Research on Operation Flexibility of Biomass Power Plants with Waste Heat Recovery System

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Abstract. At Present, the flexibility of heat-power output of biomass thermoelectric plants is no longer adapted to the demand of the grid. This paper describes a waste heat recovery (WHR) plant for biomass cogeneration plants. The absorption heat pump (AHP) is integrated into a combined heat and power (CHP) unit to save energy and enhance the dexterity of the heat output by recovering the waste heat from the exhaust steam. The result, verified by actual data from a northern power plant, shows that water temperature, pressure and driving steam have a significant impact on the AHP. CHP units with AHP offer better operational flexibility than conventional units, with a 13.2% increase in thermoelectric output through the integration of AHP. Annual energy savings amount to 491,389.246 RMB. The proposed WHR unit in this paper is important for achieving energy savings, expanding the range of thermoelectric output and improving the economic efficiency of biomass cogeneration plants.

Keywords: Bio-CHP · AHP · Waste heat recovery · Heat-power decoupling

1 Introduction

At present, various countries are actively developing clean energy power generation technologies [1]. The applications of renewable energy such as wind and solar energy are wide [2], but the power generation output is easily restricted by self-heating conditions. The grid connection leads to serious fluctuations in the power grid, which affects the process of low carbonization. Biomass power generation is the least restricted by natural conditions, and can be used as a supplement to renewable energy power generation such as wind and solar, so biomass power generation must have certain flexibility. However, the heat-power coupling phenomenon of the biomass combine heat and power (bio-CHP) is serious, which cannot absorb renewable energy generation.

To enhance flexibility in operation of CHP and accommodate renewable energy generation, a number of thermo-electric coupling technologies for thermoelectric plants have been proposed in recent years [3]. Zhang Dou [4] increased the adjustable range of power generation by adding an absorption heat pump (AHP) to the CHP unit. Zhang Yan [5] et al. established an AHP model based on the laws of thermodynamics, and analyzed

J. Li et al. (Eds.): ACCES 2022, LNEE 1013, pp. 1375–1384, 2023.
https://doi.org/10.1007/978-981-99-0451-8_139

the advantages and disadvantages of an AHP, flexible removal of low-pressure cylinders, and high back-pressure retrofit in terms of operational flexibility. Wang H [6] et al. used the electric compression heat pump (ECHP) to study the operation flexibility of the thermoelectric plant, compared with the thermoelectric plant equipped with the AHP, and clarified the advantages and disadvantages of the two devices from the perspectives of power generation, heat supply flexibility, and economic benefits. AHP are widely used in the recovery of waste heat resources due to their strong heat conversion capabilities. In research on realizing waste heat recovery, Xu Z Y [7] et al. The advantages of waste heat recovery from series heat pumps are demonstrated. Chardon G [8] integrated an AHP in a district heating station (DH) and proposed three operating modes, Xu Z Y [9] used a heat pump to recover ultra-low quality waste heat, using the heat energy ratio of the driving heat sream as a standard, and compared the recovery efficiency of the AHP and the ECHP. In the above studies, peak regulation and waste heat recovery (WHR) are considered respectively. However, the influencing factors of the heat conversion effect of the AHP itself and the flexibility in operation of the CHP need to be improved.

Therefore, this paper proposes a WHR system for biomass thermoelectric plants. Firstly, the principle of thermoelectric coupling mechanism is systematically analyzed, and each device of biomass thermoelectric plant is modeled. Secondly, the parameter configuration method of absorption heat pump is proposed. The influences of inlet and outlet water temperature of exhaust steam, driving heat source pressure, inlet and return water temperature of heat network on waste heat recovery capacity are considered. Finally, the thermal power decoupling and the economic benefits of WHR were studied for the bio-CHP unit that integrated with WHR device.

2 Heat-Power Coupling Mechanism Analysis

2.1 Typical Biomass Cogeneration System

Figure 1, it is a typical biomass cogeneration unit, which consists of biomass boiler, extraction-condensing turbine, and generator. The biomass fuel is fully burned in the boiler to release energy to heat the boiler feedwater, and the main steam of high temperature and pressure is generated to drive the turbine to rotate, and the generator connected to the turbine bearing rotates coaxially to generate electricity. At this time, the main steam is composed of three types: reheated extraction steam (extract into the heater for heating feedwater), heating extraction steam (extract into the heat network for heating water) and exhaust steam.

