SIMULATION ANALYSIS OF PERFORMANCE OPTIMIZATION OF GAS-DRIVEN AMMONIA-WATER ABSORPTION HEAT PUMP

by

Jun ZHOU and Shuhong LI*

College of Energy and Environment, Southeast University, Nanjing, China

Original scientific paper
https://doi.org/10.2298/TSCI191110063Z

The generator-absorber heat exchange ammonia-water absorption heat pump has a relatively high efficiency and the COP is improved by recovering internal heat. In order to resolve the problem that generator-absorber heat exchange effect becomes less obvious or even fails under the working condition of large temperature lift, a novel system is proposed to recover the rectification heat and absorption heat by solution split method. Compared with the method of using total strong solution to recover absorption heat after extracting rectification heat, the method of solution split avoids the problem of high temperature of inlet strong solution of the solution cooled absorber, and improves the internal heat recovery capacity of the system. When using solution split method to recover the rectification heat and absorption heat, the solution split ratio K has an important influence on the system performance. This paper will theoretically study the selection range of the solution split ratio K and the effect of evaporation temperature, cooling water temperature and generation temperature on the optimum split ratio K. Compared to the system that uses the total strong solution to recover the rectification heat and absorption heat, the performance of the novel system is significantly improved, and the novel system performance coefficient can be increased by up to 15.7%.

Key words: *generator-absorber heat exchange, solution split, the optimal split ratio, simulation performance improvement*

Introduction

In recent years, Chinese economic level has developed at a high speed, urbanization and industrialization have accelerated. Under the existing energy structure in China, a large amount of coal-based energy has been consumed. As the economy has achieved rapid development, the problem of air pollution has become more severe. Coal-fired heating is one of the main reasons of air pollution in the northern region. In order to improve the atmospheric environment, the government released the *Northern District Clean Winter Heating Plan*. The Plan has made specific arrangements for the overall plan for the *clean coal-to-gas* gas source protection for winter clean heating in key areas in the north [1].

In terms of heating, *coal-to-gas* is mainly realized by centralized heating of gas driven ammonia-water absorption heat pump systems and heating of gas-fired boilers with radiators or ground-radiation devices. Compared with gas boilers, gas driven ammonia-water absorption heat pump systems have the following advantages: gas driven ammonia-water absorption heat pumps are more efficient and cost-effective device, whose energy efficiency can reach 130%

* Corresponding author, e-mail: equart@seu.edu.cn

to 150% in winter season, ammonia-water is used as the working pairs of system, which is not only environmentally friendly, but also enables the evaporation temperature can be below low 0 °C [2]. Therefore, the significance of gas driven ammonia-water absorption heat pumps is particularly important in the context of energy saving and emission reduction and building a low-carbon society.

However, due to the high irreversibility of the heat transfer process inside and outside the system (such as absorption, solution heat exchange, and generation process), the coefficient of performance of the gas driven ammonia-water absorption heat pump is quite low [3]. In order to address this shortcoming, the research on ammonia-water absorption heat pump mainly focuses on the enhanced absorption and the internal heat recovery of the system. Incomplete absorption of ammonia in the absorber will reduce the deflation ratio, which reduces the system performance. Jaballah *et al.,* [4] used hybrid nanofluid as cooling medium to remove the absorption heat. It enhanced the heat and mass transfer in bubble absorber and improved the performance of system. Ben Hamida *et al.* [5] studied the heat and mass transfer enhancement for bubble absorption process of ammonia-water mixture without and with nanofluid. The result showed that the heat and mass transfer in absorber was enhanced by adding nanoparticles to ammonia-water. An important way to improve absorption heat pump performance is to enhance the internal heat recovery capacity of system, which demonstrates a great potential of reducing heat consumption in absorption systems. As for the absorption heat recovery, one unique feature of the ammonia-water absorption heat pumps is the presence of temperature overlap between the absorber and generator under certain working conditions, part of absorption heat, therefore, is recovered in generator-absorber heat exchange (GAX) absorption cycle [6]. Jawahar and Saravanan [7] conducted experimental investigation on the performance of an air-cooled modified GAX absorption system. The conventional system is modified by incorporating high pressure GAX, low pressure GAX, a solution cooler and an additional solution heat exchanger to reduce the heat input to the system. Chen *et al.* [8] proposed an improved absorption-compression hybrid GAX refrigeration cycle, which couplings absorption-compression to further improve the efficiency of GAX cycle. Compared with the basic GAX cycle, the COP of new cycle can be increased by more than 30%.

The GAX effect becomes less obvious or even fails as an increase of the temperature difference between the condenser and evaporator (temperature lift). One approach to tackle with the problem is to recover rectification heat. More researches about rectification heat recovery have been extensively undertaken. Experiments conducted by Fernandez-Seara and Sieres [9] shows that the quantity and quality of rectification heat monotonically increases as the evaporation temperature goes down. In order to resolve the problem that both the simple GAX cycle and the branch GAX cycle are not suitable for the working conditions that the cycle temperature lift is large, Liao [10] proposed a novel ammonia-water absorption cycle that recovers rectification heat using absorber outlet strong solution to improve the cycle performance. Sun and Du [11] studied the effect of ammonia purity at the top of the distillation column on system performance by using Aspen Plus software. It showed that impure ammonia in the top of the distillation column will have an adverse effect on the system. Consequently, when using the strong solution recover rectification heat, the mass-flow rate of strong solution that recovers rectification heat plays a critical role in making sure the purity of ammonia flowing to condenser. However, if the total strong solution is used, the recovered heat does not increase much due to the temperature rises at the cold end of spiral heat exchangers (SHE). The system performance is not improved obviously [12]. Chen *et al.* [13] proposed a novel cycle that utilizes rectification heat when the chiller is operated under a large temperature lift or low heat source temperature when GAX effect is not available. This cycle combines the solution re-circulation and heat integration of rectifier to improve the COP. The result shows 24% increase in COP compared with traditional single-stage cycle under certain working conditions.

