A Study of Boiler Flue Gas Heat Recovery for Energy Saving

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Abstract. The flue gas emitted from conventional natural gas boilers contains a large amount of water vapor, which cannot effectively recover the latent heat of water vapor condensation due to its failure to lower the flue gas temperature below the dew point temperature. This study adopts a heat pump and a counter-current heat exchanger to recover the waste heat of natural gas boiler flue gas. The field test results show that the average exhaust temperature of the system is 27.1°C, and the system can raise the average return water temperature of the heating network from 40.9°C to 55.0°C. The actual recovered heat power is 10% of the average power of the boiler, and the average coefficient of performance (COP) is about 4.6. The economic analysis shows that the cost of waste heat recovery of the system is about 139 million yuan, and it can save 61million yuan per year. The payback period is 2.3 years.

Keywords: waste heat recovery; flue gas heat; electric heat pump

1 Introduction

With the vigorous promotion of clean heating policy in northern China, natural gas consumption has increased year by year. In 2023, the national apparent consumption of natural gas will be 3.945×10^{11} m^3, with a year-on-year growth of 7.2% [1]. Boiler heating gas consumption accounts for more than half of the total consumption [2]. At present, the waste heat recovery devices of most gas-fired boilers can only recover part of the sensible heat of the flue gas, and the latent heat of condensation [3], which accounts for about 10% of the calorific value of the gas, is not recovered. The flue gas temperature is still high, and direct emission will cause a large energy waste [4].

Natural gas flue gas waste heat recovery includes sensible heat recovery and total heat recovery [5]. At present, the most common sensible heat recovery method is to use air preheater and heat network water to cool the flue gas. However, due to the large end difference of the air heat exchanger and the high water temperature of the heat supply network, it is difficult to reduce the flue gas to the dew point temperature to achieve the deep waste heat recovery of water vapor, while the total heat recovery is to reduce the flue gas to below the dew point temperature through heat pumps and other means, thereby significantly improving the waste heat recovery efficiency[6,7].

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In this context, the research on a new type of efficient heat pump with low exhaust gas temperature has become a technical problem that needs to be solved urgently. Because the natural gas flue gas needs a large temperature drop, this paper uses heat pumps to match the temperature drop process to achieve a higher coefficient of performance (COP), Compared with the conventional condensing boiler, this technology can reduce the flue gas temperature to below the dew point temperature, so as to recover the latent heat of flue gas and improve the thermal efficiency of the boiler, and also has obvious economic benefits.

2 Calculation of Heat Recovery from Flue Gas

2.1 General Situation of the Project and Introduction of the Test Bench

There are two 4.2MW and one 10.5MW gas-fired hot water boilers in the system boiler room of a residential district in Beijing. The temperature of the boiler exhaust gas after passing the flue gas heat recovery heat exchanger is about 62 °C. Under standard conditions, the total exhaust gas volume of the natural gas boiler is 15000 m^3/h. After combustion, natural gas will become carbon dioxide and water. Generally, the final moisture content of the flue gas is about 10%, that is, the absolute moisture content is about 100g/kg. When the flue gas temperature is 60 °C, the relative moisture content of the flue gas is about 70%. At this time, the natural gas flue gas contains huge steam condensation heat. The equipment lower than the flue gas dew point temperature shall be used to recover the sensible and latent heat of flue gas. The evaporator end of the heat pump heat recovery unit can be used to produce lower cold water, heat exchange with flue gas through finned tube heat exchanger, so as to recover the heat of flue gas, and the condenser of the heat pump heats hot water for heating. In order to complete the engineering application of this project, this study established a test-bed to carry out experimental research, and then carried out heat recovery and economic research on this project. Figure1 and Figure 2 are experimental system diagrams and physical diagrams, respectively.

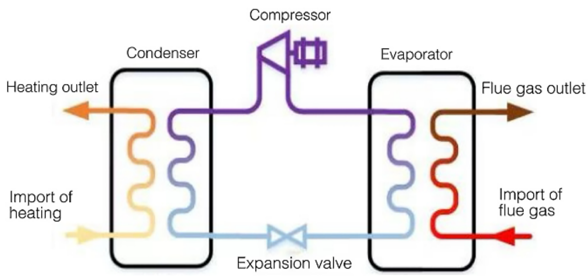

Fig. 1. the schematic diagram of the heat pump that recovers flue gas heat and is used for heating hot water.

