Application and thermal economic analysis of plate low pressure economizer in flue gas waste heat recovery

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Abstract. Low pressure economizer is an important equipment to reduce exhaust gas temperature and recover waste heat of flue gas in power plants. In this paper, the welded plate heat exchanger is applied to the field of low pressure economizer. The waste heat of coal slag and flue gas is utilized comprehensively to raise the boiler feed water temperature and reduce coal consumption. The thermal economy of plate economizer and finned tube economizer is analyzed by the equivalent enthalpy drop method. The results show that the plate economizer has obvious advantages under the same pressure drop and heat load. Compared with the finned tube economizer, the heat transfer coefficient the of the plate economizer increases by more than 50%, and the volume decreases by about 2/3. After installing the slag cooler, the heat consumption rate decreases by 119.7 KJ/kWh, and the coal consumption decreases by 4.68 g/kWh.

1. Introduction

In recent years, with the increase of the proportion of renewable energy in the power grid, the number of generating hours of thermal power units is further reduced. How to improve the thermal efficiency of the units and reduce coal consumption has become the primary goal of thermal power plants. The heat loss caused by excessive exhaust gas temperature accounts for 70%-80% in the boiler heat loss\cite{1}. When the exhaust temperature increases by 10-15°C, the boiler efficiency decreases by 1% and the standard coal consumption increases by 3-4g/kWh\cite{2}. In China, the exhaust gas temperature of thermal power unit boilers is generally between 120-140°C, and it even exceeds 160°C for some units burning high sulfur coal. High flue gas temperature will not only affect the efficiency of generating units, but also affect the efficiency of dust removal and desulphurization efficiency.

The low pressure economizer system heats the condensate water of the steam turbine by recovering the waste heat from the flue gas, thereby reducing the steam extraction regeneration of the steam turbine, and the crowding extraction steam can be returned to the steam turbine to do work, thus effectively reducing the coal consumption. Scholars have done a lot of research on the flue gas waste heat utilization system. Han et al.\cite{3} analyzed the economic performance of 320MW unit equipped with economizer. The results show that the boiler efficiency is obviously improved and the coal consumption of power supply is obviously reduced after adding low pressure economizer. Wang et al.\cite{4} studied the influence of fin structure and distribution on heat transfer characteristics, wear characteristics and ash deposit performance of H-type finned tube economizer. An et al.\cite{5} analyzed
the influence of parallel and series connection of low pressure economizer and thermodynamic system on relative internal consumption rate, absolute internal consumption rate and cycle thermal efficiency of steam turbine.

The above researches are mostly concentrated on the finned tube economizer. However, finned tube economizer covers a large area, has low heat transfer efficiency and is easy to wear. Finned tube is easy to accumulate slag during long-term operation, which causes heat transfer deterioration. At the same time, the space of old units flue is limited, finned tube economizer is not conducive to the transformation of old units. In this paper, welded plate economizer is proposed to replace finned tube economizer. The thermal economy and heat transfer characteristics of plate economizer and finned tube economizer under the same working conditions are compared by equivalent enthalpy drop method. The comprehensive utilization of waste heat and acid dew point corrosion of flue gas were considered. The low pressure economizer and slag cooler are connected in series to raise the temperature of condensate water entering the low pressure economizer so as to avoid acid dew point corrosion. The thermal economy after installing slag cooler was also studied.

2. Thermal economy analysis of low pressure economizer system

2.1. Basic principle
The low pressure economizer system is independent of the main feed water system. The exhaust heat is used to heat some condensate water of lower temperature, replacing some extraction steam of the steam turbine, so that the extraction steam is crowded to the steam turbine and continues to expand and work. After adding low pressure economizers, a large amount of flue gas waste heat enters the regenerative system, which is the additional heat obtained without increasing the amount of boiler fuel, and it is converted into electrical power with a certain efficiency. This new increment is far greater than the power loss caused by the crowding steam extraction and turbine vacuum drop, so the unit economy is improved without exception.

2.2. Thermal economic analysis method
The thermal system analysis methods adopted in this paper are based on heat balance and flow balance. The concept of equivalent enthalpy drop is adopted in the measurement of thermal economy[6]. The equivalent enthalpy drop method[7] is based on the selected initial and final steam parameters and regenerative parameters. It is premised on the fixed values of the new steam flow rate and the fuel heating rate of the unit. The economic effect of the change of the whole thermodynamic system can be obtained by quantitative calculation of the flow and heat of a certain stage of extraction steam. It is accurate and convenient to diagnose the thermal system of power plant and is the basic theory of economic diagnosis of thermal system.

