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Thermo Dynamics and Economics Evaluations: Substitution of the Extraction Steam with the Wasted Heat of Flue Gas

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Abstract. A new heat supplying system is proposed that utilizes the exhausted gas of the boiler to substitute the extraction steam from the turbine as the driving force for the adsorption heat pump regarding the recovery of the condensation heat of power plant. However, our system is not subject to the low efficiency of wasted heat utilization due to the low temperature of flue gas, which hence possesses higher performance in COP factors in the utilization of heat than that of the conventional techniques of using flues gas, so the amount of extracted gas from turbine can be reduced and the power generate rate be enhanced. Subsequently, detailed evaluation of the performance of this system in the point of views of thermodynamics and economics are presented in this work. For the instance of a 330 MW heat supply unit, 5 sample cities are chosen to demonstrate and confirm our economic analysis. It is revealed that when the heating coefficient of the heat pump is 1.8, the investment payback periods for these 5 cities are within the range of 2.4 to 4.8 years, which are far below the service year of the heat pump, demonstrating remarkable economic benefits for our system.

Keywords: Extraction steam; Wasted heat; Flue gas.

1. Introduction
It is commonly known that more than 50% of the total energy of fossil fuel combustion in power plants is lost in vain to the atmosphere via the emission of flue gas from boiler and the heat dissipation induced by recycling cooling medium in the steam condenser, which simultaneously contaminates the environment. More specifically, the available latent heat at the cold end accounts for 20% of the total energy of combusting fuels in a 300 MW heat supply unit [1]. The temperatures of exhausted gas emitted from boiler generally range from 120 °C to 130 °C, and all the heat losses occur in the operation of boiler. One of the losses caused by the emission of flue gas is the largest, accounting for 5%~8% of the energy loss of the whole power plant, and 80% or even more of the total heat loss of operating the boiler[2]. If only there is a way to reduce the exhausted gas temperature to 70 ~ 90 °C, the operating efficiency of boiler can be increased by 2~5% [3]. Accordingly, both the energy consumption of power plant and environmental pollution can be reduced while alleviating the contradiction between the limited fossil resources and environmental sustainability, as long as we can recover these two parts of wasted heat efficiently.

For reducing the consumption of coal, the utilization of wasted heat of power plants has attracted extensive attentions [4-5] .Currently, two techniques are most widely used in power plants to achieve this target, which are adopting the adsorption heat pump to recover the condensation heat of power plant and the utilization of the wasted heat of the flue gas emitted from the boiler. To clarify, adopting the adsorption heat pump to recover the condensation heat is using the circulating cooling water of water-cooled condenser or the exhaust steam from turbine as the low temperature heat resource, while...
taking part of the extracted steam from turbine as the counterpart of heat resource for the driving heat pump. The heating coefficient of this system is as high as 1.7-2.4, which can save more than 40% of the energy consumption with respect to that using the extracted steam from turbine to directly heat the heat net for heat supply [6]. However, this system utilizes the extracted steam from turbine as a driving heat resource for the heat pump, which subsequently is stuck with the reduction in the electricity production of the unit in the heating period. On the other hand, the most general way of using the wasted heat of flue gas is to add a heat exchanger at the outlet of the flue gas channel (which is normally called low-temperature economizer). In this regard, the wasted heat of the low temperature flue gas is used to heat the condensation water of turbine or heat supplying heated water, which subsequently substitutes part of the extracted steam from turbine and enhances the output of the power plant unit. Nevertheless, the energy saving efficiency is very limited using this technique, as the temperature of the flue gas located at the low-temperature economizer is rather low.

Therefore, based on a thorough investigation in these two wasted heat utilization systems, a new heat supplying system which uses the wasted heat of flue gas to substitute the extracted steam from turbine as the driving heat resource for the heat pump is proposed in present work, associated with the thermodynamic and economic analysis of this system being presented. Further, a 330 MW heat supply unit is investigated in this work as an example, revealing the feasibility of this new heat supply system in the utilization of wasted heat.

2. A Heat Supply System with the Adsorption Heat Pump using the Wasted Heat of Flue Gas as the Driving Heat Resource for the Recovering of Condensation Heat

