

Chapter 56

Waste Heat Recovery System Using Coal-Fired Boiler Flue Gas to Heat Heating Network Return Water

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Abstract At present, exhaust flue gas temperature of coal-fired boiler is generally above 120 °C, while the temperature of boiler burning high sulfur coal may be higher in China. Meanwhile, the boiler burns large amount of fuel to heat the heating network return water to the supply temperature. A specially designed waste heat recovery system, which can reduce exhaust flue gas temperature to 60–70 °C and recycle large amount of sheat and latent heat in the flue gas to heat the return water, is designed. This paper included three parts. In the first part, the return water temperature duration in the heating season of 99, 64, 29 MW boilers which are three typically used in Harbin are calculated. The feasibility of the system is verified with the results that the return water temperature kept lower than 55 °C for a long period of time. In the second part, the system implementation plan including the material of heat transfer equipment and the choice of heat pump concerned are discussed. The titanium alloy plate heat exchanger and first absorption heat pump are selected. Then thermodynamic and hydraulic calculations of the system are done to determine the amount of flue gas heat recovery, structure of water spray chamber, plate heat exchangers, and absorption heat pump design. In the third part, the dynamic payback periods of waste heat recovery system used in these three boilers are calculated and the results are less than the life cycle of the heat recovery system.

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56.1 Introduction

Because of coal-fired boiler flue gas heat recovery equipment has low temperature dew point corrosion problem, exhaust flue gas temperature of coal-fired boiler is generally above 120 °C [1] while the temperature of boiler burning high sulfur coal may be higher in China. Researchers did much work to reduce flue gas temperature. Yang et al. (2012) designed low-temperature gas waste heat recovery system by heat pipe technology and did economic analysis [2]. Li et al. (2009) designed associated heating system of solar energy and boiler afterheat [3]. Hu and Yue (2012) found that low pressure economizer was able to reduce exhaust flue gas temperature and coal consumption [4].

Exhaust flue gas temperature is so high that there is still large quantity of sensible latent heat left unused. Under this circumstance, author designed a heat recovery system which used the flue gas to heat heating system return water.

56.2 Feasibility Analysis of Coal-Fired Boilers' Flue Gas Heat Heating System Backwater

Quality regulation is most commonly used in China. According to the statistics of Xi'an in recent years, return water temperature lasts lower than 55 °C for about half time of each heating season in district heating systems with the supply and return water temperature of 95/70 °C [2].

When heating systems use quality regulation, the calculation formulas of supply and return water temperature are (56.1) and (56.2).

$$\tau_g = t_g = t_n + 0.5(t'_g + t'_h - 2t_n)\overline{Q}^{1/(1+b)} + 0.5(t'_g - t'_h)\overline{Q} \quad (56.1)$$

$$\tau_h = t_h = t_n + 0.5(t'_g + t'_h - 2t_n)\overline{Q}^{1/(1+b)} - 0.5(t'_g - t'_h)\overline{Q} \quad (56.2)$$

$$\overline{Q} = \frac{t_n - t_w}{t_n - t'_w} \quad (56.3)$$

where t_g and t_h separately represent supply and return water temperature when outdoor temperature is t_w , t'_g , and t'_h separately represent supply and return water temperature when outdoor temperature is t'_w , \overline{Q} is relatively heat load ratio, b is

radiator coefficient, t_n is design indoor temperature, t_w is outdoor temperature, t'_w is outdoor calculated temperature of heating.

The return water temperature and their duration with quality adjustment are analyzed.

t'_w in Harbin is known as $-26\text{ }^\circ\text{C}$, t_n is known as $18\text{ }^\circ\text{C}$, and the three boilers t'_g and t'_h are all $150/90\text{ }^\circ\text{C}$. Then according to (56.1, 56.2), the supply and return water temperature in corresponding to different outdoor temperature can be calculated. According to weather datas of Harbin and (56.3), duration corresponding to different Relative heat load ratios can be obtained. The results are shown in Table 56.1.

\bar{Q} is 0.48 when heating system return water temperature is about $61\text{ }^\circ\text{C}$ and duration is about 130 days. Total days of heating season are 179 days in Harbin. So the last time of heating system return water temperature below $60\text{ }^\circ\text{C}$ is 49 days.