2.2 Thermoelectric Coupling Mechanism

Figure 2, it is the operation curve of "power determined by heat" for the bio-CHP unit. Assume that the heat demand at a place over a certain duration is Q_{set}, and the adjustable range of the electric load is $P_F - P_E$, the adjustment range of the generating of the CHP can meet the need of the electric consumption. However, when the heat load demand suddenly increases to $Q_{set}^{'}$, more heating steam needs to be extracted in the turbine, resulting in less steam volume being used for power generation. At this time,

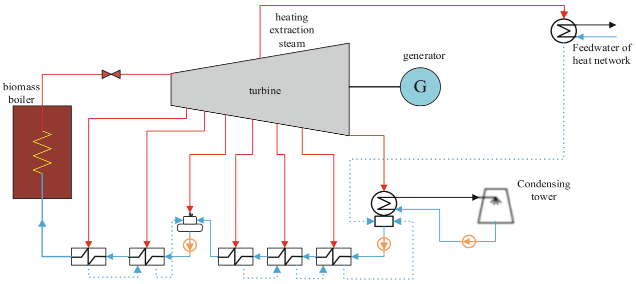
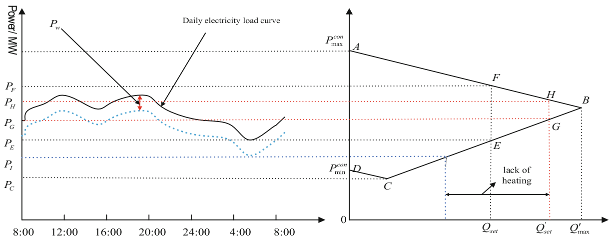


Fig. 1. Steam-water flow diagram of a typical bio-CHP unit

the generation load regulation range is in $P_H - P_G$. As shown in Fig. 1 a) that the power load demand and the power generation have not matched. In some cases, the generated power cannot meet the power load demand in certain periods (4:00–8:00, 10:00–13:00, 17:00–20:00).



a) Daily power load curve

b) Power plant heat and power output curve

Fig. 2. Diagram of the operation of the bio-CHP unit of biomass power plant

If the CHP unit adopts the operation mode of "heat determined by power" and needs to consume P_w wind and solar power generation in the process of peak shaving, the minimum power generation limit of the unit needs to be lower than or equal to P_I. Taking the generating power equal to P_I as an example, When the heating is lower than the heat demand P'_{set}, the set heating cannot be reached. The above-mentioned thermoelectric contradictions occur in CHP plants owing to the high degree of thermoelectric coupling in the CHP units themselves.

3 The CHP Unit with Integrated WHR Device

3.1 Operational Analysis of CHP System with Integrated WHR Device

The traditional extraction-condensing unit extracts the heating steam to heat the feedwater of the heat network from 30 °C to 105 °C. The cooling water (45 °C) that absorbs the waste heat of steam is generally released directly by the condensate tower spray. There are two disadvantages in this process: heating steam to achieve huge temperature rise leads to huge heat loss in the thermal transfer process; the cooling water that absorbs the waste heat of exhaust steam is released directly into the environment, resulting in a waste of heat and water resources.

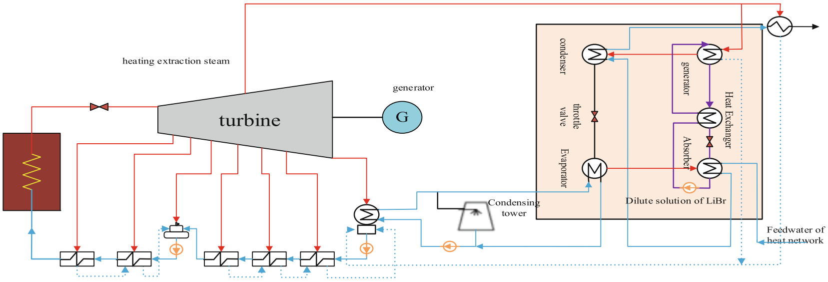


Fig. 3. Steam-water flow diagram of bio-CHP system with waste heat recovery device

In order to make up for the above two deficiencies and improve the flexibility of the thermal and electrical output of the biomass CHP unit, the method of integrating an AHP on the basis of a traditional extraction-condensing unit is chosen to solve the problem. Figure 3 shows the water flow diagram of the CHP unit integrated with the WHR device, which consists of two parts: the CHP unit and the AHP. A portion of the original heating steam enters the AHP as the driving steam to recover the waste heat from the exhaust steam and another portion of the heating steam goes directly to the heater to heat the heat network feedwater.