In this paper, a novel system that recovers absorption heat and rectification heat to improve the performance is proposed. The strong solution is split to recover absorption heat and rectification heat, respectively. Compared with by using total strong solution to recover absorption heat after extracting rectification heat, it avoids the problem of high temperature of inlet strong solution of solution cooled absorber (SCA) and strengthen the internal heat recovery further improving the COP. Since the solution split ratio, *K,* has an important influence on the system performance, the theoretical insights on the key parameters like strong solution split ratio, the ratio of heat released by the SCA to total heat released by SCA and water-cooled absorber (WCA) are investigated through studies. The simulations are carried out on MATLAB with excellent equations solving capacities.

Model

System description

A schematic representation of the gas driven ammonia-water absorption heat pump system is shown in fig. 1.

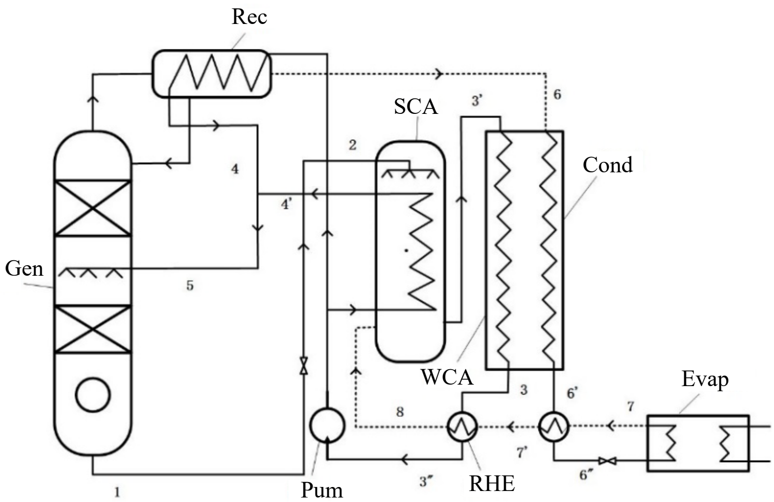

Figure 1. The schematic of gas-driven absorption heat pump;
Rec – rectifier, Gen – generator, Cond – condenser,
Evap – evaporator, Pum – pump

In the generator, the ammonia-water mixture is heated by thermal energy input provided from a gas burner to desorb the refrigerant. The refrigerant vapors flow to the rectifier where they are cooled by a part of ammonia-water strong solution on its way to the generator and which is thus preheated. This causes partial condensation of the water vapors purifying further the ammonia vapors. These flow to the water-cooled condenser where they are liquefied. The liquid refrigerant circulates then to the refrigerant heat-exchanger and further to the refrigerant expansion valve. After reduction of its pressure, the refrigerant is introduced in the evaporator where it evaporates by absorbing heat from the environment. The refrigerant vapors flows to absorber where it is absorbed by the ammonia-water weak solution returning from the generator in two steps: first, in the solution cooled absorber where the absorption heat released is used to preheat another part of ammonia-water strong solution on its way to the generator and then in the water-cooled absorber to complete the absorption process. At last, two parts of strong solution (4 and 4') meet then enter generator together.

Mathematical model

Basic assumptions of mathematical modeling

The proposed system is simulated and compared with the single-stage ammonia-water GAX absorption heat pump that recover rectification heat to evaluate its performance. The performance of the proposed system and single-stage ammonia-water GAX absorption heat pump can be obtained by solving the balance equations of each component under given working conditions. Many researchers have compiled calculation programs based on the Schulz equation to facilitate the calculation of state points, eliminating the cumbersome table look up process. In this paper, based on the Schulz equation [12], the calculation program of state points of ammonia-water is compiled by MATLAB software. The introduction of the Schulz equation is not detailed.

The mathematical model can be simplified by the following assumptions:

– The system is in steady state.
– Pressure drop along the pipe and power consumed by the pump are neglected.
– The solutions out from generator, solution cooled absorber, water-cooled absorber and rectifier are saturated.
– The fluid coming out from the condenser is saturated liquid and coming out from evaporator is saturated vapor.
– The concentration of ammonia gas at the outlet of the rectifier is 0.998, and the state parameters can be calculated as pure ammonia.
– The expansion process in throttling valves is isenthalpic.

The thermal calculation program must meet the total mass balance, the NH_3 mass balance and the energy balance of the various devices in the system:

$$\text{Total mass balance: } \sum m_{\text{in}} - \sum m_{\text{out}} = 0 \tag{1}$$

$$NH_3 \text{ mass balance: } \sum(m\varepsilon)_{\text{in}} - \sum(m\varepsilon)_{\text{out}} = 0 \tag{2}$$

$$\text{Energy balance: } \sum(mh)_{\text{in}} - \sum(mh)_{\text{out}} + Q = 0 \tag{3}$$

The split ratio, K, is defined as the ratio of the mass-flow rate of SCA inlet strong solution to the mass-flow rate of WCA outlet strong solution, and expressed:

$$K = \frac{m_{\text{SAC,in}}}{m_{\text{WCA,out}}} \tag{4}$$

The v is defined as the ratio of heat released by the SCA to total heat released by SCA and WCA, and expressed:

$$v = \frac{Q_{\text{SCA}}}{Q_{\text{SCA}} + Q_{\text{WCA}}} \tag{5}$$

The Z is defined as the ratio of ammonia vapors mass absorbed in SCA to total mass of ammonia vapors from evaporator, and expressed:

$$Z = \frac{m_{\mathrm{SCA,in}}^{\mathrm{NH_3}}}{m_{\mathrm{EVA,out}}^{\mathrm{NH_3}}} \tag{6}$$

The COP is an ideal COP without considering the burner efficiency, and expressed:

$$\mathrm{COP} = \frac{Q_\mathrm{C} + Q_\mathrm{WCA}}{Q_\mathrm{G}} \tag{7}$$

The performance improvement of novel cycle, η, can be defined as the percentage increase in COP compared with single-stage ammonia-water GAX absorption heat pump that recover rectification heat under the same conditions, and expressed:

$$\eta = \frac{\mathrm{COP_{NS}} - \mathrm{COP_{GS}}}{\mathrm{COP_{GS}}} 100\% \tag{8}$$

The mathematical model of the system is established under the given heat source temperature, cooling temperature, and cooling water temperature conditions, tab. 1. The generation temperature, evaporation temperature, condensation temperature, and absorption temperature are, respectively, determined by the heat source temperature, the cooling temperature and the cooling water temperature, which add or subtract the heat transfer temperature difference of the corresponding equipment.