According to the analysis, it is feasible to design a certain system which uses boiler exhaust flue gas to heat heating network backwater. In the case of low return water temperature, the system can take full advantage of the exhaust flue gas waste heat to raise the return water temperature in order to reduce the amount of coal and save energy.

Table 56.1 Supply and return water temperature corresponding to different outdoor temperature of $150/90\text{ }^\circ\text{C}$ heating system with quality regulation

$t_w(^\circ\text{C})$	$t_g(^\circ\text{C})$	$t_h(^\circ\text{C})$	\bar{Q}	$N(\text{d})$
5	66.8	49.1	0.3	179
3	72.8	52.4	0.34	164
0	81.6	57	0.41	145.1
-2	87.3	60	0.45	133.3
-4	92.9	62.9	0.5	123.3
-6	98.4	65.6	0.55	113.6
-8	103.8	68.3	0.59	104.5
-10	109.1	71	0.64	94.5
-12	114.4	73.5	0.68	83.2
-14	119.7	76	0.73	70.4
-16	124.8	78.5	0.77	55.5
-18	130	80.9	0.82	41.6
-20	135	83.2	0.86	28.4
-22	140.1	85.5	0.91	16.2
-24	145.1	87.8	0.95	8.3
-26	150	90	1	3.4

56.3 Introduction and Heat Gain of Coal Burned Boilers’ Gas Flue Heat Recovery System

56.3.1 System Introduction

The system using coal-buren boiler exhaust flue gas to heat heating system return water designed in this paper is shown in Fig. 56.1. In this system, the flue gas passes through 1, 2, a short duct, 3, 5 successively and then releases into the atmosphere.

Heat recovery process is divided into two parts. In the first part, water is pumped by 9, through 6 and 11, get to 3 to exchange heat with the flue gas. There is not much spray water deposit in the spray chamber. As a certain slope existed in the first spraying chamber, water flow by gravity to 7 where impurities are removed. The first water spray chamber at the same time acts as the role of dust removal and desulfurization. The backwater is heated by 6 and then fed back to the boiler. In the second part, water is pumped by 10, through 8 and 11, get to 3. As gas temperature is reduced after the first spray heat exchanger, the water temperature in 3 will not be very high. The circulating water temperature of the second paragraph is below the dew point of water vapor in the flue gas, a large number of latent heat can be obtained. Heating network backwater is heated by 8 whose low-temperature heat source is the water gained in the second paragraph and then fed back to the boiler. The quantity of heating system backwater into the plate heat exchanger or heat pump system control should be controlled by the valve based on actual situation.

Where 1 is dust collector, 2 is the first spray chamber, 3 is the second spray chamber, 4 is exhaust pipe, 5 is eliminator, 6 is plate heat exchangers, 7 is

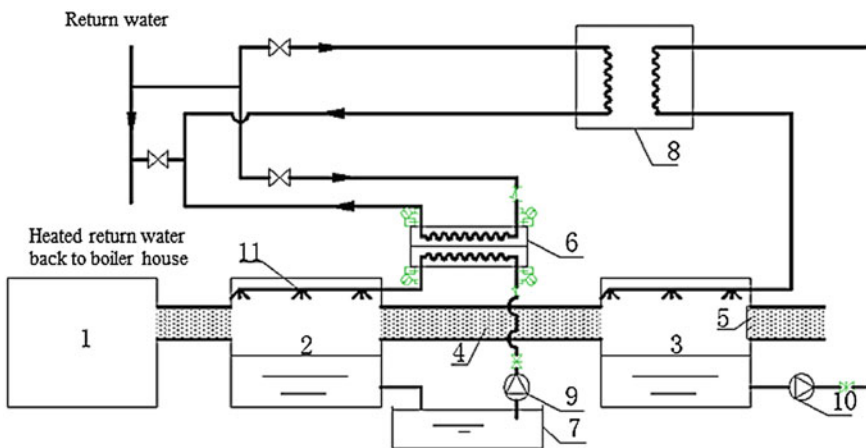


Fig. 56.1 Schematic of coal-fired boiler’s flue gas heat recovery system

Table 56.2 Operation parameters of the three different boilers under the worst condition