3.2 Modeling of Bio-CHP Unit with Integrated WHR Device

Biomass Boiler Model

The heat output is the amount of heat consumed by the main steam produced by burning the biomass fuel in the boiler, and the calculation process is as follows:

$$Q_{thermal} = \dot{m}_{steam} \cdot (h_{steam} - h_{fw}) \tag{1}$$

$Q_{thermal}$ is the heat from fuel combustion (KJ); $\dot{m}_{steam}$ is the mass flow of the main steam outlet of the boiler (Kg/h); h_{steam}, h_{fw} is the enthalpy value of the steam outlet of the boiler and the boiler feedwater, respectively (KJ/Kg).

Turbine Model

The Freugel formula is chosen to describe the relationship between the steam mass flow and the pressure in the turbine. The heating extraction steam flow after the E4 stage is very small due to the extraction steam heating, so the above formula is not fully applicable to all stages. Therefore, the turbine model can be described separately, 1) The regulation stage to the extraction stage; 2) The next stage to the last stage of the extraction steam outlet, and the assumptions of the model are as follows:

1. The steam temperature of each stage will not change before and after changing working conditions [6], that is $\sqrt{\frac{T_i}{T_i'}} = 1$;
2. No matter what the working conditions running, the exhaust pressure of the final stage is consistent, which is a certain value;
3. The pressure drops of the high-low pressure heaters are 5% and deaerator is 3% respectively, ignoring the leakage of the shaft seal;
4. The final stage is considered to be in a critical state due to the largest enthalpy drop when operating under variable operating conditions;

The calculation formula of the variable working condition from the regulating stage to the heating steam outlet ($2 \le i \le 4$) is:

$$p_i = \sqrt{p_{ex,h}^2 + \left(p_i'^2 - p_{ex,h}'^2\right)\frac{m_i^2}{m_i'^2}} \tag{2}$$

Since the final stage of the turbine is assumed to be in a critical state during the operation of variable operating conditions, the calculation formula of variable operating conditions from the heating steam outlet to the last stage is:

$$p_i = p_i' \frac{m_i}{m_i'} \tag{3}$$

p_i, p_i' and $p_{ex,h}$, $p_{ex,h}'$ are the intake air pressure and the pressures of the heating extraction steam before and after the turbine operates under variable operating conditions, respectively.

Heater Model

According to the conservation of energy and mass, the following formulas are obtained:

$$\begin{cases} \dot{m}_{\mathrm{dr},j-1}h_{\mathrm{dr},j-1} + \dot{m}_{\mathrm{ex},j}h_{\mathrm{ex},j} + \dot{m}_{\mathrm{fw},j+1}h_{\mathrm{fw},j+1} = \dot{m}_{\mathrm{dr},j}h_{\mathrm{dr},j} + \dot{m}_{\mathrm{fw},j}h_{\mathrm{fw},j} \\ \dot{m}_{\mathrm{fw},j+1} = \dot{m}_{\mathrm{fw},j} \\ \dot{m}_{\mathrm{dr},j-1} + \dot{m}_{\mathrm{ex},j} = \dot{m}_{\mathrm{dr},j} \end{cases} \tag{4}$$

$\dot{m}_{\mathrm{dr}}$, $\dot{m}_{\mathrm{ex}}$, $\dot{m}_{\mathrm{fw}}$ are the mass flow rate of drainage water, extraction steam and boiler feed water, respectively(Kg/h); h_{dr}, h_{ex}, h_{fw} are the enthalpy values of drainage, extraction steam, and boiler feed water, respectively(KJ/Kg).

AHP Model

The AHP is a WHR device that recovers low temperature waste heat resources by consuming a small amount of high-quality heat to produce a large amount of medium temperature heat [10]. Its performance can be expressed as a coefficient of performance COP (>1).

$$\begin{cases} COP = Q_{AHP} / Q_G \\ Q_{AHP} = Q_{re,w} + Q_G \\ Q_{re,w} = m_{con}c_w(T_{con,out} - T_{con,in}) \end{cases} \tag{5}$$

Q_{AHP}, Q_G, $Q_{re,w}$ are the capacity of the AHP, the heat consumption of the driving heat steam and the heat recovery of the exhaust steam, respectively; $T_{con,in}$, $T_{con,out}$ are Inlet and outlet condensate temperatures in the condenser, respectively; c_w is the specific heat capacity at a given pressure.