Fig. 2. Physical photos of flue gas heat recovery test-bed.

2.2 Theory of Flue Gas Heat Recovery and Calculation of Recovery Amount

Thermodynamic schematic diagram of flue gas recovery system is shown in Figure 3. In the figure, 1-2 is the isentropic compression process of the compressor[8], 2-3 is the condensation process of the refrigerant in the condenser, 3-4 is the adiabatic throttling process of the refrigerant, 4-1 is the evaporation process of the refrigerant in the evaporator[9]. On the fin evaporator side (flue gas heat exchanger), the flue gas is deeply cooled in the heat pump evaporator The flue gas heat exchanger absorbs the heat of flue gas to raise the temperature of refrigerant in copper tube and then enters compressor The heating temperature of the heat network backwater in the condenser is raised from t5 to t6, Because the flue gas temperature is higher than the air temperature, the evaporation temperature of the evaporator is higher, and the evaporator will not frost when running all year round. Compared with the common air source heat pump, the inlet and exhaust temperatures of the compressor are higher and the pressure ratio is lower, so that the heating COP can be higher.

When the evaporation temperature of the evaporator of the heat pump is 20-40 ℃ and the condensation temperature is 50-60 ℃, the heating efficiency of the heat pump heat recovery is 4.6-5.6,The COP of heat pump measured on site is 4.53~6.12, and the average COP is 5.32, as shown in Figure 4.

When the flue gas temperature is lower than 100 ℃, the flue gas thermal parameters are approximate to the air thermal parameters, and the flue gas thermal calculation can be carried out according to the air performance parameters. When the flue gas temperature is 60 ℃ and the relative humidity is 70%, its enthalpy value is 319.96kJ/kg; When the flue gas temperature is 30 ℃ and the relative humidity is 100%, the enthalpy value is 99.78kJ/kg. The heat recovered by 15000m ^{3} /h flue gas through heat pump is 1100kW, and the temperature of hot water outlet is 50 ℃. At this time, the heating efficiency of heat pump heat recovery is 4.6. The heat pump needs 305kw of electricity, and the heat generated is 1405kW.

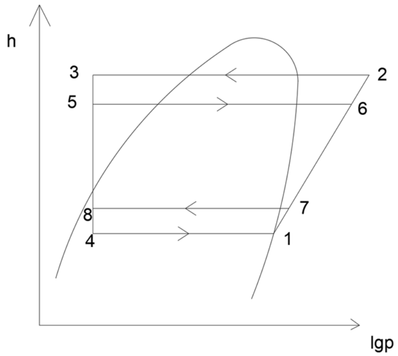

Fig. 3. Thermodynamic schematic diagram of flue gas recovery system

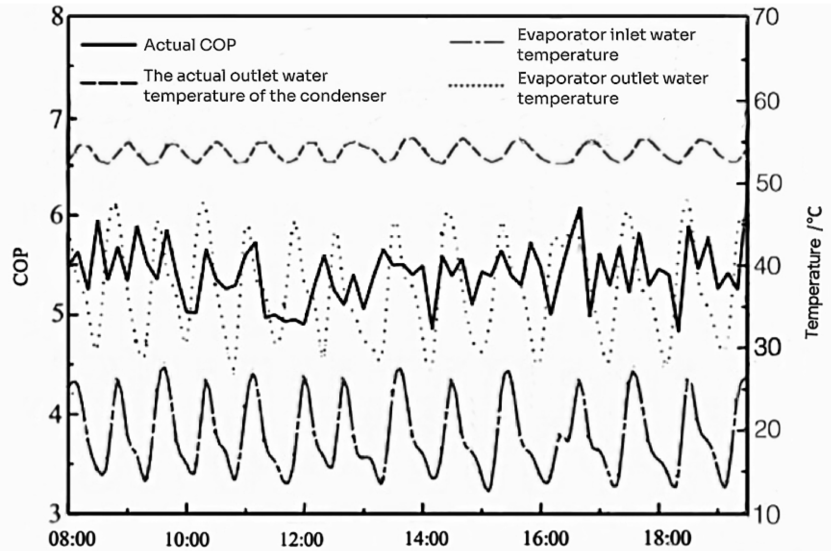

Fig. 4. COP performance curve of direct expansion heat pump.