Table 1. Range of parameters used for thermal calculation

Parameter	Ranges	Value
Difference between absorption pressure and evaporation pressure	0.01	0.01
Difference between condensing pressure and generating pressure	0.01	0.01
The increase of cooling water temperature in the condenser	4-6	5
Heat transfer temperature difference of condenser	3-4	3
Temperature difference of the hot end of generator	5-15	10
Temperature difference of the cold end of water-cooled absorber	4-8	6
Heat transfer temperature difference of evaporator	4-8	6

Mathematical model validation

In order to verify the accuracy of the aforementioned mathematical model, the simulation results of ammonia-water absorption heat pump are compared with the experiment results by Wu [14]. The schematic representation of ammonia-water absorption heat pump is shown in fig. 2(a). The variation of heating performance of the heat pump with driving source, hot water and evaporator inlet temperature were studied by experiment. The validation of mathematical model is verified by the variations of COP with evaporator inlet temperature. In the experiment, the cooling water temperature was set as 40 °C, the cooling water-flow rate was set as 12.0 m^3/h and the strong solution flow rate was set as 1.0 m^3/h, the driving source temperature was 130 °C, the evaporator inlet temperature increased from 7 °C to 30 °C. Since the temperature difference of evaporator, condenser and absorber in the reference are different from the temperature difference selected in this paper, in order to improve the verification accuracy, the temperature difference of the devices is selected the reference in the validation. The increase of cooling water temperature in the condenser is 3 °C, heat transfer temperature difference of condenser is 3 °C, temperature difference of the cold end of absorber is 5 °C and heat transfer temperature difference of evaporator is 3 °C. Due to the generator outlet temperature in the experiment is lower than the simulation, the temperature difference of the hot end of generator is selected as 15 °C to improve the accuracy of the validation.

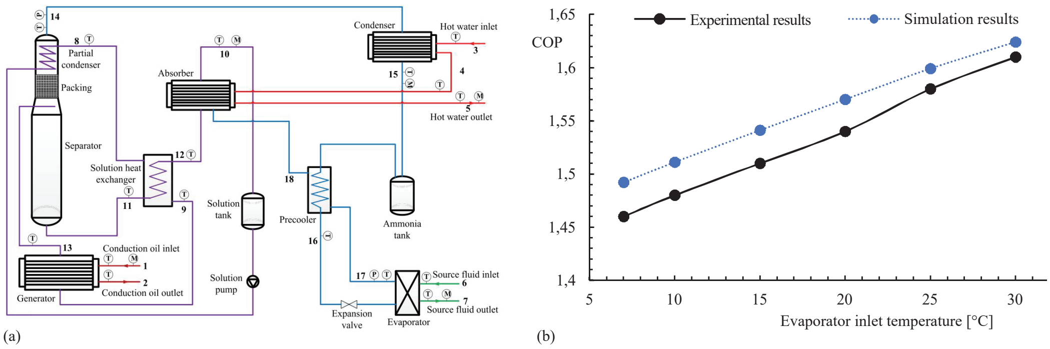

Figure 2. (a) The schematic of the conventional ammonia-water absorption heat pump [16] and (b) variation of COP with evaporator inlet temperature

The fig. 2(b) shows the variations of COP with evaporator inlet temperature at the generation temperature is 130 °C, cooling water temperature is 40 °C. In the experiment, when the evaporator inlet temperature increases from 7 °C to 30 °C, the COP increases from 1.46 to 1.61. In the simulation, when the evaporator inlet temperature increases from 7 °C to 30 °C, the COP increases from 1.492 to 1.624. In the same driving source temperature, the generator outlet solution temperature is about 104 °C in experiment and the generator outlet solution temperature is about 115 °C (driving source temperature 130 °C subtracts temperature difference of the hot end of generator 15 °C) in the simulation. In the system, rectification heat is recovered by using total strong solution to improve performance. Due to the generator outlet solution temperature in simulation is higher than the experiment, the heat load in solution heat exchanger is larger in the same working condition, which causes the generator inlet solution temperature is higher in the simulation. With the generator inlet solution temperature rises, the recovered rectification heat is more. Consequently, the generation heat in simulation is less than the generation heat in experiment and the simulation COP is higher than the COP of experiment. With the evaporation temperature rises, absorption pressure increases, which causes the saturated solution temperature decreases. The quantity of rectification heat decreases as evaporation temperature increases. Consequently, the difference between generator inlet solution temperature in simulation and generator inlet solution temperature in experiment keeps decreasing and the difference between the simulation COP and the COP of experiment keeps decreasing as evaporation temperature rises. Compared with the experiment result, when the evaporator inlet temperature is 7 °C, the maximum error is 2.19%. Consequently, the mathematical model is available.

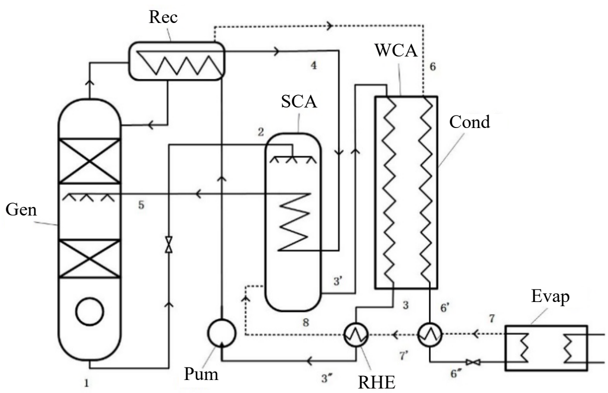

Figure 3. The schematic of gas-driven absorption heat pump; *Rec – rectifier, Gen – generator, Cond – condenser, Pum – pump, Evap – evaporator*

System simulation and results

As fig. 3 shows the single-stage ammonia-water GAX absorption heat pump using total strong solution to recover absorption heat after extracting rectification heat to improve the performance.

