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Modelling Investigation of Optimum Operating Conditions for Circulating Water Waste Heat Recovery

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This study is dedicated to present a reliable numerical methodology based on Aspen Plus simulation to assess the performance of energy-saving for circulating cooling water waste heat and water resource recovery system. Heat-pump is used in the system to assist or replace cooling towers to recover the waste heat of low-grade industrial circulating cooling water and convert the waste heat into high grade heat, such as hot water at 90 °C or low-pressure saturated steam, to meet the specific cooling and heat requirements of industrial process. The design schemes are simulated using Aspen Plus V10.0 to explore the effects of critical operating parameters, such as working medium temperature and pressure (water, steam, refrigerant), energy efficiency, economic and reliability analysis. The operating conditions of each design scheme are adjusted and optimized to achieve the best energy efficiency and economy. Results proves that it is feasible to use absorption heat pump to recover the waste heat of circulating cooling water and water resource, which provides theoretical guide and reference for the utilization of low-grade waste heat using heat pump.

1. Introduction

As the world's energy resources become increasingly depleted and low energy efficiency, the use of waste heat is becoming increasingly important and has increasing potential. At present, the available waste heat resources include steam turbine exhaust waste heat, flue gas waste heat, circulating cooling water waste heat and so on, of which the amount of circulating cooling water is the largest, and the water loss due to evaporation in cooling tower accounts for more than 50% of the total water consumption. Even with the water harvesting and water-saving devices, the water loss due to evaporation accounts for 1.2 ~ 1.6 %. With the shortage of water resources, the increase of water price and sewage charge, it is very necessary to research on energy-saving and water-saving technology for waste heat and water resource recovery of circulating cooling water in various industries. Studies have shown that heat pump can enhance the utilization of low-grade thermal energy (Li et al., 2019) and upgrade the low-grade heat. Imran et al. (2016) pointed out that power production from low grade heat and waste heat does not only mitigate environmental impact but also improve energy efficiency and reduce energy cost. Wang et al. (2020) studied the economy of heat pump system which recovering waste heat and water from high-humidity flue gas after the wet flue gas desulfurization scrubber. Zhang et al. (2020) offers an effective way to use the wastewater source heat pump recover the large amounts of waste heat which contains in urban wastewater.

At present, the energy-saving technology of heat pump is developing rapidly, and some progress has been made from experimental and theoretical research to pilot-scale process. However, there are not many cases of systematic economic analysis of heat pump technology by the combination of off-design test, theoretical research and industrial practice. Aspen Plus can be used to complete the whole process simulation of the system, and to design and optimize the key operating parameters, which is the basis of the system to industrial application. In present study, lithium bromide absorption heat pump is used to assist or replace the cooling tower

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in a power plant to recover the waste heat of circulating water to improve the heat efficiency and heating capacity of the system, the energy-saving performance of the system is evaluated by numerical method based on Aspen plus simulation and economic analysis. The result can provide theoretical basis and reference for the practical application of low-grade waste heat using heat pump technology.

2. Simulation

Aspen Plus is a general process simulation software with a huge physical property database (Somers et al., 2011) and mostly used in the chemical industry field and the field of heat pump and refrigeration (Mansouri et al., 2015), which have common theoretical bases on the fundamental equation of states, transfer equation and constitutive equation of matters (De Guido et al., 2015). In this paper, the following design conditions are simulated using Aspen Plus V10.0 (Figure 1): the total circulating water flow rate of a power plant is 80,000 t/h, the inlet water temperature of the circulating cooling water is 33 °C, the outlet water temperature is 43 °C, and 16 new cooling towers with 5,000 t/h circulating water treatment capacity per unit are planned.

1.1 Introduction of system

Generally, the circulating cooling water of the power plant goes directly into the cooling tower, cools down and then returns to the cooling water main pipe. In this design scheme, a branch is connected to the circulating cooling water main pipe (43 °C, 5,000 t/h), a certain proportion of circulating water is taken into the heat pump for precooling, and the circulating water after precooling is mixed with the original circulating cooling water (43 °C) and entered the cooling tower together, and finally returned to the circulating water system (33 °C, 4,914.5 t/h, assuming the evaporation water loss is 1.71 %). The design scheme directly used lithium bromide absorption heat pump technology to assist or replace cooling tower to cool the circulating cooling water to 33 °C or less. The temperature of wet saturated air at the cooling tower exit decreased and the humidity content decreased because of the precooling of circulating cooling water, which causing condensing of part water vapor and allowing the recovery of the condensed water recovering the condensed water.

