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Energy Saving Potential and System Energy Saving Model of Flue Gas Waste Heat in Coal-fired Power Plant Boiler

Aixia Duan*[a], Yongzhi Huang[b], Yanling Duan[a]

[a]North China University of Water Resources and Electric Power, Henan 450045, China
[b]China Resources Power Rundian Energy Science and Technology Co.,Ltd., Henan 450011, China
dax0307@163.com

In order to explore the waste heat utilization of the boiler tail gas, which can improve the thermal economy of the power plant and reduce the consumption of the power fuel, the operation characteristics of blast furnace gas boiler are deeply studied, and the energy saving potential of flue gas waste heat of blast furnace gas tail is excavated. Through the comparison of different flue gas waste heat utilization methods, the optimization of tail heating surface is combined with the cascade utilization of waste heat energy resources, the research of efficient flue gas waste heat utilization system is carried out, and the concrete optimization scheme is put forward. It is concluded that after matching, it not only reduces the exhaust temperature of blast furnace gas boiler and improves the thermal economy of the unit and the effect of environmental protection, but also finally has an important significance in the increase of power plant generating capacity.

1. Introduction

The general principle of waste heat utilization should be based on the thermodynamics. According to "quality using energy and cascade utilization", for flue gas at different temperatures and different tastes, the waste heat is recovered and utilized. For high temperature waste heat and medium temperature waste heat, in view of its high level of energy, it is generally converted into high grade electric energy through turbine generator. At present, the common methods are using waste heat boiler to recover the waste heat of high temperature flue gas, applying gas turbine for power recovery or adopting high temperature air combustion technology to directly recover medium and high temperature waste heat (Avagianos et al., 2017). Low temperature waste heat energy quality is low, but with the serious energy problem, low temperature waste heat utilization research is more and more widely. The main waste heat of low temperature flue gas is heated by air preheater and economizer, which can be used for preheating and drying raw materials or working fluids. At this stage, China's high and medium temperature waste heat utilization technology has reached the international advanced level, and the waste heat utilization technology of low temperature flue gas is not yet mature, which is still a hot research field at home and abroad.

2. Support engineering introduction

Based on the project, a high pressure natural circulation boiler for pure blast furnace gas produced by Shanghai boiler works is developed. The boiler adopts two-stage economizer and single pole air preheater arrangement, and has separate heat pipe gas heater at the same time. The rated evaporation rate of the boiler is 240t/h, the superheated steam parameter is 9.8MPa/540, the boiler thermal efficiency is 89.83%, and the exhaust gas temperature design value is 150 DEG C (Cabral and Mac Dowell, 2017).
The steam turbine is C50-8.83/0.981-4 type, and 50MW extraction steam turbine. In the rated steam turbine rated output condition, mechanical parameters are: p_0=8.83MPa and t_0=535 DEG C. The exhaust pressure of steam turbine is A=0.0041MPa. The extraction steam is 130t/h and the pressure is 0.9807MPa. Enthalpy rise of feed water pump is $\Delta\tau_p = 15.74kj/kg$; enthalpy rise of condensate pump is $\Delta\tau_{cp} = 3.21kj/kg$. The thermodynamic parameters of the unit are as follows:

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Table 1: Unit thermodynamic parameters

Parameters	Symbol	Unit	Value
Rated generating power	P	MW	50
Main steam flow	D_0	kg/s	80.56
Industrial steam extraction	D_{hi}	kJ/kg	36.11
Unit steam consumption rate	3600*D/Nd	kg/(kW*h)	5.74
Unit heat consumption rate	HR	kJ/kW*h	6991.06
Boiler efficiency	η_b	%	90
Pipeline efficiency	η_{gb}	%	98
Electro mechanical efficiency	η_{mg}	%	97
Ambient temperature	t_0	°C	20
Exhaust gas temperature	t_y	°C	150

Under rated steam extraction rated condition, the heat characteristic data of steam turbine is shown in table 2.

Table 2: Thermodynamic characteristic curve of 50MW steam extraction steam turbine

Levels	0	1	2	3	4	5
hi	3474.36	3207.8	3112.5	2999.57	3083.41	2776.5
h_{wi}	—	958.12	829.37	667.18	531.48	425.75
h_{di}	—	959.5	828.33	—	543.39	437.3
qi	2516.24	2248.3	2284.17	2468.09	2540.02	2339.2
γ_i	—	—	131.17	296.85	—	106.09
	—	128.75	162.19	135.7	105.73	186.97

The regenerative cycle system of steam turbine is composed of 2 high pressure heaters, 3 low pressure heaters and 1 deaerator. The thermodynamic characteristics data of steam turbine are shown in table 3.

