smoke extraction in traditional boiler disables the latent heat of water vapor in the flue gas. Based on the assumption of "dry flue gas", only the sensible heat of flue gas and steam is calculated in the thermodynamic calculation of boiler. As the latent heat of water vapor in the flue gas of condensing boiler is released and used, the calculation of condensing section of condensing boiler is different from that of traditional boiler.

2. Analysis of Moisture Condensation of Flue Gas
The flue gas of condensing boiler refers to the condensation of water vapor in a large amount of non-condensable mixed gases. According to Dalton’s principle of partial pressure, the total pressure of flue gas refers to the sum of the partial pressure of steam in flue gas and the partial pressure of non-condensable gas. When water vapor mixed with a large amount of non-condensable gases encounters the heating surface below the temperature of its acid dew point, the water vapor molecules condense at the condensation core, where the partial pressure of water vapor decreases while the partial pressure of non-condensable gas increases. After condensation of water vapor, the liquid film is surrounded by non-condensable gas to form a layer of non-condensable gas film. Water vapor molecules outside the film need to pass through it to reach the surface of the liquid film to condense. Different from the columnar condensation of pure water vapor, the condensation of steam in condensing boiler flue gas has an impact on non-condensable gas, which is worthy of analysis [3].

The columnar condensation of steam in flue gas can be divided into three steps:
2.1. The water vapor starts to condense in the condensation core to form tiny liquid droplets, which gradually grow up to form condensation chamber on the wall’s surface. The initial formation of condensation is the so-called nucleation process.

2.2. The condensation droplets grow further to form a thin liquid film on the whole condensation surface. With the continuous thickening of the liquid film, it reaches the critical thickness and splits into small droplets, a process called liquid film growth.

2.3. The small liquid droplets formed by liquid film splitting are constantly polymerized and fall off from the heating surface of the boiler when they reach the critical size. The is the aggregation of bead condensation. During liquid droplet polymerization, the speed of droplet polymerization is faster with a minimum amount of heat transfer, which can be regarded as an adiabatic process [3].

3. Analysis of Convection Heat Transfer in Condensing Section of Boiler Flue Gas

Through the analysis of the whole condensation process of steam in the flue gas, it can be found that when the temperature of steam in the flue gas drops to the acid dew point, the latent heat of vaporization is released and condensed into liquid state. As for the heat transfer in the condensing section of the boiler, it is different from the heat transfer in the condensing part of the flue gas: the temperature of the flue gas is above the acid dew point, and the heat transfer process of the two is consistent, both are sensible heat of non-condensable gas in flue gas and heat exchange between sensible heat and boiler heated medium. The heat exchange of flue gas in the traditional boiler is terminated and exhausted from the system before its temperature drops to the acid dew point. When the temperature drops to the acid dew point, the condensation heat transfer consists of sensible heat from non-condensable gas and heat exchange between latent water vapour and heated medium in the boiler, with the location of heat transfer being flexible. As the flowing flue gas encountering the heated surface in the process of cooling, latent heat is released from water vapor condensation. This is inseparable from the position of acid dew point, and the condensation of water vapor in the flue gas is a continuous process.

The heat transfer of boiler can be divided into radiation heat transfer and convection heat transfer, where heat transfer in condensing section of boiler is categorized as convection heat transfer. Coefficient of convective heat transfer represents the intensity of convective heat transfer, directly related to fluid property, flow status and the arrangement of heated tubes. Based on the structure of the boiler, the thermodynamic calculation of the convective heat transfer in heated surface is carried out through the following formula.

3.1. Convective exothermic coefficient of cross-flush straight tube bundles

$$ a_d = 0.2C_sC_z^{0.65}Pr^{0.33}Re \lambda $$

Kw/(m² °C) (1)

where:
- \( a_d \) Convection exothermic coefficient Kw/(m² °C)
- \( C_s \) Correction coefficient of geometric arrangement of tube bundle
- \( C_z \) Correction factor of the number of pipe rows in the direction of flue gas travel
- \( \lambda \) Average temperature of flue gas thermal conductivity Kw/(m² °C)
- \( Re \) Reynolds criterion number
- \( Pr \) Prandtl number
- \( D \) Equivalent diameter m

3.2. Convective exothermic coefficient of staggered cross-flow tube bundles

$$ a_d = C_sC_z^{0.65}Re^{0.6}Pr^{0.33} $$

Kw/(m² °C) (2)
3.3. Convection exothermic coefficient of longitudinal scour heating surface

\[ a_d = 0.023C_tC_l \frac{\lambda}{d} Re^{0.8} Pr^{0.4} \]  \text{Kw/(m}^2 \text{°C)} \tag{3}

Where

- \( C_t \) Correction coefficient, \( C_t = 1 \) when the flue gas is cooled
- \( C_l \) Relative length correction coefficient, the inlet of the round pipe is straight only when \( l/d < 50 \).