In the rectifier, using total WCA outlet strong solution to remove the rectification heat, the enthalpy at state 4 is calculated:

$$h_4 = \frac{fh_{3''} + Q_{\text{Rec}}}{f} \tag{9}$$

In the SCA, according to the mass conservation and energy conservation law, the enthalpy at state 3' and 5 are calculated:

$$h_5 = \frac{fh_4 + Q_{\text{SCA}}}{f} \tag{10}$$

$$Z = \frac{(f-1)(\varepsilon_{3'} - \varepsilon_1)}{0.998 - \varepsilon_{3'}} \tag{11}$$

$$h_{3'} = \frac{(f-1)h_2 + Zh_8 - Q_{\text{SCA}}}{f - 1 + Z} \tag{12}$$

As can be seen from aforementioned, with the increase of v (Q_{SCA} increases), generator inlet strong solution temperature rises, which causes the increase of rectification heat. Using total strong solution recover the rectification heat causes SCA inlet strong solution temperature (4) to rise and SCA outlet solution temperature (3') to decrease as v increases. Because of countercurrent heat transfer is used in SCA, in order to guarantee the progress of recovering absorption heat, SCA inlet strong solution temperature should be lower than SCA outlet solution temperature (3') and SCA outlet strong solution temperature should be lower than SCA inlet weak solution. In this paper, the minimum difference between SCA inlet weak solution temperature (2) and SCA outlet strong solution temperature (5) is set to 10 °C ($t_2 - t_5 \geq 10$ °C). The minimum difference between SCA outlet solution temperature (3') and SCA inlet strong solution temperature (4) is set to 5 °C ($t_{3'} - t_4 \geq 5$ °C).

Figure 4 shows the variations of SCA outlet strong solution temperature with v at cooling water temperature of 30 °C, evaporation temperatures of –11°C, generation temperatures of 140 °C. In order to increase generator inlet strong solution temperature to improve the COP, the outlet strong solution of WCA is preheated in rectifier and SCA. As can be seen from the fig. 4, with increase of v, generator inlet strong solution temperature rises, which results in the increase of rectification heat. Due to using total strong solution to recover absorption heat after extracting rectification heat, the temperature of inlet strong solution of SCA rises as v increases. According to the Energy conservation law, with the increase of v, the enthalpy of SCA outlet solution decreases. Thereby, the difference between SCA inlet strong solution temperature and SCA outlet solution temperature keeps decreasing as v increases. In Figure 4, generator outlet weak solution temperature is 130 °C, the highest SCA outlet strong solution temperature is 108 °C. The minimum temperature difference between SCA inlet weak solution temperature and SCA outlet strong solution is 22 °C, which is larger than the setting temperature difference. As can be seen from the fig. 5, at same condition, the difference between temperature (3') of outlet solution of SCA and temperature (4) of inlet strong solution of SCA decreases from 10 °C to 5 °C when v increases from 0.385 to 0.439, which limits to recover more absorption heat released by SCA. When the temperature difference between SCA inlet strong solution and SCA outlet solution is 5 °C, the recovered absorption heat by strong solution and COP reaches the maximum. As a result, when using total strong solution to recovers absorption heat after extracting rectification heat to improve the performance, there is a problem that SCA inlet strong solution temperature rises limiting to recover more absorption heat.

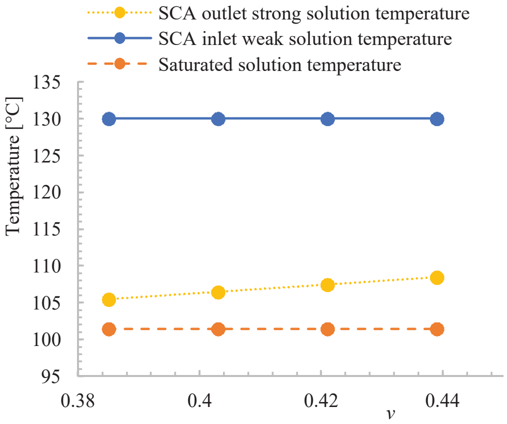

Figure 4. Variation of SCA outlet strong solution temperature with *v*

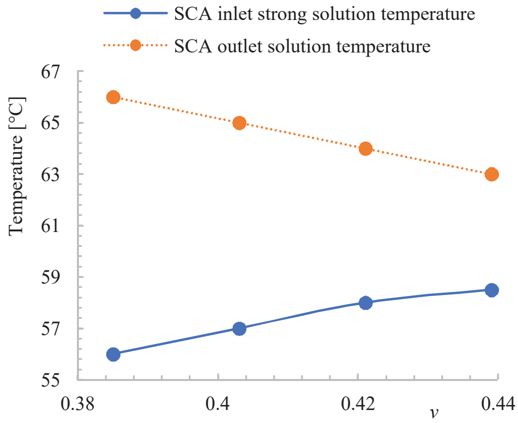

Figure 5. Variation of temperature of outlet solution of SCA and inlet strong solution of SCA with respect to *v*

Figure 6 shows the variations of COP of conventional ammonia-water absorption heat pump and the single-stage ammonia-water GAX absorption heat pump with respect to evaporation temperature at cooling water temperature of 30 °C and generation temperatures of 140 °C. The evaporation temperature varies between –3 °C and –15 °C. Step length 3 °C. The COP of single-stage ammonia-water GAX absorption heat pump is the value that corresponds to the maximum *v*. As can be seen from fig. 6, compared with conventional ammonia-water absorption heat pump, using total strong solution to recover absorption heat after extracting rectification heat improves the system heat recovery capacity and the COP is higher. When evaporation temperature increases from –15 °C to –3 °C, the COP of GAX absorption heat pump increases from 1.574 to 1.783 and the COP of conventional traditional ammonia-water absorption increases from 1.491 to 1.57. As a result, using total strong solution to recover rectification heat and absorption heat is a beneficial way to improve COP of ammonia-water absorption heat pump. However, the method of using total strong solution to recover absorption heat after extracting rectification heat causes SCA inlet strong solution temperature to rise, which limits the further improvement of system heat recovery capacity.

