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Thermodynamic analysis of a combined absorption power and cooling cogeneration cycle

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ABSTRACT

This study proposes a novel ammonia-water power and cooling cogeneration system in which an extraction Rankine cycle is introduced to drive the absorption refrigeration cycle to produce cooling and power simultaneously. The system mathematical model is established and the thermodynamic analysis is carried out to investigate the influence of key thermodynamic design parameters on system performance. Under design conditions, the cooling and power output are calculated to be 78.17 kW and 104.56 kW, and the thermal efficiency and exergy efficiency are equal to 21.81% and 43.69%, respectively. The parameter analysis results show that as boiler temperature rises, the system total output increases significantly, but the exergy efficiency and the thermal efficiency exhibit no significant changes. The results also show that an increase of circulating high pressure will lead to a decrease of system total output, and thus the thermal efficiency and exergy efficiency are decreased.

Keywords: Ammonia-water; Cycle coupling; Cogeneration system;

NONMENCLATURE

A	heat transfer area (m2)
C	*purchase cost ($)*
CRF	*capital recovery factor*
Ex	*exergy (kW)*
h	*specific enthalpy (kJ/kg)*
I	*exergy destruction (kW)*
m	*mass flow rate (kg/s)*
P	*pressure (MPa)*
Q	*heat duty (kW) or quality (-)*
s	*specific entropy (kJ/(kg·K))*
T	*temperature (K)*
W	*power (kW)*
x	*ammonia mass concentration*
η	*efficiency*

1. INTRODUCTION

In recent years, the issues of energy overconsumption, carbon emissions and environmental pollution are raised, and more attention have been paid to the energy utilization improvement and environmental protection. Low grade heat sources, such as geothermal resources, waste heat in industrial production and solar energy have the advantages of widely distributed, clean and sustainable. The efficient utilization of low-grade energy has a great significance to alleviate global problems such as energy shortages, environmental pollution, and climate warming. However, as low-grade heat sources temperature is low, the traditional, steam Rankine cycle, is difficult to convert the low-grade thermal energy. Therefore, more attention have been focused on low-grade energy

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conversion technology. Kalina [1] proposed to use ammonia-water as working fluid to form a new cycle named Kalina cycle, in which the working fluid undergoes an isobaric evaporation during the evaporation process. At the same time, due to the low ammonia content of mixed working fluid during condensation, the shortcomings of large condensation losses are solved [2,3]

Another significant feature of using ammonia-water as working medium is that this medium can produce power and cooling simultaneously. Compared with a single power cycle, the cogeneration cycle has the advantages of high energy utilization efficiency and wide application range [4].

In this paper, an absorption power and cooling cogeneration cycle is proposed firstly. As showed in Fig.1, the proposed system, which includes a power cycle and a refrigeration cycle, extracts part of ammonia vapor what is not fully expanded to drive the refrigeration system. Furthermore, two independent absorbers are arranged to absorb low pressure ammonia vapors of power generation cycle and absorption refrigeration cycle respectively, by which these two sub-cycles can operate at their respective conditions (i.e., the respective temperature, pressure and concentration of ammonia water), and it favors that the proposed system can adjust the ratio of ammonia solution flow into the two sub-cycles.