4 Example Simulation

4.1 Basic Data

Based on the above CHP unit with integrated waste heat recovery device, the extraction-condensing unit (C30–8.83/535) of a biomass thermoelectric plant in a county in northern China is selected. Table 1 shows the basic data of CHP unit with THA working condition.

Table 1. Main Parameters of C30–8.83/535 unit

Parameters	Values
Max. Main steam flow/t/h	140
Rated main steam flow/t/h	124
Min. Intake steam flow /t/h	20
Main steam pressure/MPa	8.83
Rated exhaust pressure/KPa	0.49
Rated extraction steam pressure/MPa	0.98
Extraction steam flow range/t/h	0–50

4.2 Analysis of Heating Capacity

According to the absorption heat pump model in Sect. 3.2.2, the heating power of the absorption heat pump includes two parts: 1) the absorbed heat of the exhausted steam heat source; 2) the heat of the driving heat steam. The higher the COP, the less heat is consumed by the driving heat steam, and the stronger the WHR capability is. Therefore, analyzing the influencing factors of COP can facilitate the analysis of the most economical and safest operation scheme of bio-CHP system with integrated heat storage device.

As can be seen in Fig. 4, the higher the inlet water temperature of the waste steam heat source within a certain temperature range, the greater the COP. This is because the higher the inlet water temperature of the heat source, the more heat is recovered by the AHP and the COP of the heat pump increases accordingly. However, as the inlet temperature of the exhaust heat source continues to increase up to a certain threshold, the concentration of the LiBr solution decreases, resulting in a slow increase in COP. Therefore, the inlet temperature of the exhaust steam heat source must not be too high, generally the exhaust range is between 0.03 and 0.06, and the AHP heating effect best.

The influence of the AHP outlet temperature on COP was analyzed, and the simulation results were shown in Fig. 5. When the temperature of the water outlet of the AHP

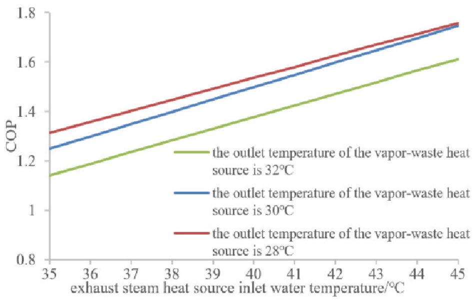


Fig. 4. Influence of inlet water temperature of exhaust steam heat source on COP

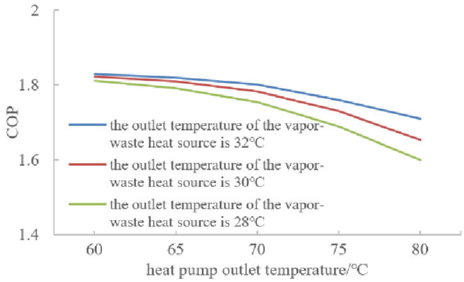


Fig. 5. Influence of AHP outlet temperature on COP

increases, the COP gradually decreases, and when the temperature is higher, the speed of reduction is faster. This is because the increase in the AHP outlet temperature leads to a consequent increase in the internal pressure of the generator and condenser. When the internal temperature of the generator remains unchanged, the concentration of the solution decreases, so that the vent range, that is, the solution concentration difference, decreases and the COP of the heat pump becomes smaller.

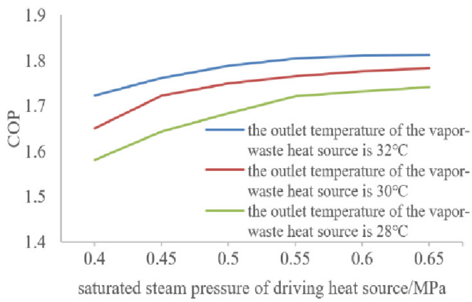


Fig. 6. Influence of saturated steam pressure of driving heat source on COP

The relationship between driving heat source pressure and COP is shown in Fig. 6. With the raise of the saturated steam pressure of the driving heat source, the COP gradually increases, but the growth rate slows down. This is because the pressure of the driving heat source increases, so that the temperature of the saturated steam of the generator increases, and the value of COP increases. However, it is not necessary to set higher pressure because of the positive effect of the driving heat source, because higher steam pressure will reduce the power generation regulation capacity of the power plant, on the other hand, too high driving pressure will make the concentration of the concentrated solution become very large, increase the risk of crystallization.