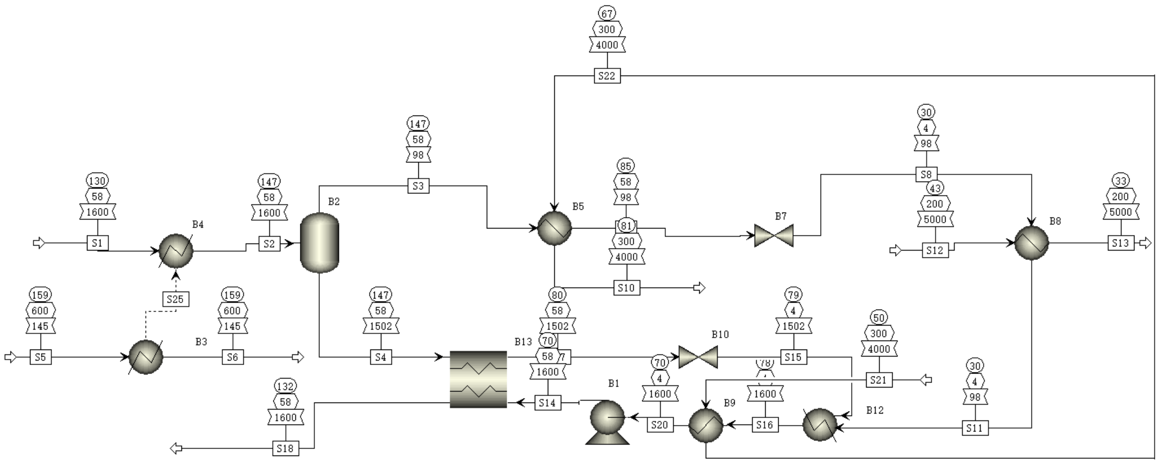


Figure 1: The cycle model implemented in Aspen Plus

At the same time, a small amount of low-grade steam (0.2 ~ 0.8 MPa) is used to drive the absorption heat pump, to recover a large amount of low-grade waste heat from circulating cooling water and convert it into higher-grade heat (high-temperature hot water, ≤ 90 °C, temperature adjustable) or cooling capacity (refrigeration) for users. The construction cost of cooling towers with corresponding circulating water treatment capacity is saved and the evaporation water loss is nearly zero, this design scheme not only can decrease the construction and operation cost of cooling tower whitening, but also decrease the humidity content of the wet saturated air even further using a small part of high-temperature heat source produced by the heat pump to heat the humid saturated air, which achieving the goal of water recovery and energy conservation. This design scheme will have a very broad application prospects in the circulating cooling water treatment of electric power, chemical industry and other industries.

1.2 Model description

The design schemes are simulated using Aspen Plus V10.0 to explore the effects of critical operating parameters, such as working medium temperature and pressure (water, steam, refrigerant), energy efficiency, economic and reliability analysis and so on. This software has an integrated structure and includes processrelated unit operation modules besides components, properties and state equations (Mansouri et al., 2015). Every component of heat pump system is designated the corresponding module. The description of the module symbols used in the models: B3- generator, B5-condenser, B9-absorber, B8-evaporator, 81- pump and B13-heat exchanger. Typical state point of basic working condition results from Aspen Plus models is shown in Table 1. The operating conditions of each design scheme are adjusted and optimized to achieve the best energy efficiency and economy, so as to guide and modify the engineering practice.

Table 1: Typical state point of basic working condition results from Aspen Plus models

State point	Position	Temperature (°C)	Pressure (kPa)	Flow rate (t/h)
21	Absorber Inlet	55	/	5,500
10	Condenser outlet	80	53	5,500
5	Generator inlet	250	/	/
12	Evaporator inlet	43	4.16	5,000
13	Evaporator outlet	32	4.16	5,000

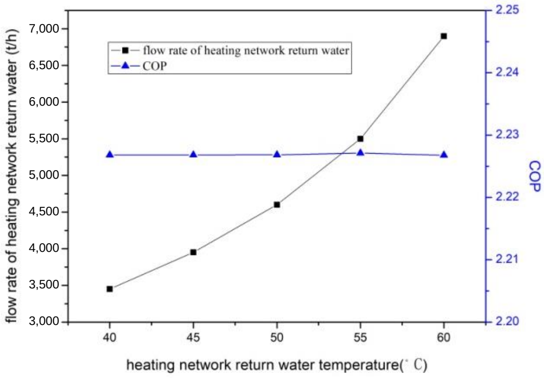
In order to simplify the mathematical model, several assumptions in the process of model building are adopted as follows (Yang et al., 2013): first, the system is in a steady state; second, the condensation pressure is the same as the generator pressure; third, the refrigerant water at the condenser outlet and the refrigerant at the evaporator outlet are in a saturated state; fourth, the pressure drop of the piping and valves in the system, the power consumption of the circulating pump and the heat loss are ignored.