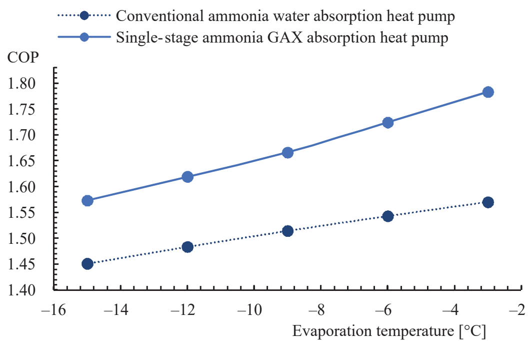

Figure 6. Variation of COP of conventional ammonia-water absorption heat pump and the single-stage ammonia-water GAX absorption heat pump with respect to evaporation temperature

In order to further improve the system heat recovery capacity, solution split method is proposed to recover rectification heat and absorption heat to resolve the aforementioned problem . The WCA outlet strong solution temperature is much lower than the temperature of strong solution that recovers rectification heat, which avoids the aforementioned problem. Because of WCA outlet strong solution temperature is much lower than the temperature of strong solution that recovers rectification heat, more absorption heat is recovered by WCA outlet strong solution, which is beneficial to reduce the need for external heat in the generator. Under a certain working condition, with the v increases, the generator inlet strong solution temperature rises, which causes the increase of rectification heat. In rectifier, with solution split ratio, K, increases, the mass-flow rate of strong solution flowed to rectifier decreases. If the mass-flow rate of strong solution flowed to rectifier is insufficient, it will cause the ammonia flowed to condenser to be impure, which results in an adverse effect on the system performance. For the purpose of guaranteeing the purity of ammonia flowing to condenser, the enthalpy of strong solution of rectifier outlet is not higher than the value of saturated solution ($h_4 \leq h_s$). The maximum value of solution split ratio, K, corresponding to a certain v is calculated as following formula and the maximum, K, decreases as v increases:

$$\frac{(1-K)fh_{3''}+Q_{\mathrm{Rec}}}{(1-K)f}=h_4 \leq h_s \tag{13}$$

In the SCA, according to the mass conservation and energy conservation law, the enthalpy at state 4' and 5 are calculated:

$$Z=\frac{(f-1)(\varepsilon_{3'}-\varepsilon_1)}{0.998-\varepsilon_{3'}} \tag{14}$$

$$h_{4'}=\frac{(f-1)h_2+Zh_8-Q_{\mathrm{SCA}}}{f-1+Z} \tag{15}$$

$$h_5=\frac{f(1-K)h_4+fKh_{4'}}{f} \tag{16}$$

In SCA, if the mass-flow rate of strong solution flowed to rectifier is excessive, it will cause the SCA outlet strong solution temperature higher than SCA inlet weak solution temperature. Since countercurrent heat transfer is used in SCA, the temperature of the SCA inlet weak solution is higher than the temperature of the SCA outlet strong solution. In this paper, the minimum difference between temperature (2) of inlet weak solution of SCA and temperature (4') of outlet strong solution of SCA is set to 10 °C ($t_2 - t_{4'} \geq 10$ °C). Consequently, there is the minimum value K corresponding to a certain v, which makes the temperature of the SCA outlet strong solution lower than the temperature of the SCA inlet weak solution 10 °C and it increases as v increases. According to the previous analysis, when using solution split method to recover the rectification heat, the difference between the maximum value K and the minimum value K keeps decreasing as v increases under a certain working condition. When v cannot increase, the range of strong solution split ratio, K, is determined under a certain working condition. According to the eq. (16), when the range of strong solution split ratio, K, is determined, no matter which value is chosen in the range of K, the enthalpy of strong solution of generator inlet is constant. Because the quantity of recovered absorption heat is much larger than the recovered rectification heat, the maximum value of K is chosen as the optimal value of K in this paper. Due to the strong solution split ratio, K, plays an important role in recovering internal heat, how to determine the range of strong solution split ratio, K, and the effect of evaporation temperature, cooling water temperature and generation temperature on the optimum split ratio, K, will be discussed under given working conditions.

Figure 7 shows variation of SCA outlet solution temperature and the range of solution split ratio, K, with respect to v at cooling water temperature of 30 °C, evaporation temperatures of –11 °C, generation temperatures of 140 °C. According to the previous analysis, the difference between the maximum K decreases and the minimum K keeps decreasing as v increases under a certain working condition. As can be seen from the fig. 7, when v increases from 0.493 to 0.595, the maximum value of K decreases from 0.64 to 0.57 and the minimum value of K increases from 0.47 to 0.56. The maximum value v is 0.595, the range of strong solution split ratio, K, is 0.56 to 0.57 and the optimum split ratio, K, is 0.57 under this working condition. Comparing with fig. 5, it can be seen that under the same working conditions, by using the solution split method, the maximum value v increases from 0.475 to 0.595, which indicates that the internal heat recovering capacity of the system is strengthened and the COP is improved. The COP increases from 1.642 to1.83 increasing 11.4%. The SCA outlet solution temperature is 54 °C and the WCA outlet strong solution temperature is 41 °C (cooling water temperature adds the sum of the increase of cooling water temperature in condenser and the temperature difference of the cold end of WCA). The difference between SCA outlet solution temperature and WCA outlet strong solution temperature is larger than 5 °C.