Table 3: Thermodynamic parameters of regenerative heaters at all levels

Parameters	Extraction steam pressure /MPa	Extraction enthalpy /(kJ/kg^{-1})	Inlet water temperature/°C	Extraction steam flow /(t·h^{-1})
No.2 high pressure heater	2.69	3207.8	193.63	16.61
No.1 high pressure heater	1.51	3071.2	158.09	15.33
Deaerator	0.9807	2977.6	126.35	34.28
No.3 low pressure heater	0.2879	2923.2	101.35	2.46
No.2 low pressure heater	0.1284	2776.5	56.75	7.05
No.1 low pressure heater	0.021	2516.7	29.25	1.98

3. Flue gas waste heat transformation scheme

3.1 Preliminary scheme of flue gas waste heat transformation

Because the domestic power plant flue gas waste heat utilization system uses low temperature economizer technology, after the heat transfer surface is arranged on the air preheater, it limits the heated temperature rise of condensate and condensate extraction point. The action capability of excluded turbine extraction steam power is limited, and the heat utilization rate of the flue gas is only 15%-20% (Darmawan et al., 2017). Therefore, we can learn more from cascade recycling flue gas waste heat method of foreign power plants. A low temperature economizer is installed in the tail flue, and the condensate flow through the low pressure heater is reduced, as shown in figure 1. Based on the principle of optimal utilization of waste heat, although this scheme increases the heat increase of turbine caused by cold source loss and reduces the turbine efficiency, the heat owned power of Captive Power Plant was improved with the increase of cycle efficiency, the generating capacity of steam turbine increases, and the overall economy increases.

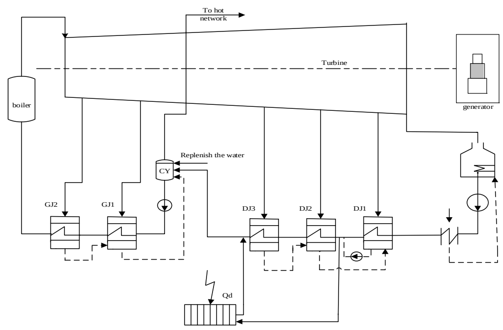

Figure 1: Arrangement of flue gas waste heat utilization system

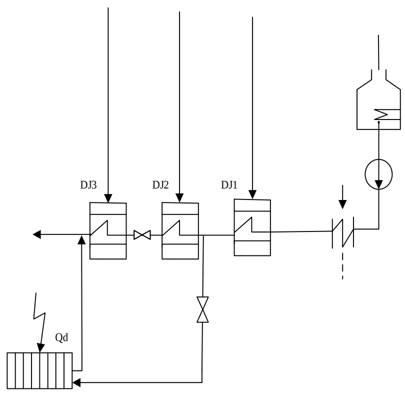

Figure 2: Schematic diagram of scheme 1

3.2 Concrete scheme of optimization transformation

The exhaust gas temperature of boiler in the case is 150 DEG C. Through the above thermodynamic calculation principle, the condensed water temperature into low economizer should not exceed the temperature of exhaust gas, and the highest extraction parameters are limited. Then, considering the boiler gas, tail flue installation and other factors, the lowest outlet temperature of low temperature economizer is designed to 100 DEG C. Thus, three schemes have been adopted (Friesenhan et al., 2017):

Scheme 1: parallel with No. 2 low pressure heater. Partial condensation water is introduced from the entrance of No. 2 low pressure heater, and the low temperature economizer is introduced into the heat system after absorbing and determining the heat, and it is connected with the main condensate water at the outlet of No. 2 low pressure heater. At this point, the flue gas waste heat can replace some second stage steam extraction.

Scheme 2: tandem between No.1 and No.2 low pressure heaters. The shunt valve is arranged in the outlet of No.1 low pressure heater, which can control all or part of the condensed water into low temperature economizer. In the meanwhile, we set the pressure of millet and return the condensate water having absorbed certain heat to the thermal system, and meet with the main condensate water at the entrance of No.2 low-pressure heater (Oluleye et al., 2016). At this point, flue gas waste heat can replace some second stage steam extraction.

Scheme 3: cross stage parallel connection with No.2 and No.3 low power heaters. From the inlet of No. 2 low pressure heater, the condensed water is diverted and some condensed water enters into the low temperature economizer (Santhanam et al., 2016). After absorbing a certain amount of heat, it returns to the regenerative system and joins the main condensed water phase at the outlet of No.3 low-pressure heater. At this point, flue gas waste heat can replace some second and third stage steam extraction.

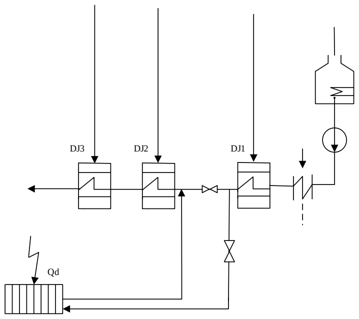

Figure 3: Schematic diagram of scheme 2

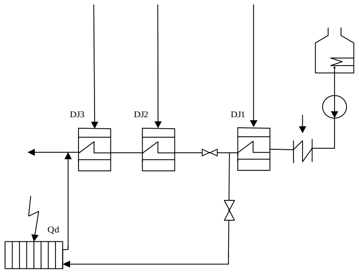

Figure 4: Schematic diagram of scheme 3

4. Thermodynamic analysis

4.1 Analysis of flue gas composition

Through 50MW full blast furnace gas high pressure boiler burning furnace gas parameters, after calculation, each flue gas composition is as follows (Wen et al., 2017):