3. Modelling result and discussion

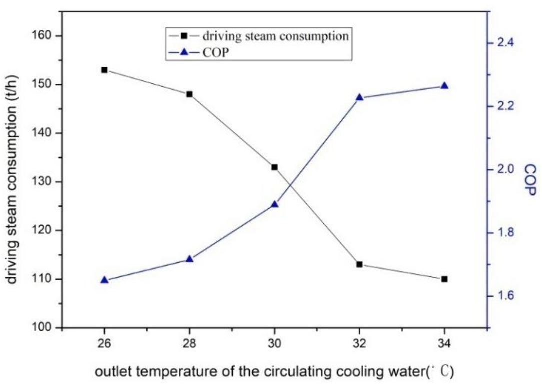
An off-design analysis model of recovering the waste heat from the circulating cooling water using lithium bromide absorption heat pump technology is built, and the performance of the system design is simulated under the design working condition. Then the system performance under off-design condition is studied by changing the input parameters.

2.1 Effect of heating network water temperature on COP

The heating network temperature of the water supply and the return water for users has a great influence on the coefficient of performance (COP) of the whole system. Heating network water gets into the absorber of heat pump, come out from the condenser, and absorbs the heat and then the temperature of heating network water rises. The outlet heating network water temperature from condenser represents the grade of heat for users. The simulation conditions of the model are based on the design parameters of the basic working conditions, such as the data in Table 2. Change one or more of these parameters to design the others accordingly. All simulations follow this principle and will not be repeated in other section.



(a)



(b)

Figure 2: Effect of water parameter of heating network (a) and circulating cooling water temperature (b) on COP

Modelling result indicated that increasing the heating network water supply temperature can promote the energy efficiency of the whole system. The temperature of circulating water will drop greatly when the heating network water supply temperature is increased to 95 °C or more, which directly affect the stable operation of heat pump system. The maximum heating network water supply temperature in this work is 90 °C. To further increase the temperature of hot water for specific applications, or even to produce saturated steam, the hot water can be

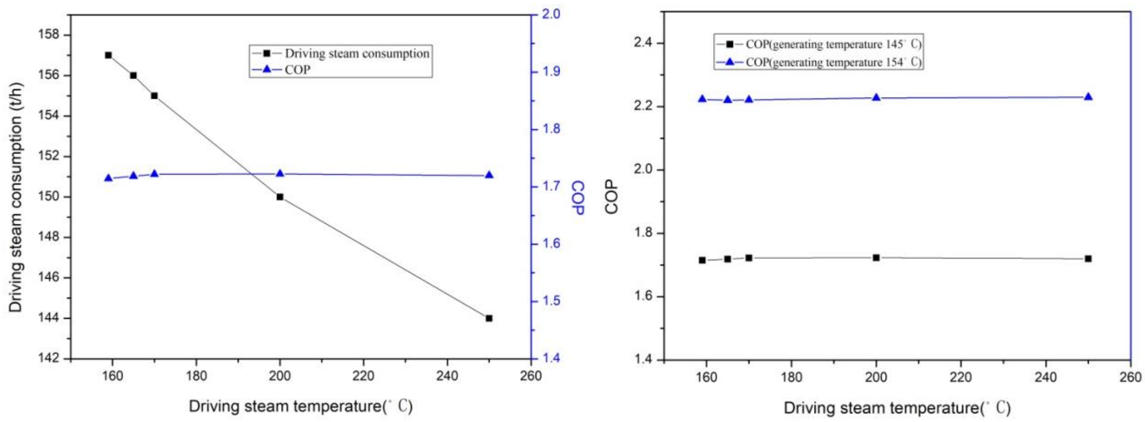
heated to about 90 °C by heat pump, and then further heated to a higher temperature by a peak heater (Che et al., 2014), or directly using the second type of absorption heat pump.
The effect of temperature and flow rate of heating network return water on COP is shown in Fig. 2a. Results show that the system COP changes little with the increase of the heating network return water temperature when keeping the heat release of the absorber and condenser constant and adjusting the heating network water flow rate. With a constant heat production by the heat pump system and heating network water supply temperature, the system COP is not affected by the temperature and flow rate of the heating network return water, and the system is the most stable at this time with the best off-design performance.