Figure 1 depicts the flow chart of an adsorption heat pump using the wasted heat of flue gas as the driving heat resource to recover the condensation heat [8]. As shown in Figure 1, the flue gas at the outlet of the economizer is first cooled down by the air pre-heater, and then enters the heat pump units generator, in which the flue gas is further cooled down to around 90 °C before it eventually enters the filter. On the other hand, in the generator, the flowing flue gas serving as a driving heat resource heats the dilute lithium bromide solution up, leading to the generator being full of water vapor as the boiling point of lithium bromide is much higher than that of water. As a consequence, the dilute lithium bromide solution turns into concentrated solution after the working fluid evaporates. Afterwards, the concentrated lithium bromide solution preheats the dilute lithium bromide solution existing in generator via the solution heat exchanger, which then enters the adsorber, adsorbing the water vapor from evaporator to turn itself into dilute solution. While the heat released in the adsorbing process is used to heat the heat net water, the dilute lithium bromide solution is pumped into the generator, accomplishing the entire solution cycle. The water vapor that is heated to evaporate in the generator is then condensed into liquid when it enters the condenser, releasing latent heat to heat the heat net water. The condensation water formed in the condenser enters the evaporator after the pressure of which is reduced by the throttle valve; part or all of the thermo cycle cooling water of the condenser enters the evaporator of an adsorption heat pump unit, which heats the refrigerant heat water into saturated vapor in the evaporator, and subsequently returns back to the turbine. The refrigerating fluid eventually enters the adsorber, in which it is adsorbed by the concentrated solution. Accordingly, the whole recycle system operates repeatedly following the flowchart.
According to the analysis above, using the wasted heat of flue gas of boiler to replace the traditional counterpart of the extraction steam from turbine of power plant, has overcome the drawback of reducing the output of the unit when the extraction steam from turbine is used for supplying heat. It hence maximizes the output rate of the turbine as the flow rate of the main steam is fixed, improves the power generating efficiency and reduces the consumption of coal. Equivalently, it increases the heat supplying area as the electricity generating capacity is maintained constant; which simultaneously reduces the temperature of flue gas in the filter, leading to the reduction in the dust resistivity and improving the capture efficiency of electrostatic dust collector. Subsequently, using this technique, the targets of saving the input energy and reducing the emission at the same time can be achieved in the cogeneration systems.

2.1. Thermodynamic Analysis
As revealed by the principles of heat transfer, the heat, $Q_g$, released from the tail flue gas of boiler, which is used to heat the condensation water in the driving heat pump, is roughly equivalent to the heat released from flue gas into the working fluid when the flue gas passing by the heating surface. This value reads as

![Diagram](image)

**Figure 1.** Schematic diagram in power plant

**Figure 2.** The relation curve
Using COP to denote the heating coefficient of the adsorption pump, then the heat released from the circulating cooling water in the heat pump is:

\[ Q_0 = Q \times \frac{(COP - 1)}{COP} \]  

where \( Q \) denotes the heating load, which follows:

\[ Q = Q_g + Q_o = Q_g \times COP \text{ kJ/h} \]  

According to that, after the heat pump is adopted, the enhancement in the efficiency of using the wasted heat of flue gas is as high as COP factors. The fact that accounts for this enhancement is that adopting the adsorption heat pump induces an increment in the entropy by reducing the matching discrepancy between the flue gas and the heat supply coefficient of the heat supply net, which subsequently reduces the entropy losses. Figure 2 illustrates the variation of the exergetic efficiency of heat exchanging versus the heating coefficient. It is seen that using the wasted heat of flue gas increases the exergetic efficiency of heat exchanging of the system from 0.61 for the original gas-gas heater to 0.7635; the exergetic efficiency of heat exchanging increases with the increase in the heating efficiency of the heat pump. Moreover, compared to the system using flue gas to directly heat the water, a system using the wasted heat of flue to drive the heat pump is more efficient in the point of view of thermodynamic principles, which definitely improves the thermodynamic performance.

Since the wasted heat of flue gas is used to exempt the extraction of steam from the turbine, this part of steam is hence remained in the turbine to work, and the amount of this part of steam can be calculated like this:

\[ D_h = \frac{Q_g}{h_h - h'_h} \text{ kg/s} \]  

The increment in the power generating rate is

\[ \Delta P_e = D_h (h_h - h'_h) \eta_m \eta_\varepsilon \text{ kW} \]  

where \( I_2, I_{2o} \) are the enthalpies of flue gas at the entrance and exit of the heat pump, with the unit of kJ/kg; \( G \) is the flow rate of flue gas of system with the utilization of flue gas, with the unit of kg/s; \( Q_g \) is the needed heat for a the driving heat resource, which is in the unit of kJ/h; \( h_h, h'_h \) are the steam and dewatering enthalpies of the extracted heat supplying steam, respectively, with the unit of kJ/kg; \( h_c \) is the enthalpy of exhausted steam of turbine, kJ/kg; \( \eta_m, \eta_\varepsilon \) are the mechanic efficiency of turbine and the efficiency of generator.

3. Techno-Economic Analysis

Generally, the thermoelectricity cost accounting of a heat supply unit differs significantly depending on the way, which is used to allocate the heat. The estimated profit for recovering the condensation heat with the utilization of the heat pump that is driven by the wasted heat of flue gas will vary with the change in the boundary conditions [7].

Adopting the wasted heat of flue gas to drive the adsorption heat pump to recover the condensation heat efficiently increases the heat supply capacity of the unit, increasing the heat supply area, and the profit of which is given as:

\[ \Delta R = 10^4 \beta \Delta Q = 10^7 \beta \int_0^\infty Q \text{ 104 REB} \]  

where \( \beta \) is heat supply price, CNY/GJ; \( Q \) is the increment in the heat supply capacity is, GJ, and \( b \) is the collecting heat and heating hour.