2.2.1. Expression of heat release for heater
For any heater $j$, the heat release can be classified into three types: the enthalpy rise of feed water in the heater $\tau_j$, the heat release of steam in the heater $q_j$, and the heat release of drainage in the heater $\gamma_j$. In addition, There are other steam brought into the heater, the heat release of this part of the external steam is recorded as $q_{sj}$.

The expressions of the heat release of drainage heater are

$$\tau_j = h_{wj} - h_{w(j-1)}$$  \hspace{1cm} (1)

$$q_j = h_{j} - h_{j-1}$$  \hspace{1cm} (2)

$$\gamma_j = h_{d(j+1)} - h_{dj}$$  \hspace{1cm} (3)

The expressions of the heat release of collection heater are

$$\tau_j = h_{sj} - h_{w(j-1)}$$  \hspace{1cm} (4)
\[ q_j = h_j - h_{w(j-1)} \]  \hspace{1cm} (5)  

\[ \gamma_j = h_{d(j+1)} - h_{w(j-1)} \] \hspace{1cm} (6)  

where, \( h_{w(j)} \), \( h_j \), \( h_{d(j)} \) are the enthalpy of the outlet water, extraction steam and drainage of heater \( j \) respectively.

### 2.2.2. Equivalent enthalpy drop method for thermodynamic system

For any heater \( j \), the equivalent enthalpy drop is expressed as

\[ H_j = (h_j - h_r) - \sum_{r=1}^{j-1} \eta_r A_r \text{(kJ/kg)} \] \hspace{1cm} (7)  

where, if the heater \( j \) is a drainage heater, \( A_r = \gamma_r \) below heater \( j \) until the collection heater (including this collection heater), and for the subsequent stages of the collection heater, \( A_r = \tau_r \). If the heater \( j \) is a collection heater, \( A_r = \tau_r \).

The gross equivalent enthalpy drop of 1kg new steam

\[ H_{gr} = (h_r - h_r) - \sum_{r=1}^{j-1} \tau_r A_r \text{(kJ/kg)} \] \hspace{1cm} (8)  

The equivalent net enthalpy drop of the new steam can be calculated after deducting shaft seal leakage and other losses.

\[ H = H_{gr} - \sum_{r=1}^z \Pi \text{(kJ/kg)} \] \hspace{1cm} (9)  

### 2.3. Analysis of thermal economy after installing low pressure economizer

#### 2.3.1. Rated condition of unit

There are two 55MW extraction heat supply turbines in a power plant. The exhaust gas temperature of boilers exceeds 135°C. The potential of flue gas waste heat utilization is great. With the application of low temperature corrosion resistant steel in heat exchangers, the utilization potential can be further improved. The original thermodynamic system diagram of the power plant is shown in Figure 1.

![Figure 1](image-url)  

**Figure 1.** The thermodynamic system diagram of original rated condition

The condensed water after the steam seal heater with an enthalpy of 130.88kJ/h and a flow rate of 100t/h is derived and heated to 85°C by the slag cooler and brought to the condensate system before the #2 low pressure heater.

#### 2.3.2. Transformation scheme of unit waste heat utilization

The thermodynamic system diagram after transformation is shown in Figure 2.
Considering that if the inlet water temperature of low pressure economizer is too low, it is easy to cause low pressure corrosion of the tube, and the high water temperature will make the heat transfer temperature difference too small and increase the heat transfer area, so the low pressure economizer and the slag cooler are connected in series. The rated outlet water temperature of the slag cooler (85°C) is set as the inlet water temperature of the low pressure economizer. Due to the adoption of new sulfuric acid corrosion resistant special steel, the flue gas outlet temperature of low pressure economizer system can be designed to be lower. Under the modified design conditions, the inlet temperature of flue gas side is 145°C, the flow rate is 2.5×10⁵m³/h. The exhaust temperature is finally reduced to about 100°C, which is close to or below the dew point temperature of flue gas.

3. Characteristics of plate low pressure economizer

The plate bundles of the new plate low pressure economizer are stacked together by two identical plates. A circular channel with elliptical cross section is formed by laser penetration welding and charging. The circular channel is a condensate water channel, as shown in Figure 3. The plates are staggered and stacking. The space between the plates is the flue gas ripple channel, as shown in Figure 4.

Compared with the traditional finned tube low pressure economizer, the advantage of the new type plate low pressure economizer is that its heat transfer component is plate. Its characteristics are: firstly,
all the heat transfer surfaces of the medium in the core are primary surfaces, which improves the heat transfer efficiency; secondly, the structure is compact, high temperature resistance and not easy to scale; thirdly, it can be made into multiple modules, easy to remove and clean.