2.2 Effect of circulating cooling water temperature on COP

For the circulating cooling water of power plant, the larger the temperature drop of circulating cooling water, the higher the energy efficiency. However, there is no linear relationship between cooling water temperature drop and energy efficiency for certain system, such as heat pump system, considering the economy and COP of the whole system. In this section of model, the outlet temperature of circulating cooling water increased with the decrease of the temperature drop of circulating cooling water in the evaporator, which will affect the pressure of the evaporator and the absorber when the inlet temperature of circulating cooling water and other parameter are constant. Results are shown in Figure 2b. The COP of heat pump system is increased with the increase of the outlet temperature of the circulating cooling water. The reason is that the temperature drop decreases with the increase of the outlet temperature of the circulating cooling water, causing the increasing of the circulating cooling water quantity and the decreasing of driving steam consumption, which leading to the increasing of COP. This is consistent with the conclusion of that the performance coefficient of heat pump, unit power and the exergy efficiency increased with the increase of the outlet temperature of circulating cooling water or the decrease of the temperature drop of circulating cooling water in evaporator make (Zhang and Chen, 2013). It is necessary to adjust the temperature of circulating cooling water in order to improve the performance and economy of the whole system.

2.3 Effect of driving steam parameter on COP

The COP of heat pump and the energy efficient of the whole system all will be affected by the driving steam parameters, including steam temperature, pressure and flow rate. Driving steam consumption is also a key parameter to measure the economy of the whole heat pump system. In this model section, the effects of driving steam temperature, flow rate and generating temperature in the generator on the system COP are simulated under the basic working conditions. The condensing pressure and evaporating pressure remain unchanged, and the temperature and flow rate of circulating cooling water remain constant. Results are shown in Figure 3.



(a) (b)

Figure 3: Effect of driving steam parameter (a) and generating temperature (b) on COP

As shown in Figure 3a, the COP of the system changes little with the increase of driving steam temperature and the decrease of the steam consumption, when keeping the heat produced by the heat pump system as a certain amount, which means that under the condition that the heat produced by the heat pump system constant, the system COP is not affected by the temperature and flow rate of the driving steam, and the system is stable at this time with the best off-design performance.
Considering that the temperature and pressure of the driving steam directly affect the generating temperature of the generator, the effect of the generating temperature in the generator on the system COP is then simulated

and analyzed, assuming that the heating network water temperature rises from 55 °C to 80 °C, the flow rate is constant, the condensing pressure and evaporating pressure remain constant and the temperature and flow rate of circulating cooling water remains unchanged. Results are shown in Figure 3b, the system COP is unchanged with the increase of driving steam temperature while the COP increases with the increase of generator temperature, when keeping the heat produced by the heat pump system as a certain amount. The COP of the system is about 2.224 when the generator temperature reaches the maximum of 154 °C in this work. The results indicated that the waste heat recovery model can raise the thermal economy of the system, however, the improvement of the energy-saving performance of the model depends on the development of the heat pump technology.

4. Economic analysis and comparison

The economic analysis and comparison are conducted for a single cooling tower of a power plant circulating cooling water treatment capacity of 5,000 t/h, circulating cooling water temperature cooling from 43 °C to 33 °C, assuming that the total water loss of evaporation, floating and Sewage is 1.71 %. 4 technical solutions are compared: cooling tower with hot air mixture, 10 % of circulating water into the heat pump, 20 % of circulating water into the heat pump, 100 % of circulating water into heat pump.

The following calculation results are based on the following principles: 5,000 t/h circulating water treatment capacity of a single cooling tower, the annual operating time is 7,200 h, the water price is 0.1416 USD/t, the electricity price is 70.7 USD/MWh, and the driving heat source and recovering heat/cooling capacity are calculated on the basis of GJ and the price is 4.25 USD/GJ.

Table 2: Comparison of water saving performance of heat pump for recycling waste heat of circulating water

Items	Unit	Solution 1	Solution 2	Solution 3	Solution 4
Water saving	t/h	9.8	23	36	85.5
Water saving rate	%	13.87%	27	42	100 (theoretical)
Annual water saving	t/y	70,560	165,600	259,200	615,600

According to Table 2, for a single cooling tower of the same scale (the circulating water treatment capacity is 5,000 t/h), the water saving rate of a single cooling tower is 42 % and the annual water saving is 259,200 t/y when 20 % of circulating cooling water directly get into heat pump. Combined with a small amount of driving heat source (0.2 ~ 0.8 MPa low-grade saturated steam), 764,600 GJ of heat/cooling capacity can be produced every year for users. When the cooling tower is completely replaced by heat pump system, which means all the circulating cooling water into the heat pump, the water saving rate can reach 100 % theoretically. Results show that the waste heat recovery model can greatly reduce the evaporation loss of circulating cooling water and save water resources. The technical economy of several system design schemes is compared for a single cooling tower of 5,000 t/h circulating water treatment capacity.