Figure 8 shows the relationship of optimal value of K and recovered absorption heat with respect to generation temperature at evaporation temperature of –11 °C, cooling water temperature of 30 °C. The generation temperature varies between 130 °C and 155 °C. As generation temperature rises, the generator outlet weak solution temperature increases, which causes the decrease of generator outlet weak solution concentration. Because of decrease of generator outlet weak solution concentration, the circulation ratio, f, decreases, which leads to the mass-flow rate of WCA outlet strong solution decreases. Increase in generator outlet weak solution temperature leads to the maximum temperature of SCA outlet strong solution rises, which results in the increase of rectification heat. Consequently, as generation temperature rises, SCA outlet strong solution temperature and rectification heat increase and the mass-flow rate of WCA outlet strong solution decreases. It causes the optimal solution split K and internal heat recovered go down. As can be seen from the fig. 8, when generation temperature increases from 130 °C to 155 °C, the optimal value of K decreases from 0.8 to 0.5. The recovered internal heat in the proposed system decreases form 3199 kW to 2324 kW and the recovered internal heat in the GAX system decreases form 2551.6 kW to 1742.6 kW.

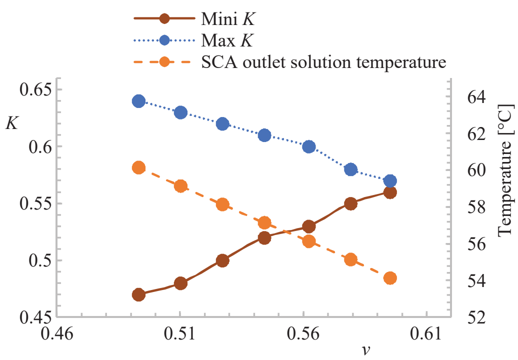

Figure 7. Variation of SCA outlet solution temperature and the range of solution split ratio with respect to *v*

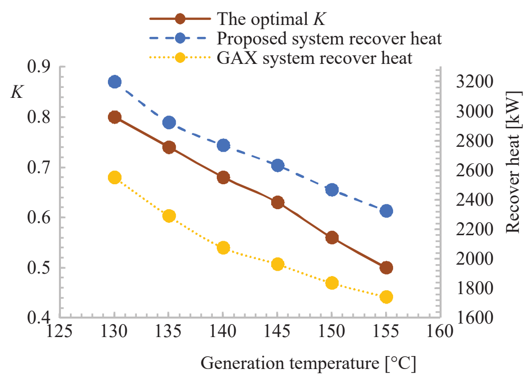

Figure 8. Variation of optimal value of *K* and recovered absorption heat with generation temperature

Figure 9 shows the relationship of optimal value of K and recovered absorption heat with respect to cooling water temperature under evaporation temperature of –11 °C, generation temperature of 140 °C. The cooling water temperature varies between 22 °C and 35 °C. As cooling water temperature rises, WCA outlet strong solution temperature and generation pressure go up, which causes increase of generator outlet solution concentration and decrease of WCA outlet solution concentration. Because of the increase of generator outlet concentration and decrease of WCA outlet concentration, the circulation ratio, *f*, increases, which results in the increase of the mass-flow rate of WCA outlet strong solution. Due to the increase of generation pressure and decrease of WCA outlet strong solution concentration, the saturated solution temperature rises. It leads to the maximum temperature of the rectifier outlet strong solution rise. The proportion strong solution flowed to rectifier goes down. Consequently, as cooling water temperature rise, the mass-flow rate of WCA outlet strong solution and temperature of the saturated solution increase. It causes the optimal solution split *K* and internal heat recovered go up. As can be seen from the fig. 9, when the cooling water temperature increases from 22 °C to 35 °C, the optimal *K* increases from 0.42 to 0.7. The recovered internal heat in proposed system increases form 1811 kW to 3230 kW. The recovered internal heat in GAX system increases form 1619.1 kW to 2525.1 kW. The difference between the recovered heat of both systems keeps increasing as cooling water temperature rises.

Figure 10 shows the relationship of optimal value of *K* and recovered absorption heat with respect to evaporation temperature under cooling water temperature of 30 °C, generation temperature of 140 °C. The evaporation temperature varies between –3 °C and –15 °C. As evaporation temperature goes down, absorption pressure decreases, which causes the decrease of WCA outlet strong solution concentration. Due to the decrease of WCA outlet solution concentration, the circulation ratio, *f*, and the temperature of the saturated solution rises, which causes the mass-flow rate of WCA outlet strong solution and the maximum temperature of the rectifier outlet strong solution rise. The proportion strong solution flowed to rectifier goes down. Consequently, as evaporation temperature goes down, the mass-flow rate of WCA outlet strong solution and temperature of the saturated solution increase. It causes the optimal solution split *K* and internal heat recovered go up. As can be seen from the fig. 10, when the evaporation temperature decreases from –3 °C to –15 °C, the optimal *K* increases from 0.47 to 0.61. The recovered internal heat in proposed system increases form 1640.8 kW to 2683.9 kW. The recovered internal heat in GAX system increases form 1640.8 W to 2263.1 kW. The difference between the recovered heat of both systems keeps increasing as evaporation temperature goes down.

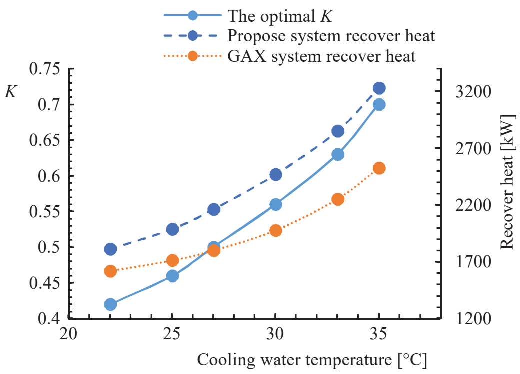

Figure 9. Variation of optimal value of *K* and recovered absorption heat with cooling water temperature