4. Calculation and analysis of thermal economy

4.1. Calculation results
Under the design condition, the condensate water with a flow rate of 90 t/h and a temperature of 85°C at the outlet of the slag cooler is evenly distributed to the tube row of the heat exchanger through the inlet header. After absorbing the heat of the flue gas, it is sent back through the outlet header and collected with the unheated condensate water and then enters the inlet of the #2 low pressure economizer. When the slag cooler needs to be shut down, the low pressure economizer can also be operated separately, that is, the slag cooler is bypassed. The water inlet temperature of the low pressure economizer is still 31.3°C and the flow rate is still 90t/h before the #1 low pressure heater in the rated working condition of the thermal system. The condition of two types of low pressure economizer operating separately and in series connection with slag cooler are simulated by using Fluent numerical simulation software. The results are shown in Table 1.

| Table 1. Comparison of two kinds of low pressure economizer operating conditions. |
|-----------------------------------|-------------------|-----------------|-----------------|-----------------|-----------------|
| heat exchanger                     | flue gas temperature/°C | condensate water temperature/°C | heat transfer coefficient/w(m²·k) | heat exchange area/m² | total heat exchange/kw |
| run separately                     | plate inlet 145 | outlet 78 | inlet 31.3 | outlet 73.1 | 69 | 1043 | 4320 |
| finned tube                        | inlet 145 | outlet 79.7 | inlet 31.3 | outlet 72.1 | 41.6 | 1908.4 | 4267 |
| run with slag cooler               | plate inlet 145 | outlet 103 | inlet 85 | outlet 109.6 | 75.5 | 1043 | 2510 |
| finned tube                        | inlet 145 | outlet 110.3 | inlet 85 | outlet 106.6 | 42.6 | 1908.4 | 2275.8 |

The total heat transfer of the two kinds of low pressure economizer is basically the same under the condition that the slag cooler is connected in series. The equivalent enthalpy drop method is used to calculate the energy saving state of the system connected with low pressure economizer. The calculation results of the total energy saving effect of the series system are shown in Table 2.

| Table 2. The thermal economy when the low pressure economizer and the slag cooler are installed in series |
|-------------------------------------------------|--------|-------|
| Item                                        | value  | unit  |
| Net equivalent enthalpy drop $H_{eq}$           | 987.5  | kJ/kg |
| Equivalent heat drop increment $d_{H}$          | 13.22  | kJ/kg |
| Unit thermal economic increase ratio            | 1.36%  | -     |
| Unit heat consumption reduction                 | 119.7  | kJ/kWh|
| Saving of coal consumption rate                 | 4.68   | g/kWh |
| Turbine efficiency                              | 0.3873 | -     |

Because of absorbing of external heat sources, the steam extraction of the steam turbine is saved. When the extracted steam is returned to the steam turbine's regenerative system and worked, the thermal economy of the unit can be increased by 1.36%, the heat consumption of the steam turbine can be reduced by 119.7 kJ/kWh, and the standard coal consumption can be reduced by 4.69 g/kWh.
Results show that compared with the traditional finned tube economizer, the new plate-shell heat exchanger has the advantages of high compactness, good heat transfer effect and small volume.

Taking the design condition of the slag cooler in series as an example, it can be seen from Table 1 that the heat transfer coefficient of the new type of plate economizer is much higher than that of the finned tube economizer. Under the same transmission pressure drop, the heat transfer coefficient is increased by more than 50%. Therefore, when the heat transfer area is reduced by nearly half, the heat exchange quantity is increased on the contrary. As the heat transfer area is greatly reduced, the volume of plate economizer is also reduced by about 2/3 than that of finned tube economizer. The comparison visual histogram of two kinds of economizer is shown in Figure 5.

![Comparison of Heat Exchanger Types](image)

**Figure 5.** The data comparison of the two kinds of low pressure economizers

5. Conclusion

In this paper, the welded plate heat exchanger is applied to the field of low pressure economizer. The thermal economy of plate economizer and finned tube economizer is analyzed by the equivalent enthalpy drop method. The results show that,

1. If the low pressure economizer system is connected in series with the original slag cooler system, the condensate state can be further improved, and the thermal economy of the unit can be greatly improved compared with the separate slag cooler system. The low pressure economizer system can make full use of the waste heat of boiler flue gas.

2. Under the same pressure drop, the heat transfer coefficient of the new plate economizer is increased by more than 50% compared with the finned tube economizer, and the volume of economizer is reduced by about 2/3.

3. After adding the slag cooler, the flue gas temperature increases, which is beneficial to avoid dew point corrosion of economizer. The heat consumption rate decreases by 119.7 KJ/kWh, and the coal consumption decreases by 4.68 g/kWh.

4. Compared with the traditional finned tube low pressure economizer, the pressure drop of the plate low pressure economizer is only about 10% higher. The influence of the equipment on the flue fan is completely acceptable.

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