2. SYSTEM DESCRIPTION

The proposed absorption power and cooling system is described in Fig.1. In the combined system, the basic working fluid (1) at absorber 1 (ABS1) outlet is pressurized by the pump 1 (P1) and then exchanges heat through the recovery heat exchanger (RHE) to recover heat of weak ammonia-water solution at the bottom of the boiler (3), and then enters the boiler for heating. The rich ammonia vapor (4) generated by boiler (B) is first superheated in the superheater (6), and then enters the turbine to expand. When the working fluid pressure reaches an intermediate pressure, part of the ammonia vapor (7) is taken into the absorption refrigeration subsystem, and another stream continues to expand to produce power. The diluted saturated liquid at the bottom of the boiler is divided into two streams by throttling valve 1 (V1), one (16) enters the absorber 1, and absorbs the turbine exhaust steam (8), another (17) is adjusted to evaporation pressure and enters absorber 2 (ABS2) to absorb evaporator (EVA) outlet working fluid (14). The saturated liquid at the absorber 2 outlet (19) is pressurized by the pump 2 (P2) and enters the absorber 1. The diluted saturated liquid (10) at the rectifier bottom is throttled (11) and then enters the absorber 2, and the high-concentration ammonia vapor generated at top of the rectifier is first condensed into a saturated solution (12) by the condenser (CON), and then throttled to low pressure (evaporation pressure) (13) through throttle valve 3 (V3) The ammonia solution with high purity is then evaporated and cooled in evaporator (EVA); the evaporator outlet saturated vapor enters the absorber 2 to be absorbed by the dilute solution, thereby the cycle process is compled.

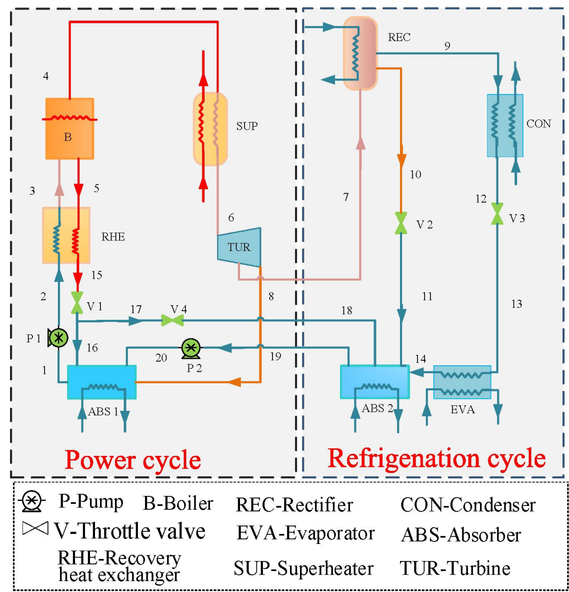

Fig 1 Schematic of the combined absorption power and cooling cogeneration system.

3. MATHEMATICAL MODEL

3.1 Thermodynamic model

Exergy analysis not only be used for assessing energy utilization, but also providing guidance for raising the system thermodynamic performance. The thermal exergy can be expressed as

$$E_{x,Q}=(1-\frac{T_0}{T})\cdot Q$$

where, Q and T are heat exchanging amount and heat source temperature, respectively.

The exergy balance equations for system components are given by

$$\sum m_{in} \cdot e_{in} - \sum m_{out} \cdot e_{out} + E_{x,Q} - W_u - I = 0$$

where, is the system exergy destruction,is the system useful outputs, and is the system input exergy.

3.2 Economic model

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In the system, the investment costs of the boiler, the superheater, the evaporator, the rectifier and the absorber are related to their respective heat exchange area, and the logarithmic mean temperature difference (LMTD) method is employed to calculate the size of all the heat exchange components. The equations for calculating the investment cost of each component are shown in Table 1.

Table 1 Equations for calculating investment cost [5,6]

Components	Investment cost
Boiler	$C_b = 17500(A_b/100)^{0.6}$
Rectifier	$C_{rec} = 17000(A_{rec}/100)^{0.6}$
Absorber 1	$C_{abs1} = 16500(A_{abs1}/100)^{0.6}$
Absorber 2	$C_{abs2} = 16500(A_{abs2}/100)^{0.6}$
Evaporator	$C_{eva} = 16000(A_{eva}/100)^{0.6}$
Condenser	$C_{con} = 8000(A_{con}/100)^{0.6}$
Recovery heat exchanger	$C_{rhe} = 130(A_{rhe}/0.093)^{0.78}$
Superheater	$C_{sup} = 16000(A_{sup}/100)^{0.6}$
Pump	$\lg C_p = 3.3892 + 0.0536\lg W_p + 0.1538\lg^2 W_p$
Turbine	$\lg C_{tur} = 2.6259 + 1.439\lg W_{tur} - 0.1776\lg^2 W_{tur}$