Project		SHW99-1.6/150/ 90-H	SHW64-1.6/150/ 90-H	SHW29-1.25/130/ 70-H
Coal type		Lignite	Lignite	Lignite
Exhaust gas temperature		156 °C	165 °C	158 °C
Total amount of smoke (under exhaust gas temperature)		301526 m ³ /h	227586 m ³ /h	107273 m ³ /h
Dust content		-	-	-
Amount of coal		$M_1 = 30\,431.5$ kg/h	$M_2 = 19\,818.8$ kg/h	$M_3 = 9\,034$ kg/h
Flue gas composition	Actual flue gas volume	6.8536 Nm ³ /kg	6.8536 Nm ³ /kg	8.1311 Nm ³ /kg
	RO ₂ Volume fraction	0.0982	0.0982	0.0993
	H ₂ O Volume fraction	0.1204	0.1204	0.1089

sedimentation pool, 8 is heat pump system, 9 and 10 are both circulating pump, 11 is stainless steel nozzles, 12 is evaporator, 13 is absorber, 14 is generation, 15 is condenser, 16 is throttle valve, 17 is solution valve, 18 is working fluid pump, 19 is solution pump, and 20 is solution heat exchanger.

56.3.2 Heat Gain of Heat Recovery System

In the flue gas heat recovery system, flue gas contacts with water directly and force spray heat exchange happened which is complex heat and mass transfer process. In this article, the recovery heat quantity of spray chamber is obtained by calculating the difference between the enthalpy of the flue gas at different temperatures.

In this paper, three typical boilers fed by brown coal are chosen for example in Harbin, which are 99, 64, and 29 MW boiler. The three boilers operation parameters are shown in Table 56.2.

The process of heat exchange in the heat recovery system is divided into two sections. The gas flue temperature is expected to reduce from 130 to 100 °C in the first spray chamber and then to 60–70 °C in the second one. In this paper, it is assumed that the flue gas temperature is reduced to 100 °C in the first paragraph, to 60 °C in the second one when the heat gain calculation is done. Excess air ratio is assumed as 1.6. The results of heat gain calculation are shown in Table 56.3.

Table 56.3 Heat gain of spray chamber

Boiler type (MW)	Heat gain (kW)	
	First paragraph	Second paragraph
99	4216	2971
64	3188	1953
29	1448	984

56.4 Equipment Selection Analysis and Calculations of Heat Exchange System

56.4.1 Design of Plate Heat Exchangers

Plate heat exchangers and evaporator of heat pump system in this paper both contact with the recycled water which exchanged heat with the gas flue directly. As there are still little impurities and sulfide left after the flue gas go through the dust collector and the sulfide would react with water to generate sulfate, acid corrosion should be taken into account. Given that titanium and titanium alloy are highly corrosion resistant and have long service life, titanium alloy are chosen as materials of heat exchangers in this article.

Take design of 99 MW boiler's plate heat exchanger for example. Known conditions are that heat exchanging quantity without considering heat loss. Inlet and outlet temperature of high temperature water obtained by the water exchanging heat with the flue gas side (which is called hot side of plate heat exchanger below) are 80, 70 °C. Inlet temperature of return water side (which is called cool side below) is 55 °C. Outlet temperature of cool side can be calculated according to energy conservation law.

$$Q_1 = cM_c(t_{co} - t_{ci}) \quad (56.4)$$

where c (kJ/(kg·K)) is specific heat of water, M_c (t/h) is water flow into plate heat exchangers equals to 1/3 of boiler circulating water, t_{ci} (°C) and t_{co} (°C) separately represent in and out water temperature of plate heat exchangers' cool side.

So

$$t_{co} = \frac{Q_1}{cM_c} + t_{ci} = \frac{4216 \times 10^3 \times 3600}{4.2 \times 473 \times 10^6} + 55 = 63 \text{ °C}$$

Water flow of plate heat exchangers' hot side can be calculated.

$$M_h = \frac{Q_1}{c_h(t_{hi} - t_{ho})} = \frac{4216 \times 3600}{4.2 \times (75 - 65)} = 361.4 \text{ t/h}$$

where M_h (t/h) is water flow of plate heat exchangers' hot side, t_{hi} (°C) and t_{ho} (°C) separately represent in and out water temperature of plate heat exchangers' hot side.