As the wasted heat of flue gas is used to substitute the heat supply extraction steam, the power generating capacity of the unit is enhanced, and the additionally generated electricity is available to sell
on the power system, which subsequently increases the power generation indicator

\[ \Delta R = 10^4 c \Delta W - 10^4 \int_0^\infty \Delta Pe \, dREB \]  \hspace{1cm} (7)

where, \( c \) is the generation price of electricity; \( \Delta W \) is the increased generation capacity, Kw/h

With the consideration of a wide range of economic indicators and parameters [9-11], we decide to use the intuitive investment payback period as the economic indicator, and the formula for the calculation of the investment payback period is given below:

\[ \Delta C = \Delta Z / P(i,n) \]  \hspace{1cm} (8)

where, \( \Delta Z \) is the additionally required investment for the project, \( \Delta C \) is the annual profit of the project, in the unit of 10K, \( i \) is the benchmark earning rate, \( n \) is the payback period; and in eq. (8), \( (P,i,n) \) is the equality corpus capital recovery coefficient.

\[ \Delta C = \Delta R - \Delta B - \Delta W \]  \hspace{1cm} (9)

\( \Delta R \) is the annual profit, the detailed calculation of its value is given in the equations (6) and (7); \( \Delta B \) is the cost of fuels, the cost of the utilization of the wasted heat of flue gas is zero in this system, \( \Delta W \) is the cost for the maintain and operation.

Take the example of a 330 MW unit with the utilizations of coal combustion and direct air-cooling, we calculated the economic performance of this system for 5 cities with different heat supply days, including Haerbin, Huhehaite, Beijing, Taiyuan, Xian. For this unit, the efficiency of the boiler is 92.49%, and the designed emission the factors including the coal, the material of the flue gas channel, and the acid dew point corrosion, the minimum temperature for the flue gas at the exit is set as 85 °C; the supply and recovery temperatures for the heating circulating water are 90/60 °C; and the two heat pump with the power of 25 MW are adopted in this system. However, all the other specific parameters of this system are given in Table 1. Further, the profit estimating model based on the increment in the electricity load is used in present work, and the calculated results are given in Table 2.

| Table 1. Basic parameters for calculation |
|-------------------------------------------|
| Item                                      |
| The heating steam enthalpy /kJ.kg-1       | 3149.9 |
| Drain enthalpy/kJ•kg-1                    | 745.2  |
| Exhaust enthalpy/kJ•kg-1                  | 2537.5 |
| Total investment cost /104RMB             | 2270   |
| Heating price/yuan/RMB•GJ-1               | 26.69  |
| The benchmark rate of return funds /%     | 6      |
| Depreciation period/year                  | 15     |

| Table 2. Calculation results of the new arrangements |
|-----------------------------------------------------|
| COP        | 1.4 | 1.6 | 1.8 | 2.0 | 2.2 | 2.4 |
| Haerbin    | 3.4 | 2.8 | 2.4 | 2.1 | 1.9 | 1.7 |
| Huhehaote  | 3.7 | 3.1 | 2.6 | 2.27| 2.0 | 1.8 |
| Taiyuan    | 4.9 | 4.0 | 3.4 | 2.9 | 2.6 | 2.4 |
| Beijing    | 5.6 | 4.5 | 3.8 | 3.27| 2.9 | 2.6 |
| Xian       | 8.2 | 6.4 | 4.8 | 4.4 | 3.9 | 3.4 |

It is known from Table 2:

(1) With the substitution of flue gas to the extraction steam that was originally used to drive the heat pump to recover the condensation heat and supply heat, when the heating coefficient of the heat pump is
1.8, the dynamic investment payback period is between 1.8 and 4.8, which is far below the durable years of the devices.

(2) The performances of this system in these 5 cities are different, and it achieves the best performance in Haerbin while it performs worst in Xian with the longest investment payback period. The interpretation of this phenomenon indicates that the longer heat collection period will lead to the higher efficiency of the heat pump and the better economic performance by this system.

(3) It can also be seen from Table 2 that, the investment payback period decreases with the reduction in the efficiency of the heat pump, which indicates that increase the efficiency of the heat pump can effectively increase the operating efficiency and the economic performance of the system. Certainly, the efficiency of the heat pump is also dependent on the heat supply temperature, flue gas emission temperature, and the temperature of the circulating water.

(4) The heat price in Taiyuan was adopted in our calculations for the heat price, and the heat price in Taiyuan is lower than the average heat price of the whole country due to the historical issues. Therefore, if we adopt the average heat price, 30.6 CNY/GJ, the investment payback period will become shorter.

4. Conclusions
(1) In present work, a new system is proposed that uses the wasted heat of flue gas to drive the adsorption pump to recover the condensation of power plant for the purpose of supplying heat, which replaces the conventional technique that utilizes the extraction steam from turbine as the driving force for the adsorption pump. Our system overcomes the limitation from the temperature of flue gas, increasing the energy utilization efficiency by COP factors and providing a new way for utilizing the wasted heat of flue gas.

(2) Detailed engineering techno-economics analysis is also presented in this work, which reveals that when the heating coefficient of the heat pump is 1.8, the investment payback periods range from 2.4 to 4.8 years for 5 different cities with diverse heating days, and these periods are far below the service life of the heat pump. Apparently, our system is of remarkable economic benefits.

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