Table 3 Comparison of investment and operating costs of system (unit: MUSD)

Items	Solution 1	Solution 3	Solution 4
Cost of cooling tower	65.14(including fans and pumps)	65.14(including fans and pumps)	0
Cost of water saving measures	42.48	21.24	0
Cost of heat pump	0	113.28(1×30 MW)	155.76 (3×50 MW)
Cost of civil construction and installation	51.68	95.86	224.29
Total investment costs	180.82	335.45	785.03
Electricity consumption cost	11.89	0.92	4.59
water replenishment cost	7.50	5.10	0
Cost of driving heat	0	165.25	856.40
Total annual operating costs	19.40	171.34	860.93
annual recovery costs	0	324.83	1624.15

According to Table 3, the investment cost of the cooling tower with water saving scheme is lower than other schemes, however, the annual operating cost is 19.4 MUSD without any recovery cost and all the waste heat of circulating cooling water is wasted, which has no return on investment. In addition, a lot of running costs every year will be needed in this scheme.

According to the economic comparison results and assuming that all of the recovered energy can be used efficiently, the investment cost of system scheme of cooling tower + heat pump is 335.45 MUSD, the annual operating cost is 171.34 MUSD, the annual recovery cost is 324.83 MUSD and the payback period is about 2 years. In practice, however, the recovered energy cannot be used completely due to the technical constraints and practical application conditions. If 40 % of the recovered energy can be used efficiently, the investment payback period for the system scheme of cooling tower and heat pump would be approximately 4 years and the payback period for the system scheme of heat pump is approximately 3 years, which far less than the service life of the equipment, which shows that it is feasible to use absorption heat pump to recover the waste heat of circulating cooling water and water resource.

5. Conclusion

This paper studied the system design scheme of circulating cooling water waste heat and water resource recovery model. The absorption heat pump is effectively connected with the circulating cooling water. Using Lithium Bromide absorption heat pump to assist/replace the cooling tower to recover a large amount of waste heat in circulating cooling water and convert into a higher grade of heat output. The energy-saving performance of the circulating cooling water waste heat and water resource recovery system are evaluated by a numerical method based on Aspen plus simulation, the effect of heating network temperature of the water supply and the return water for users, the temperature and flow rate of circulating cooling water, the temperature and pressure of the driving steam and the generating temperature of the generator on COP were analyzed. At last, the economic analysis and comparison are conducted. Results prove that it is feasible to use the absorption heat pump to recover the waste heat of circulating cooling water and water resource, which provides a theoretical basis and reference for the utilization of low-grade waste heat using heat pump.

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References

Che D., Lv J., Gao L., Li S., Bai Z., 2014, Using lithium bromide absorption heat pump to recycle circulating water heat: a simulation. Thermal Power Generation, 43, 38-43.

De Guido G., Langè S., Pellegrini L.A., 2015, Refrigeration cycles in low-temperature distillation processes for the purification of natural gas, Journal of Natural Gas Science and Engineering, 27, 887-900.

Imran M., Usman M., Park B.S., Lee D.H., 2016, Volumetric expanders for low grade heat and waste heat recovery applications, Renewable and Sustainable Energy Reviews, 57, 1090-1109.

Li T., Yang M., Feng X., 2019, A simulation-optimisation method for targeting the optimal placement of heat pumps in heat exchanger networks. Chemical Engineering Transactions, 76, 319-324.

Mansouri R.B., Bourouis M., Bellagi A., 2015, Modelling and testing the performance of a commercial ammonia/water absorption chiller using Aspen-Plus platform, Energy, 93, 2374-2383.

Somers C., Mortazavi A., Hwang Y., Radermacher R., Rodgers P., Al-Hashimi S., 2011, Modeling water/lithium bromide absorption chillers in ASPEN Plus, Applied Energy, 88, 4197-4205.

Wang X., Zhuo J., Liu J., Li S., 2020, Synergetic process of condensing heat exchanger and absorption heat pump for waste heat and water recovery from flue gas, Applied Energy, 261,114401.

Yang X., You S., Zhang H., 2013, Simulation of off-design performance of double effect LiBr-H2O absorption heat pump, Acta Energiae Solaris Sinica, 34, 420-425.

Zhang Q., Zhang X., Yin C., Liu F., Wang G., 2020, Experimental evaluation of heat transfer performance of falling film evaporator for wastewater source heat pump with backwash system, International Journal of Refrigeration, 113, 80-93.

Zhang X., Chen H., 2013, Thermodynamic analysis of heat pump heating supply systems with circulating water heat recovery, Proceedings of the CSEE, 33, 1-8.