It is adopted when there is no rounded edge.

3.4. Convective exothermic coefficient of cross flow convection with transverse strip bundle or circular fin in line arrangement

\[ a_d = 0.015C_zC_s \frac{\lambda}{S_p6} \left( \frac{d}{S_p6} \right)^{-0.34} \left( \frac{h_{p6}}{S_p6} \right)^{-0.34} \left( \frac{\omega S_p6}{v} \right)^{0.72} \]  \text{Kw/(m}^2 \text{°C)} \tag{4}

where:

- \( S_p6 \) Fin pitch \text{mm}
- \( h_{p6} \) Fin height \text{mm}
- \( \omega \) Flue gas flow rate/m/s
- \( v \) Kinematic viscosity of flue gas \text{m}^2/s

With SZS type gas condensing boiler as an example, the convection bundle between the upper and lower boiler barrel is built by cross-flow light tube bundles in line arrangement. Calculated by Formula (1), the economizer adopts cross-flow spiral finned tube. When Calculated by Formula (4), the structure of the condenser is also cross-flow spiral finned tube. Considering the heat from condensation of flue gas, the results would be below the normal range if calculated by Formula (4).

For condensing boiler with natural gas as the fuel, as the composition of natural gas is relatively stable with a low content of sulfur, the acid dew point of flue gas does not generally go higher than 130 ℃. When the temperature of inlet water into the condenser goes over 40 ℃, the inlet flue gas temperature below160 ℃ and outlet smoke temperature above 80 ℃, we combined the coefficient formula of convective heat transfer for traditional cross - flush tube bundles with transverse strip or circular fin in line arrangement with the field test data of different furnaces to form a formula suitable for calculation within the following temperature range.

\[ a_d = 0.015C_zC_s \frac{\lambda}{S_p6} \left( \frac{d}{S_p6} \right)^{-0.34} \left( \frac{h_{p6}}{S_p6} \right)^{-0.34} \left( \frac{\omega S_p6}{v} \right)^{0.72} \]  \text{Kw/(m}^2 \text{°C)} \tag{5}

\( t_p \) Mean flue gas temperature ℃

### Table 1 Summary of Theoretical Calculation and Field Data

| Furnace Type | Inlet smoke temperature of condenser (℃) | Inlet water temperature of condenser (℃) | Outlet smoke temperature of condenser (℃) | Outlet water temperature of condenser (℃) | Heat transfer coefficient | Difference between Smoke Temperature (℃) |
|-------------|------------------------------------------|------------------------------------------|-------------------------------------------|-------------------------------------------|--------------------------|------------------------------------------|
| SZS58-1.6 /130/70-Q | Formula (4) | 152 | 45 | 89 | 62 | 40.5 | 6 |
| Field Data | 152 | 45 | 83 | 64 | / | / |
| SZS70-1.6 /130/70-Q | Formula (5) | 152 | 45 | 81 | 65 | 51.8 | 2 |
| Field Data | 159 | 42 | 90 | 61 | 41.2 | 10 |
Table 1 gives some typical field data of gas condensing hot water boiler condenser. Figure 1 shows that when Formula (5) is used for calculating convective exothermic coefficient in the condenser section of condensing boiler, the result is quite close to the field data. When calculated by traditional Formula (4), there is a greater difference between the exhaust gas temperatures, an inaccurate reflection of the actual heat transfer performance of the boiler. Because the exhaust gas temperature is lower than 80℃, the amount of condensed water will increase greatly, as indicated by the results by Formula (5), which is greatly different from the actual value.

4. Conclusion

Based on differences between condensing boiler and traditional boiler in heat transfer in condensing section, Formula (6) is given based on convective heat transfer coefficient of spiral finned tube of traditional boiler and numerous field calculations.

\[
a_d = 0.015 \zeta \frac{1.6}{t_p/100} \frac{d}{d_{ps}} \left( \frac{h_{pe}}{h_{ps}} \right)^{-0.14} \left( \frac{\omega_{pe}}{\omega_{ps}} \right)^{6.72}
\]

\(\text{Kw}/(m^2 \cdot ^\circ C)\) \hspace{1cm} (6)

When the inlet water temperature of the condenser is above 40℃, the inlet temperature of the flue gas is less than 160℃, and the outlet smoke temperature is more than 80℃, the calculated value of the formula is highly consistent with the field data (see Figure 1)
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