3 Operation Analysis of Direct-Expansion Heat Pump for the Flue Gas Recovery System

After using the flue gas heat recovery heat pump, the exhaust gas temperature decreases from 60 °C to 16-38 °C. Figure 4 shows the exhaust gas temperature after heat recovery. The heat recovered from the heat pump heats the heating return water. When the outlet temperature of the heat pump is 55 °C, the COP of the heat pump is about 4.6, and the power of the heat pump is 305 kw, which can provide heat for the heating system.

Under the same heating capacity (1405kW), calculate the initial investment and operation cost of gas boiler heating and heat pump recovery. See Table 1 for detailed calculation.

The operation cost is calculated by the following method. Q is the heat produced by the heat pump. If this part of heat is heated by natural gas, the natural gas consumption is

$$V = \frac{3600Q}{0.9q} \tag{1}$$

Where: Q is the heating power of the heat pump, kW; V is the consumption of natural gas per hour, m^3/h; q is the calorific value of natural gas, kJ/m^3; The boiler efficiency of natural gas boiler is 0.9.

The natural gas cost is 2.78 yuan/m^3, so the natural gas cost saved is

$$C = 2.78V \tag{2}$$

Where: C is the natural gas operation cost saved every day, yuan/day.

If the electricity charge is 0.8 yuan/(kW·h), the heat pump operation cost is

$$C_{HP} = \frac{0.8Q}{COP} \tag{3}$$

Where: C_{HP} is the operating cost of heat pump per hour, yuan/h; COP is the heat pump performance coefficient.

Table 1. Calculation of heat pump recovery of exhaust heat and cost savings.

	Unit	natural gas boilers	heat pump heat recovery COP=4.6
total calories	kW	1405	1405
The energy approach	/	Natural gas	electricity
energy calorific value (Heat pump capacity)	kJ/m^3 (kW)	34000	1405[a]
unit price of energy	Yuan/m^3 (Yuan/kWh)	2.78	0.8[a]
Efficiency	/	0.9	4.6
energy consumption	m^3/h (kW·h)	165.29	305.43[a]
hourly running costs	Yuan/h	459.50	244.34
total running costs	Million yuan/year dollars/year	132.34	70.37
Savings value	Million yuan/year	/	61.97

Note: superscript a in the above table indicates that the unit of this figure is (kW·h). The electricity price is calculated according to the weighted average value of peak and valley electricity prices, and the total operating cost is calculated according to 24 hours/day and 120 days/year.

Within 120 days of a heating season and 24 hours of operation, the electricity charge for heat recovery using heat pumps is 70.37 million yuan, of which the electricity charge is 0.8 yuan/kW · h. The fuel gas cost required for using the gas boiler is 132.34 million yuan, of which the fuel gas cost is 2.78 yuan/m ^{3}. Comparisons show that savings of about 61.97 million yuan can be realized in one heating season.

For the initial investment estimation of heat pump system equipment, refer to the industry market price[10]. Table 2 shows the costs of main components and auxiliary equipment. The total heat recovered by the heat pump of this project is 1405kW, and the total initial investment is 140.49 million yuan. The annual operation cost saved by using the heat pump to recover heat is 61.97 million yuan, and the calculated investment recovery period is 2.3 years.

Table 2. Investment in components.

Components	Initial investment/yuan	Specific investment/(yuan/kW)
direct-expansion heat pumps	818834.1	582.8
finned tube heat exchanger	380052.5	270.5
water pumps and other ancillary equipment and installation costs	206113.5	146.7

4 Conclusion

In this project, the direct expansion heat pump is used to recover the heat of gas exhaust. The average performance coefficient of the heat pump is 4.6, which can save 476000 m ^{3} of natural gas every year, 10% of the total gas consumption. The operation cost was saved by 61.97 million yuan, and the payback period of investment was 2.3 years. From the above analysis, it can be seen that the application of heat pump system in the exhaust gas heat recovery system has good energy saving effect, reliable and economical technology, and at the same time, the heat pump system operates safely and stably, with high heat recovery performance coefficient, high degree of automation, and no need for manual duty. It has good applicability in the boiler flue gas heat recovery and utilization project, and should be vigorously promoted.

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