The cost of other equipment (such as throttles) which is relatively small that can be ignored. The total cost of the components is calculated as

$$C_{tot}' = \sum C_i$$

The cost of capital rate is defined as

$$C_{tot} = \frac{C_{tot}' CRF}{N}$$

where, N is system annual use time, CRF is capital recovery factor expressed as

$$CRF = \frac{j(1+j)^n}{(1+j)^n - 1}$$

where, life time (n) is 20 years, interest rate (j) is 6% and annual use time(N) is 7000 hours .

3.3 Performance indexes

This paper selects the thermal efficiency as one of system performance indexes defined as the ratio of the system total power output (the sum of cooling capacity and power output) to system total input heat, defined as

$$\eta_t = \frac{W_{net} + Q_c}{Q_{in}}$$

The exergy efficiency is selected as another system performance indexes, and the exergy efficiency is determined by the ratio of system total exergy output to total exergy input, given by

$$\eta_{exg} = \frac{W_{net} + E_c}{E_{in}}$$

where,is the exergy related to refrigeration produced, described as

$$E_c = E_{13} - E_{14}$$

4. RESULT AND DISCUSSION

4.1 Calculating result

In this section, the calculation program for cogeneration system is written by MATLAB software. The base working fluid at absorber 1 outlet is assumed as 1 , and the other input parameters are shown in Table 2.

Table 2 The input parameters for simulation

Parameters	Values
Absorber 1 pressure (P_1) / MPa	0.35
Ammonia concentration at the top of rectifier (x_9)	0.999
Circulating high pressure (P_{high}) / MPa	2.6
Circulating low pressure (P_{low}) / MPa	0.25
Extraction pressure / MPa	1.2
Boiler output temperature (T_4) / K	415.15
Reference temperature (T_0) / K	290.15
Reference pressure (P_0) / MPa	0.1
Recovery heat exchanger(RHE) efficiency (η_r)	0.8
Condensing pressure (P_{12}) / MPa	1.2
Extraction ratio (-)	0.20
Turbine isentropic efficiency ($\eta_{tur,s}$)	0.8
Pump isentropic efficiency ($\eta_{p,s}$)	0.8

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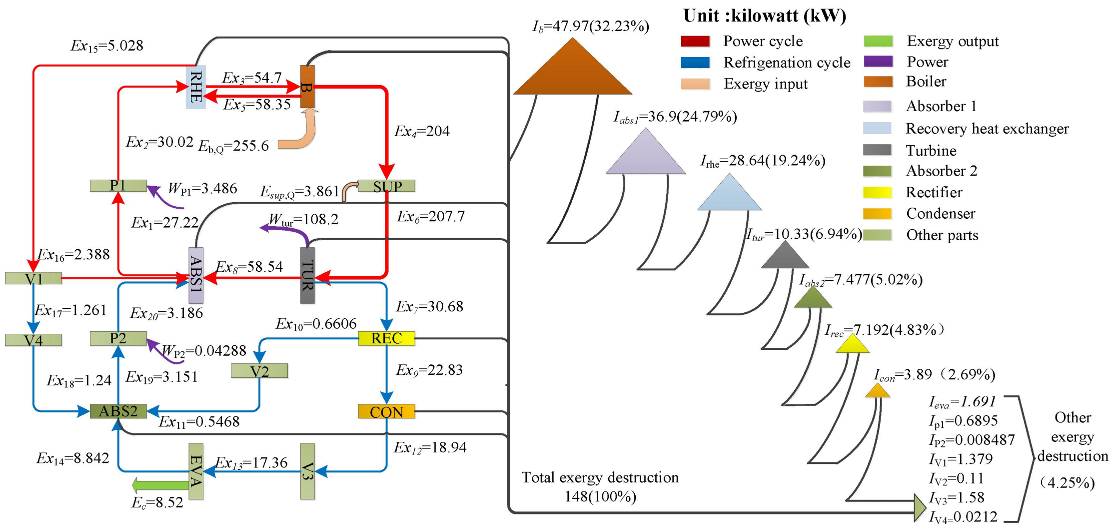