The technical parameters adopted by the heat pump in this paper are shown in Table 2.

Table 2. Optimal absorption heat pump parameters

Parameters	Value
Heat pump outlet temperature/°C	70
Heat pump return water temperature/°C	30
Exhaust steam heat source inlet water temperature/°C	45
Steam deficiency heat source outlet water temperature/°C	30
Driving heat source pressure /MPa	0.65

4.3 Analysis of Peak Shaving Capacity

Traditional CHP unit safe operation of the thermo-electric output range is shown in Fig. 7, the main production task of biomass thermoelectric plant is mainly to meet the needs of residents, the required heat supply is 25 MW, fluctuating around 5 MW.

peak-shaving capacity is the difference between the maximum and minimum power generated under a certain heating load.

$$\Delta P = P_{\max}(Q_{chp}) - P_{\min}(Q_{chp}) \tag{6}$$

As shown in Fig. 7, it is assumed that the heat supply of the biomass plant remains constant at 25 MW per period, with an adjustable power generation range of (20.67 MW–23.832 MW), thus giving a peak regulation capacity of 3.162 MW.

Figure 7 shows the range of thermoelectric output of the CHP unit with integrated WHR unit, which is expanded when equipped with the AHP. With a heat supply of 25 MW, the range of electrical power regulation is (19.499 MW–25.804 MW) with a peak regulation capacity of 6.305 MW.

4.4 Economic Analysis

In order to verify the economic benefits of an AHP installation and to analyze the extent of savings from biomass energy, a comparison was made between a typical bio-CHP unit with and without a WHR device.

$$Q = m_{waste}(h_{waste-in} - h_{waste-out}) \tag{7}$$

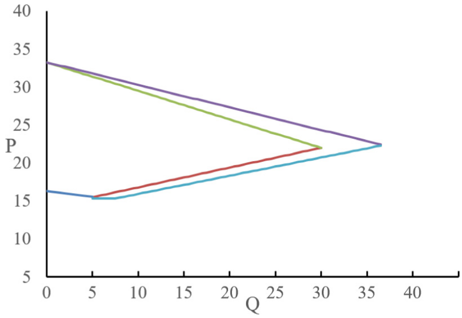


Fig. 7. The range of heat and power output of with integrated waste heat recovery device

$$R = C \cdot (\frac{Q \times 24 \times 365}{1000 \times q_{coal}}) \tag{8}$$

Q is the energy of recovered waste heat, m_{waste}, $h_{waste-in}$, $h_{waste-out}$ are the mass flow of waste heat and the enthalpy before and after entering and leaving the heat pump, respectively; R is the additional income; C is the unit price of coal.

The traditional unit does not have waste heat recovery capability, resulting in energy loss on the exhausted steam side. Reduced energy losses and significant economic benefits with the integration of WHR units. From the formula 7, it can be known that the waste heat recovery amount per hour is 3.143MW/h, calculated by formula 8, the additional income per year is 491389.246 RMB.

5 Conclusion

In this paper, a CHP unit with integrated WHR device is introduced. The main conclusions are as follows:

1. The use of recovered steam waste heat to participate in customer heating reduces the heat extraction from the CHP unit itself, and the reduced extraction is used to generate electricity or reduce the coal input to the unit, thus allowing for a wider safe operating area. And to a certain extent, the greater the heat demand, the more pronounced the decoupling effect.
2. The overall heating effect of the AHP is strongly influenced by the coefficient of performance (COP), the higher the inlet temperature of the exhaust heat source the greater the COP value, but this effect is not continuous and increases slowly towards saturation when the temperature threshold is exceeded.
3. In terms of economy, the CHP unit with WHR improves the energy utilization rate of 9.133% compared with the traditional unit, reduces the biomass fuel by 1563.562 tons.

Acknowledgements. The present work was supported by the State Grid Corporation of China [National Bio Energy Co., Ltd., Grant Number: 52789922000G].

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