Table 4: Analysis of composition characteristics of flue gas

Items	Data
N_2 volume share /%	72.5
CO_2 volume share/%	16.3
SO_2 volume share/%	0.1
Steam volume share/%	11.1
Absolute humidity of humid air /kg/kg	0.01
Fly ash fraction afh	0.92

The exhaust gas temperature was reduced from 150 DEG C to 100 DEG C by using the flue gas waste heat utilization system (Terhan and Comakli, 2016). Look-up table shows that the gas density and constant pressure specific heat value can calculate the heat release of flue gas, that is, flue gas residual heat.

Table 5: Gas density and specific heat value at constant pressure

Gases	150°C		100°C	
	Density, kg/m^3	Specific heat at constant pressure (kJ/kg)	Density, kg/m^3	Specific heat at constant pressure (kJ/kg)
N_2	0.7879	1.0478	0.9147	1.0433
CO_2	1.2399	0.9678	1.4407	0.9194
SO_2	1.8103	0.7001	2.1078	0.6736
H_2O	0.5107	1.9804	0.5976	2.0798

4.2 Heat transfer analysis of waste heat utilization

Heat exchanger is not only the widely used equipment to ensure certain process and conditions, but also the main equipment for the development and utilization of industrial secondary energy and realization of waste heat recovery and energy saving. Based on heat transfer and fluid theory as the principle, the heat transfer of low temperature economizer can be analyzed theoretically. In this paper, the most commonly used carbon steel pipe in the market is taken as an example to calculate and analyze. According to the material properties of carbon steel pipe and convection heat transfer theory, the transverse erosion heat transfer tube of flue gas is analyzed.

$$\Phi = hA\Delta A_m \tag{1}$$

$$\Delta t_m = \frac{\Delta t_{max} - \Delta t_{min}}{\ln(\Delta t_{max} / \Delta t_{min})} \tag{2}$$

In the above formulas, Φ refers to the heat exchange amount, kJ/s, h suggests the heat exchange coefficient W/m^2. K, A indicates the heat exchange volume, m^2, and Δt_m is the heat transfer difference. The convective heat transfer coefficient is

$$h = 0.332\frac{\lambda}{d} Re^{1/2} Pr^{1/3} \tag{3}$$

In the above formula, λ means the thermal conductivity of flue gas, $W/m^2 \cdot K$, d suggests the diameter, *m, Re indicates the Reynolds, and Pr* is Prandtl coefficient (Li et al., 2016). According to the thermal analysis method mentioned above, combined with the actual operation data, the equivalent flame drop method is used to calculate the thermodynamic performance of the three integration schemes on LJA:

Table 6: Thermodynamic calculation results of waste heat utilization system

Main thermodynamic data	Scheme 1	Scheme 2	Scheme 3
Large temperature difference / DEG C	48.65	93.25	43.25
Small temperature difference / DEG C	43.65	43.25	23.65
Logarithmic temperature difference / DEG C	46.105	65.08	32.47
Condensate water flow / (kg • s^{-l})	6.02	25.11	3.84
Alternative enthalpy rise of condensed water /(kJ • kg^{-1})	186.97	44.81	292.7
Increase thermal efficiency /%	0.2	0.39	0.42
Annual increase in power generation /ten thousand kWh	68.68	107.62	118.25

5. Conclusions

In the three schemes, the condensate flow in series is the largest when the residual heat is recovered, and the condensation water in parallel and in cross parallel is greatly different from that in series (Chen et al., 2017). The condensate flow in the cross parallel is still slightly less than that in the parallel connection mode.

The heat transfer temperature difference is the largest in series, parallel in the second, and the minimum is in cross stage parallel heat transfer, which determines that energy saving potential in series is the maximum.

Because the exhaust flue gas temperature is relatively low, the condensing water temperature is relatively low after heating. In the three schemes, for the condensation water replacing the LP (Low Pressure) heater, the maximum is the cross - stage parallel, followed by parallel connection, and finally the cross - stage parallel.

The thermal efficiency of series connection and cross parallel connection is obviously increased, and the optimal scheme of the waste heat utilization system is determined by the weak advantage of 0.03% in the cross parallel connection.

According to the above calculation results, it can be seen that, the high efficiency flue gas waste heat utilization system with low temperature economizer is adopted in the project, and the three schemes are feasible transformations. The unit efficiency can be increased by at least 0.2%, especially the thermal efficiency of the cascade parallel scheme is increased by 0.42%. With the comprehensive analysis of engineering thermodynamics, heat transfer and fluid mechanics, without affecting the operation safety and reliability, for the heat transfer temperature, pipe resistance, small number of low pressure heater, not high temperature of condensed water into low temperature economizer and so on effects, the extraction cross level parallel has the best energy-saving thermal economic benefits, and the cross level parallel is the optimal scheme.

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