Fig. 2 Exergy flow and exergy destruction of the combined system

Table 3 shows the performance calculation results. Under designed conditions, it can be calculated that the thermal and exergy efficiency are 21.81% and 43.69%, respectively. The refrigeration output is 78.17 kW , and the power output is 104.56 kW. Because the absorber 1 and the absorber 2 are independent of each other, the pressure in the absorber 1 can be higher than the evaporation pressure, and the concentration of the basic working fluid is much higher than that of the absorber 2 outlet, and the system adjustability is improved accordingly.

Table 3 Performance calculation results

Parameters	Calculation results
Work generated by turbine / kW	108.2
Work consumption of pump 1/ kW	3.49
Work consumption of pump 2 / kW	0.043
Boiler heat input / kW	826.2
Refrigeration output / kW	78.17
Net power output / kW	104.56
Thermal efficiency /%	21.81
Exergy efficiency /%	43.69

The exergy flow and exergy destruction calculation results are shown in Fig. 2. The system exergy destruction is mostly concentrated in boiler, absorber 1 and recovery heat exchanger. Because ammonia concentration of base working fluid is increased, it can absorb more heat in boiler, which increases the system heat input through the boiler. Therefore, the boiler exergy destruction is the largest, accounting for 32.23%. The absorber 1 has a high thermal load and its exergy destruction accounts for 24.79%.

4.2 Thermodynamic analysis

Figs. 3-5 show the influence of the circulating high pressure (Phigh) and the boiler temperature (T4) on the system thermal performance (thermal efficiency, exergy efficiency and power output). The circulating high pressure and the boiler temperature have a significant impact on system heat input and the rich ammonia-vapor flow at boiler outlet. When the circulating high pressure rises, the boiler outlet working fluid flow decreases, and the superheated vapor entering turbine and the refrigeration subsystem decreases. It leads to a reduction in power output (Wnet) and cogeneration cooling capacity. However, the heat and exergy input are reduced, and the system thermal and exergy efficiency are increased, as shown in Figs. 3 -4. On the contrary, as the boiler temperature rises, the power output, the cooling capacity, the system total heat input and the exergy input are increased consequently. In addition, the rising trend of power output is lower than the increasing trend of exergy input, hence the system exergy efficiency is decreased when the circulating high pressure (Phigh) and the boiler temperature (T4) increase at the same time, the system total output shows a downward trend, shown in Fig. 5.

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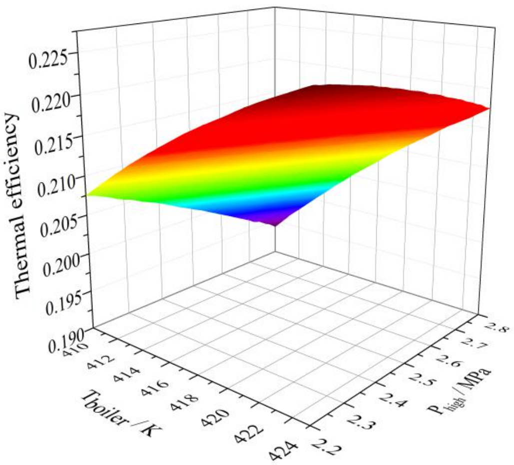

Fig.3 Effect of circulating high pressure and boiler temperature on the thermal efficiency

