Experimental Analysis of Thermal Efficiency of Biomass-burning Hot Blast Furnace

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Abstract: This paper analyzes the main factors affecting the thermal efficiency of biomass hot blast furnaces, and compares the theoretical factors with the experimental ones that influence the thermal efficiency so as to provide suggestions for the improvement of the biomass hot blast furnace.

1. Introduction
In some areas of northern China, a hot blast furnace is needed in the process of grain drying. The hot blast furnace heats the air, and the hot blast can directly pass through the grain drying equipment to dry the grain. The materials used to produce energy for hot blast furnace installation include coal, gas, biomass and fuel [1]. The working principle of the hot blast furnace is: first, the fuel is fully burned in the combustion chamber of the hot blast furnace, and the hot gas after combustion enters the heat exchanger to exchange heat with the cold air outside; the gas after heat exchange is discharged into the atmosphere through the ash removal system, and the hot blast outside is sent to the grain drying tower through the pipeline to dry the grain. The hot blast furnace is mainly composed of three systems, namely, the fuel combustion system, the heat exchange system, and the gas exhaust system. The efficiency of the combustion system and the exhaust system can be analyzed according to the efficiency of the boiler. At present, there are many domestic studies on boiler efficiency [2]. Tubular hot blast furnace is mainly used domestically [3, 4], and its efficiency is related to the efficiency of combustion and heat exchanging.

2. Thermal efficiency of hot blast furnace
According to the literature and standards [5,6], the thermal efficiency of the hot blast furnace is related to the hot blast flow rate, the diameter of the air flue, the hot blast temperature and the inlet air temperature. It can be calculated with the heat of boiler and the heat of heat exchanger taken into consideration.

2.1 Thermal efficiency algorithm of hot blast furnace

2.1.1 Output heat

\[ Q_e = q \rho \times (\Delta CT) \]  

In the formula, \( q \) is the hot blast flow, \( \rho \) is the hot blast density, and the \( \Delta CT \) is the difference between the products of the average constant-pressure mass specific heat capacity and the temperature.
2.1.2 Input heat

\[ Q_r = Q_{\text{net,}v,\text{ar}}B \] (2)

In the formula, \( Q \) is the input heat; \( Q_{\text{net,}v,\text{ar}} \) and \( B \) is the low calorific value of the fuel; \( B \) is the average fuel consumption per hour.

2.1.3 Thermal efficiency

\[ \eta = \frac{Q_c}{Q_r} \times 100\% \] (3)

In the formula, \( \eta \) is the heat transfer efficiency of the hot blast furnace

2.2 Heat calculation formula of heat exchanger

\[ A = \frac{Q}{K(Tr - \Delta t)} \] (4)

In the formula, \( A \) is the heat exchange area, \( Q \) is the total heat transfer, and \( K \) is the thermal conductivity. The thermal conductivity varies from material to material and from medium to medium. If the same material is used in the heat exchangers with different structures, the \( K \) value will be different. \( Tr \) is the average temperature of the hotter medium, and \( \Delta t \) is the average temperature of the second hottest medium.

Theoretically, the main factors influencing the thermal efficiency of the boiler include the heat loss from exhaust gas, from incomplete solid combustion, from incomplete gas combustion, from heat dissipation and from physical heat loss of ash.

The area and the average temperature of the heat exchange surface are related to the calculation of heat exchanger. The heat transfer coefficient directly affects the overall efficiency of the hot blast furnace. In order to increase the efficiency of the heat exchanger, it is necessary to enlarge the heat transfer area, expand the average temperature difference between the hot and cold fluids, and increase the heat transfer coefficient.

Therefore, the selection calculation of the boiler and the heat exchanger is particularly important in the aspects of reducing heat loss of the boiler and improving the heat exchange efficiency so as to improve the thermal efficiency of the hot blast furnace.

3. Test and analysis of the hot furnace

3.1 Basic situation of the hot furnace

The tested hot blast furnace is a biomass hot blast furnace with a rated power of 4.2 MW. It is reconstructed from the original coal hot blast furnace, with the chain grate stoker unchanged. The combustion space inside the furnace is rebuilt and the original furnace body is re-insulated. The original heat exchanger belongs to the built-up type, and some convective heat exchange tubes are replaced after the ash is removed. Part of the gas is drained from the gas exhaust system and mixed with the fresh air before entering the combustion chamber.