Plate heat exchangers' calculation of 64 and 29 MW boilers is same as 99 MW boiler. The results are shown in Table 56.4.

56.4.2 Selection Analysis and Calculations of Heat Pump System

The second paragraph of the heat exchange system is combined of the second spray chamber and a heat pump system. Given that the boiler can supply high temperature water as driving heat source, absorption heat pump can be used here.

Working fluid of heat pump is HBr-H₂O. Heat load of each heat exchanging equipment is shown in Table 56.5.

56.4.3 Design of Spray Chamber

Structure sizes would be obtained by controlling flue gas flow rate, the results were shown in Table 56.6. Model number of stainless steel nozzles should be decided by flue gas flow. 99 MW boiler needs 16 nozzles, 64 MW boiler needs 12 nozzles, 29 MW boiler needs 8 nozzles.

Under the premise to meet heat exchange requirements, spray chambers' structure sizes, nozzles' number and arrangement form can be serialized for different boilers' heat recovery system.

56.5 Economic Analysis of the Heat Recovery System

Dynamic investment return period is the time that takes present value of project annual net income to recover present value of all investment.

$$\sum_{i=0}^{\text{PBP}} (\text{CI} - \text{CO})_i (1 + j)^{-i} = 0 \quad (56.5)$$

Table 56.4 Design calculation parameters of plate heat exchangers

Boiler type (MW)	Heat exchange amount (KW)	Heat side			Cool side	
		Inlet temperature (°C)	Outlet temperature (°C)	Flow (t/h)	Inlet temperature (°C)	Outlet temperature (°C)
99	4216	80	70	361	55	63
64	3188	75	65	273	55	64
29	1448	80	70	124	55	64

Table 56.5 Each heat exchange equipment's load of absorption heat pump

Equipment	$Q_c(\text{kW})$	$Q_g(\text{kW})$	$Q_a(\text{kW})$	$Q_c(\text{kW})$
99 MW boilers	2971	3941.9	3784.1	2907.5
64 MW boilers	1935	2567.3	2464.6	1893.6
29 MW boilers	984	1305.6	1253.3	963

COP of absorption pump is 1.698

Table 56.6 Structure sizes of spray chamber corresponding to different boilers

Structure sizes boiler type (MW)	Length (m)	Width (m)	Height(m)	Length of inlet and outlet (m)	Width of inlet and outlet (m)
99	4	4.5	3	1.75	4
64	4	4	3	1.5	3.5
29	4	3	3	1.5	2.5

where *PBP* (year) is dynamic investment return period, *j* is annual interest rate which is 10 % in this paper, *CI* is income in year *i*, *CO* is expenditure in year *i*.

Obviously, a project is not feasible when its *PBP* is longer than its project life cycle. When a project is feasible, the *PBP* is shorter, the project is more economic.

PBP of 99 MW boiler heat recovery system is 4.7 year, *PBP* of 64 MW boiler heat recovery system is 3.74 year, *PBP* of 29 MW boiler heat recovery system is 5.65 year. It can be seen from economic analysis that *PBP* for different boilers is shorter than heat recovery system's life cycle which means that the project is feasible.

56.6 Conclusion

In this paper, a heat recovery system which used the flue gas to heat heating system return water is designed and studied. The return water temperature duration in the heating season in Harbin is calculated. The feasibility of the system is verified with the results that the return water temperature kept lower than 55 °C for a long period of time.

The system implementation plan of 99, 64, 29 MW boilers which are three typically used in Harbin including the material of heat transfer equipment and the choice of heat pump concerned are discussed. The titanium alloy plate heat exchanger and first absorption heat pump are selected. Then thermodynamic and hydraulic calculations of the system are done to determine the amount of flue gas heat recovery, structure of water spray chamber, plate heat exchangers and absorption heat pump design.

The dynamic payback periods of waste heat recovery system used in these three boilers are calculated and the results are less than the life cycle of the heat recovery system.

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