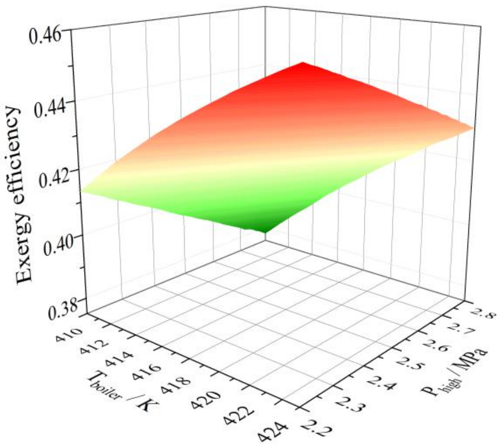

Fig. 4 Effect of circulating high pressure and boiler temperature on the exergy efficiency

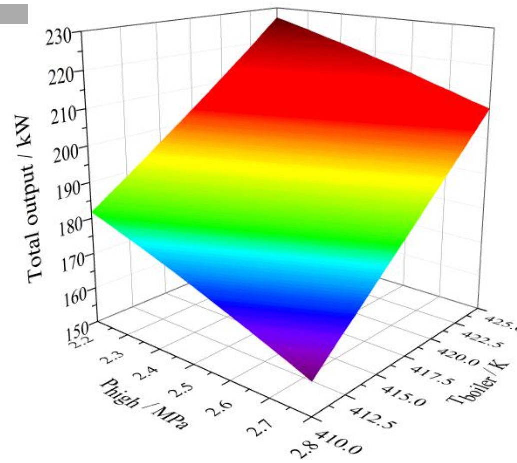

Fig. 5 Effect of circulating high pressure and boiler temperature on the total output

Fig. 6 shows the effects of absorber 1 pressure (P1) and circulating high pressure (Phigh) on the exergy efficiency, and Fig. 7 shows the effects of P1 and Phigh on total output (power and cooling capacity). When the absorber 1 pressure rises, the concentration of the base working fluid is increased. This is mainly because the condensation temperature keeps constant. At the same temperature and pressure, the saturation temperature of the ammonia solution decreases as the concentration increases. Therefore, the working fluid flow at the boiler outlet increases lead to the increment of the turbine working fluid mass flow, which improves the working capacity of the turbine. On the other hand, the increase of turbine back pressure will reduce the turbine power output. But increased power output is bigger than the power output augmentation, so the total power output is increased, as shown in Fig. 7. As mentioned above, when the circulating high pressure increases, the boiler outlet ammonia-rich vapor flow decreases, and the working fluid entering the turbine and refrigeration subsystem decreases, and it causes power output and cooling capacity reduce. However, the exergy input reduces at the same time, so the system exergy efficiency is not change obviously, shown in Fig. 7.

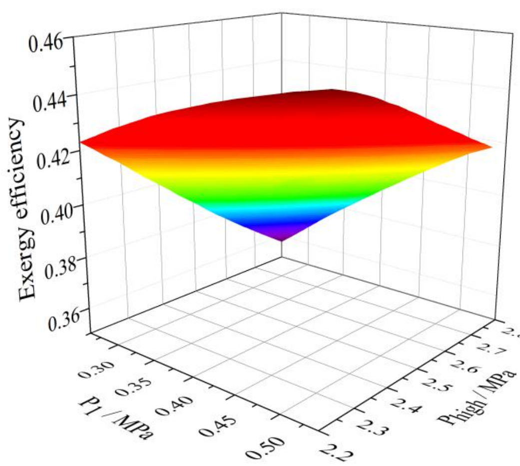

Fig. 6 Effect of absorber 1 pressure and circulating high pressure on the exergy efficiency