3.2 Test situation

The use of the hot blast furnace is tested during its operation. The measure point map is shown in Figure 1 and the test results are shown in Table 1.
Figure 1 Measure point map of biomass hot blast furnace

1- measure point of biomass consumption; 2- measure point of exhaust gas; 3- measure point of heat exchanging; 4- measure point of hot blast temperature and flow; Note: slag and ash sampling and gas pressure test are not shown in the map.

For the hot blast furnace and the heat exchanger, the heat that can be obtained mainly include the heat loss of the gas, the recovered waste heat of gas, and the heat used by the hot blast furnace.

Table 1 Test data

| Item                              | Before rebuilding | After rebuilding |
|-----------------------------------|-------------------|------------------|
| Temperature /°C                   | -5                | -6               |
| Humidity /%                       | 32%               | 35%              |
| Hot blast temperature /°C         | 120               | 135              |
| Hot blast pressure /Pa            | 2000              | 2000             |
| Unit fuel quantity /Kg/h          | 950               | 950              |
| Low calorific value of biomass /KJ/Kg | 14280           | 14280            |
| Exhaust gas temperature /°C       | 140.90            | 109.45           |
| Exhaust gas temperature /%        | 1.66              | 1.30             |
| Carbon content of ash /%          | 10%               | 7%               |

The average exhaust gas temperature is reduced from 140.90°C to 109.45°C after building. The average temperature of the exhaust gas is reduced by 31.45°C or 22%. When the amount of fuel in the hot blast furnace and the air volume of the heat exchanger are kept substantially constant, reducing the exhaust gas temperature can greatly reduce the heat loss of the exhaust gas.

Figure 2 Comparison of exhaust gas temperature before and after rebuilding

The heat loss curves obtained before and after the hot blast furnace rebuilding are shown in the figure below. It can be seen from the figure that after rebuilding, the heat loss of exhaust gas is...
reduced by 34.71%, the heat loss of incomplete solid combustion is reduced by 25.30%, and the heat dissipation is reduced by 24.47%, while the physical heat loss of ash remains the same. The heat loss of incomplete gas combustion sees an increase of 50.00% after rebuilding. But the heat brought by gas is not enough to offset the heat loss of incomplete gas combustion.

After rebuilding, the average hot blast temperature rises from 120.60°C to 135.70°C, an increase of 15.10°C or 12.53%. When the amount of fuel entering the hot blast furnace and the air volume of the heat exchanger are kept substantially constant, higher hot blast temperature leads to higher efficiency of the hot blast furnace.

4. Conclusion
Based on the analysis and measurement of a nominal 4.2MW hot blast furnace in a grain depot, this paper draws the following conclusions.

(1) When the amount of fuel in the whole hot blast furnace and the air volume of the heat exchanger are kept basically constant, for the hot blast furnace after rebuilding and ash removing, its average exhaust gas temperature is reduced from 140.90°C to 109.45°C, a reduction of 31.45°C or 22%. Reducing the exhaust gas temperature can greatly reduce the heat loss of the gas, thereby improving the thermal efficiency of the hot blast furnace.

(2) When the amount of fuel in the whole hot blast furnace and the air volume of the heat exchanger are kept substantially constant, for the hot blast furnace after rebuilding and ash removing, its average hot blast temperature jumps from 120.60°C to 135.70°C, an increase of 15.10°C or 12.53%. It can be proved that the ash removing can significantly improve the heat transfer coefficient of heat exchangers, especially for those using the original coal-fired furnace as a heating source.

(3) When the amount of fuel in the whole hot blast furnace and the air volume of the heat exchanger are kept substantially constant, the heat lost of the incomplete gas combustion increases by 50.00% after rebuilding when the exhaust gas is partially introduced into the combustor. But the heat brought by gas is not enough to offset the heat loss of incomplete gas combustion. It can be seen that the introduction of exhaust gas for combustion reaction has no positive effect on the improvement of the thermal efficiency of the entire system.
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