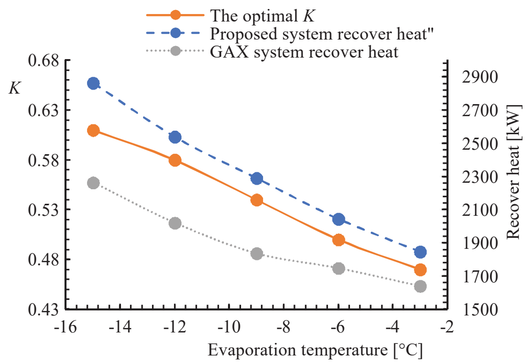

Figure 10. Variation of optimal value of *K* and recovered absorption heat with evaporation temperature

As can be seen, by using solution split method, the recovered heat by strong solution always great than the single-stage ammonia-water GAX absorption heat pump in the same working conditions. The reason why the solution split method is more advantageous is that the WCA outlet strong solution temperature is much lower than the temperature of strong solution that recovers rectification heat, which enables WCA outlet strong solution to recover more absorption heat. From figs. 8-10, as the difference between evaporation temperature and cooling water temperature keeps increasing or generation temperature goes up, the recovered heat in proposed system are always more than the heat recovered in single-stage ammonia-water GAX absorption heat pump. Consequently, compared with single-stage ammonia-water GAX absorption heat pump, the advantage of the propose system internal heat recovery is more obvious.

Figure 11 shows the relationship of the COP of the proposed system and the COP of single-stage ammonia-water GAX absorption heat pump with respect to evaporation temperature under cooling water temperature of 30 °C, generation temperature of 140 °C. As can be seen from fig. 11, when the evaporation temperature decreases from –3 °C to –15 °C, the trend of COP of single-stage ammonia-water GAX absorption heat pump and the proposed system are same. It goes down as evaporation temperature decreases. The COP of proposed system dropped from 1.882 to 1.766, the COP of GAX system dropped from 1.783 to 1.573. As can be seen from fig. 10, at same condition, by using the method of solution split, the heat recovered by strong solution is more than the single-stage ammonia-water GAX absorption heat pump and the difference increases as the evaporation temperature goes down. Consequently, the generator inlet solution temperature in the proposed system is higher than the generator inlet solution temperature in the GAX system and the difference increases as the evaporation temperature rises. As evaporation temperature rises, the down trend of proposed system COP always slower than the trend of GAX system COP and the difference between proposed system COP and GAX system COP increases.

Figure 12 shows the relationship of the COP of the proposed system and the COP of single-stage ammonia-water GAX absorption heat pump with respect to cooling water temperature under evaporation temperature of –11 °C, generation temperature of 140 °C. As can be seen from fig. 12, when the cooling water temperature rises from 22 °C to 35 °C, the COP of single-stage ammonia-water GAX absorption heat pump and the proposed system decrease as cooling water temperature goes up. The COP of proposed system dropped from 1.869 to 1.774, the GAX system COP dropped from 1.784 to 1.541. As can be seen from fig. 9, at same condition, by using the method of solution split, the heat recovered by strong solution is more than the single-stage ammonia-water GAX absorption heat pump and the difference increases as the cooling water temperature rises. Consequently, the generator inlet solution temperature in the proposed system is higher than the generator inlet solution temperature in the GAX system and

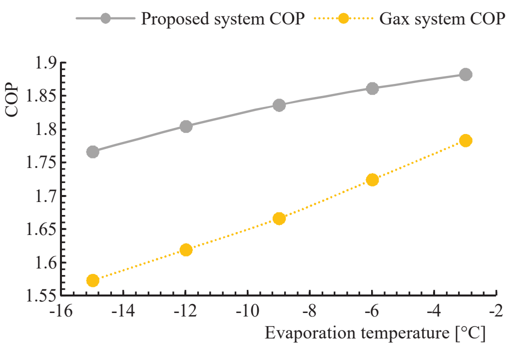

Figure 11. Variation of GAX heat pump COP and the proposed heat pump COP with evaporation temperature

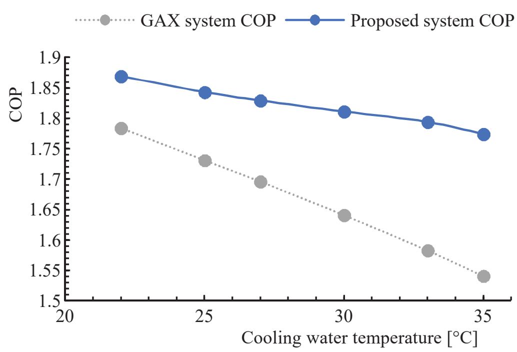

Figure 12. Variation of GAX heat pump COP and the proposed heat pump COP with cooling water temperature

the difference increases as the cooling water temperature rises. As cooling water temperature rises, the down trend of proposed system COP always slower than the trend of GAX system COP and the difference between proposed system COP and GAX system COP increases.

Figure 13 shows the relationship of the COP of the proposed system and the COP of single-stage ammonia-water GAX absorption heat pump with respect to generation temperature under evaporation temperature of –11 °C, cooling water temperature of 30 °C. When the generation temperature is lower, as it increases, the circulation ratio, *f*, and the mass-flow rate of strong solution decrease. It is beneficial to reduce the need for external heat in the generator. However, when the generation temperature rises to a certain degree, the down trend of circulation ratio, *f*, slows down. After that, the generation temperature continues to rise, the need for external heat in the generator will not decreases with the decrease of circulation ratio, *f*, but will increase due to the increase of generation temperature. In fig. 13, when the generation temperature increases from 130 °C to 155 °C, the proposed system COP increases from 1.734 to 1.877, then falls to 1.793, single-stage ammonia-water GAX absorption heat pump COP increases from 1.526 to 1.6235 and then drops to 1.584. Consequently, with the generation temperature increases, the COP will increase, but when the generation temperature reaches a certain value, there is the maximum value of COP. In this working condition, the COP reaches the maximum when the generation temperature is 145 °C. Therefore, the most suitable generation tion temperature should be selected according to the specific working conditions.