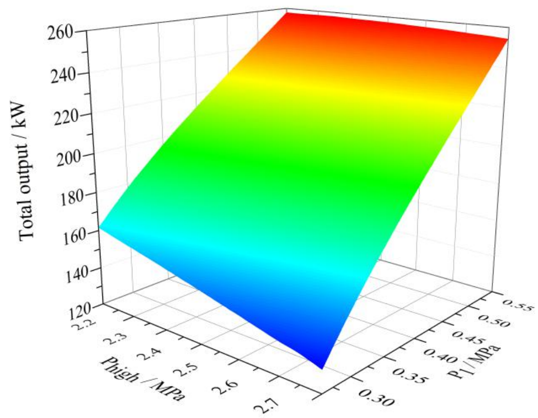

Fig. 7 Effect of absorber 1 pressure and circulating high pressure on the total output of the system

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Fig. 8 and Fig.9 show the influence of absorber 1 pressure and boiler temperature on system total output and the operating cost. When the boiler temperature and absorber 1 pressure rise, the working fluid flow at the boiler outlet increases, and the turbine output power and the cooling capacity increase significantly. When the boiler temperature is increased from 413 K to 424 K and the absorber 1 internal pressure is increased from 0.26 MPa to 0.55 MPa, the total output is increased from 126.7 kW to 279.3 kW, shown in Fig. 8, however, the operating cost is also increased, shown in Fig. 9. When the cost of capital rate and the total output are taken as optimization goals, there is a clear conflict between the two variables. While increasing the total system output, the cost of capital rate has also increased.

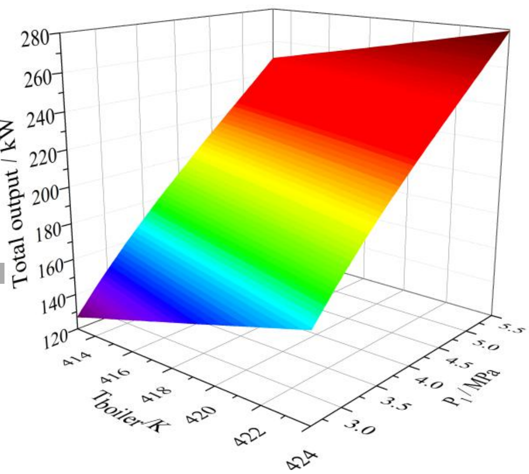

Fig. 8 Influence of absorber 1 pressure and boiler temperature on the total output

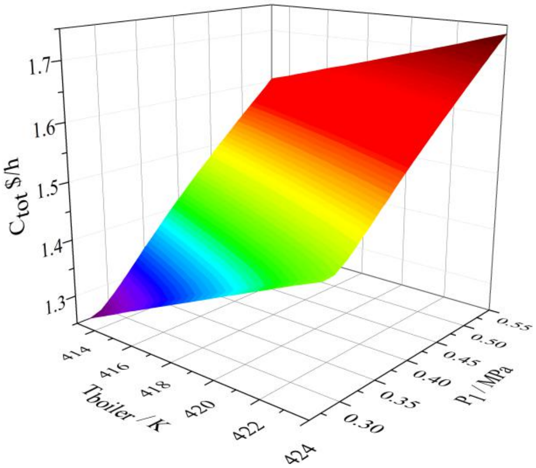

Fig. 9 Impact of absorber 1pressure and boiler temperature on cost of capital rate

5. CONCLUSIONS

A novel combined absorption cooling and power cogeneration cycle is proposed. The system model is established and the thermodynamic analysis is performed. The main conclusions are listed as follows:

Under design conditions, the power and cooling capacity output are 104.56 kW and 78.17 kW, and the thermal and exergy efficiency are 21.81% and 43.69%, respectively. The analysis results show the system exergy destruction is mostly concentrated on the boiler, the absorber 1 and the recovery heat exchanger.

Parameter analysis shows that when boiler temperature rises, the system total output increases significantly, but the exergy and thermal efficiency do not change significantly. When the circulating high pressure increases, the system total output decreases, the system thermal and exergy efficiencies are increased; when the boiler temperature is low, the effect of circulating high pressure on the system performance is more obvious. When the pressure in the absorber 1 rises, the total output of the system rises significantly.

ACKNOWLEDGEMENT

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