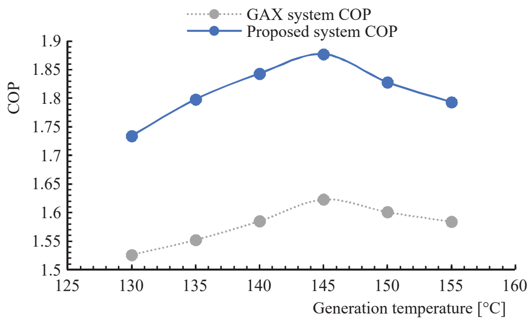

Figure 13. Variation of GAX heat pump COP and the proposed heat pump COP with generation temperature

Conclusions

After the discussion, the following conclusions can be drawn.

In single-stage ammonia-water GAX absorption heat pump, using total strong solution recovers absorption heat after extracting rectification heat is beneficial to improving the COP. Compared with conventional ammonia-water absorption heat pump, the maximum performance improvement is 13.5% under the discussion working condition. However, SCA inlet strong solution temperature rises limiting to recover more absorption heat. Using the method of solution split effectively resolves the problem about single-stage ammonia-water GAX absorption heat pump and further improves the COP. For solution split ratio, *K*, plays an important role in improving COP, the method that how to choose the optimal value of solution split ratio, *K*, and the effect of evaporation temperature, cooling water temperature and generation temperature on the optimal value of solution split ratio, *K*, are analyzed. It provides a reference for the design and optimization of the system.

In the discussed working conditions, at evaporation temperature is –11 °C, cooling water temperature is 30 °C generation temperature is 145 °C, compared with the GAX absorption heat pump, the maximum performance improvement is 15.7%. Moreover, the degree of COP improvement is more obvious as evaporation temperature goes down or cooling water temperature goes up.

Acknowledgment

The work of this paper is financially supported by the National Natural Science Foundation of China (No.51876033).

Nomenclature

f – circulation ratio, [–]
h – enthalpy, [kJkg^{-1}]
K – split ratio, [–]
m – mass-flow rate, [kgs^{-1}]
Q – heat load, [kW]
t – temperature, [K]
v – ratio of recovered absorption heat to total absorption heat, [–]
Z – ratio of absorbed ammonia in solution cooled absorber to total ammonia, [–]

Greek symbols

ε – ammonia concentration in saturate liquid, [kgkg^{-1}]
η – relative increasing ratio of COP, [–]

Subscripts

C – condensation
EVA – evaporator
G – generation
GS – GAX system
NS – novel system
Rec – rectification
s – saturated state
SCA – solution cooled absorber
WCA – water cooled absorber

Acronyms

GAX – generator-absorber heat exchange
RHE – refrigerant heat exchanger
SCA – solution cooled absorber
WCA – water cooled absorber

Reference

[1] ***, National Energy Administration Winter Clean Heating Planning in the North (2017-2021) (in Chinese), 2017
[2] Wu, W., *et al.,* Design and Theoretical Analysis of Ammonia-Water Air Source Absorption Heat Pump (in Chinese), *Proceedings*, Celebrating the 30th Anniversary of the Beijing Refrigeration Society and the Annual Academic Conference, Bejing, China, 2010
[3] Chen, X., *et al.,* Heat Integration of Ammonia-Water Absorption Refrigeration System Through Heat-Exchanger Network Analysis, *Energy*, *141* (2017), Dec., pp. 1585-1599
[4] Jaballah, M. B *et al.,* Enhancement of the Performance of Bubble Absorber Using Hybrid Nanofluid as a Cooled Absorption System, *International Journal of Numerical Methods for Heat and Fluid Flow, 31* (2019), 4, pp. 3857-3871
[5] Ben Hamida, J., *et al.,* Numerical Study of Heat and Mass Transfer Enhancement for Bubble Absorption Process of Ammonia-Water Mixture Without and with Nanofluid, *Thermal Science, 22* (2019), 6B, pp. 3107-3120
[6] Jawahar, C. P., Saravanan, R., Generator Absorber Heat Exchange Based Absorption Cycle – A Review, *Renewable and Sustainable Energy Reviews, 14* (2010), 8, pp. 2372-2382
[7] Jawahar, C. P., Saravanan, R., Experimental Studies on Air-Cooled NH_3-H_2O Based Modified GAS Absorption Cooling System, *International Journal of Refrigeration, 34* (2011), 3, pp. 658-666
[8] Chen, G., *et al.,* Theoretical Performance Analysis of an Improved Absorption-Compression Hybrid GAX Refrigeration Cycle (in Chinese), *Proceedings*, CSEE, *36* (2016), 12, pp. 3250-3255
[9] Fernandez-Seara, J., Sieres, J., The Importance of the Ammonia Purification Process in Ammonia-Water Absorption Systems, *Energy Conversion & Management, 47* (2006), 13, pp. 1975-1987
[10] Liao, J., Performance Analysis of Ammonia Water Absorption Refrigeration GAX Cycle (in Chinese), Ph. D. thesis, Southeast University, Nanjing, China, 2004
[11] Sun, S., Du, W., Analysis of the Influence of Ammonia Distillation Purity on the Performance of Ammonia Absorption Refrigeration System (in Chinese), *Refrigeration Technology, 38* (2018), 161, pp. 14-18
[12] Du, S., *et al.,* Optimal Ammonia Water Absorption Refrigeration Cycle with Maximum Internal Heat Recovery Derived from Pinch Technology, *Energy, 68* (2014), Apr., pp. 862-869
[13] Chen, X., *et al.,* An Improved Cycle for Large Temperature Lifts Application in Water-Ammonia Absorption System, *Energy, 118* (2016), Jan., pp. 1361-1369
[14] Wu, W., *et al.,* NH_3-H_2O Water Source Absorption Heat Pump (WSAHP) for Low Temperature Heating: Experimental Investigation on the Off-Design Performance, *Energy, 115* (2016), Part 1, pp. 697-710

Paper submitted: November 10, 2019
Paper revised: January 18, 2020
Paper accepted: January 24, 2020