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ORIGINAL ARTICLE

Influence of vapor absorption cooling on humidification-dehumidification (HDH) desalination

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KEYWORDS

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Abstract The desalination yield in humidification-dehumidification (HDH) process is increased by proposing cooling plant integration with two stage operation. The current work is targeted on the investigation of vapor absorption refrigeration (VAR) parameters on overall energy utilization factor (EUF). The dephlegmator heat is recovered internally in VAR instead of rejecting to environment. This work can be used to control the operational conditions of VAR to enhance the desalination and cooling together. The studied process parameters in VAR are strong solution concentration, separator or generator temperature, dephlegmator effectiveness, circulating water inlet temperature and evaporator temperature. Out of these five variables, lower limit of separator temperature, upper limit of dephlegmator effectiveness and lower limit of circulating water temperature are fixed in the specified range to attain the optimum strong solution concentration and optimum evaporator temperature. At the specified boundaries of three variables, the optimized strong solution concentration and evaporator temperature are 0.47 and 10 °C respectively. At this condition, the maximized cycle EUF is 0.358.

1. Introduction

Humidification-dehumidification (HDH) desalination cycle can be integrated with the cooling cycle to gain the dual benefits of enhanced desalination and added cooling as the existed HDH desalination has low yield. The previous work is focused on the theoretical and experimental investigation of integrated desalination and cooling plant [1,2]. The considered desalination plant is a double stage desalination to get the cumulative and enhanced desalination yield. Vapor absorption refrigeration (VAR) has been chosen to generate the chilled water to be used in the last stage of desalination plant. VAR is thermally operated plant having low coefficient of performance (COP) compared to the vapor compression refrigeration (VCR) system. But VAR operates on low grade energy which is available at low cost compared to the electricity. Therefore the VAR benefits on long run by proving the payback period. Single effect VAR is selected to suit the current two stage desalination plant.

HDH desalination has the advantages of cost effective, simple design and easy operation. Adding VAR improves the

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Nomenclature

A	area (m^2)
EUF	energy utilization factor
G	solar radiation (W/m^2)
h	specific enthalpy (kJ/kg dry air)
m	mass flow rate (kg/s)
n	number
Q	heat (kW)
T	temperature (°C)
TD	temperature difference (°C)
TTD	terminal temperature difference (°C)
W	work (kW)
x	concentration (kg/kg mixture)
ε	effectiveness
Suffix	
APH	air preheater
chw	chilled water
da	dry air
fg	fluid-gas (phase change)
hw	hot water
PC	parabolic collector
SWH	solar water heater
ts	two stage
VAR	vapor absorption refrigeration

attraction of the HDH desalination by converting into multi objective plant. Colonna and Gabrielli [3] studied the VAR in 10 MW_e trigeneration plant. They analyzed the options of VAR coupling to internal combustion (IC) engines and gas turbine exhaust. VAR system can also be extended for the simultaneous benefit of cooling and power called as cooling cogeneration cycle [4]. Tsoutsos et al. [5] optimized the solar cooling system to a hospital with the VAR system. Kaynakli and Kilic [6] recommended a higher evaporator temperature to result more COP for the VAR. Sieres and Fernández-Seara [7] conducted experiment on packed bed rectifier and studied the heat and mass transfer processes. Horuz and Callander [8] conducted an experiment on 10 kW cooling capacity ammonia-water mixture VAR plant and showed that the cooling effect increases with increase in chilled water inlet temperature. Muthu et al. [9] conducted on 1 kW capacity R134a-DMAC VAR plant at 80 °C and resulted −4 °C evaporator temperature. Fernandez-Seara et al. [10] designed a traveler chiller using vehicle exhaust gas with ammonia-water based VAR system. Berlitz et al. [11] modified the VAR plant by using mixing column, two absorbers and three expansion valves. Horuz [12] compared the VAR with ammonia-water mixture and lithium bromide-water mixture and suggested to consider the issues of danger of crystallization and impossibility of maintaining very low temperatures if water is used as the refrigerant.

The VAR performance parameters are cooling effect and COP. The optimized process conditions differ based on the objective of maximum cooling or maximum COP. For example a higher generator temperature favors the cooling effect but not COP. The behavior of VAR on its own performance differs compared to its working as a subsystem in an integrated plant. Therefore the optimum conditions change from the individual plant optimization to the integrated plant optimization. The influence of VAR's operational conditions is not reported in the literature with a focus on maximizing the desalination and cooling performance. Therefore the current work is aimed on checking the influence of VAR's operational conditions on the performance of integrated cycle and plant. The novelty in the considered VAR configuration is the use of internal heat recovery from dephlegmator instead of heat rejection to surroundings. In this work the desalination process conditions are kept constant during the analysis applied for the VAR's process parameters. The study of HDH plant is not the scope of the current work.

2. Methodology

Thermodynamic simulation with reasonable assumptions gives the best operational conditions for the plant processes. It helps in planning of the research work with a feasible working of the concept/idea or proposed product. It also improves the probability of success rate. After completion of the thermodynamic optimization, the immediate steps involved are sizing of the components and manufacturing. Without the thermodynamic study, the development of thermal system is a trail and error work which does not have the scientific base. Therefore thermodynamic study is a primary and mandate activity before implementing the proposed plant. Since the thermodynamic work for the desalination is well reported in the literature, the current results are focused on examining the VAR's influence on desalination, cooling and EUF for cycle and plant.

Fig. 1 details the process flow of two stage desalination and VAR plant which are coupled by the evaporator and final dehumidifier with the chilled water circuit. The diagram shows recirculation of hot saline water lines linked to solar water heater, open circuit air circulation used for desalination and cooling, recirculation chilled water lines, ammonia-water mixture lines in VAR, recirculation thermic fluid lines from the solar concentrating collector and circulating water lines for condenser and absorber. The study of two stage desalination is not the scope of the current work. The VAR plant consists of pump, solution heat exchanger, vapor generator (boiler), separator (part of generator) dephlegmator, condenser, subcooler, throttling devices, evaporator and mixing chamber.

The VAR works on the operating principle of separation of fluid pair (ammonia and water in this case) by heating and mixing by cooling (rejecting heat) at the sink temperature (absorber). In the boiler or vapor generator, the weak solution is heated and turns into liquid-vapor mixture. In the separator, the weak solution is divided into ammonia rich vapor and strong solution. A further enrichment of ammonia concentration to increase the cooling is carried out in the dephlegmator by rejecting heat. The role of condenser, throttling and evaporator is similar in VCR plant. Absorber, pump and boiler are used in place of compressor. Subcooler and solution heat

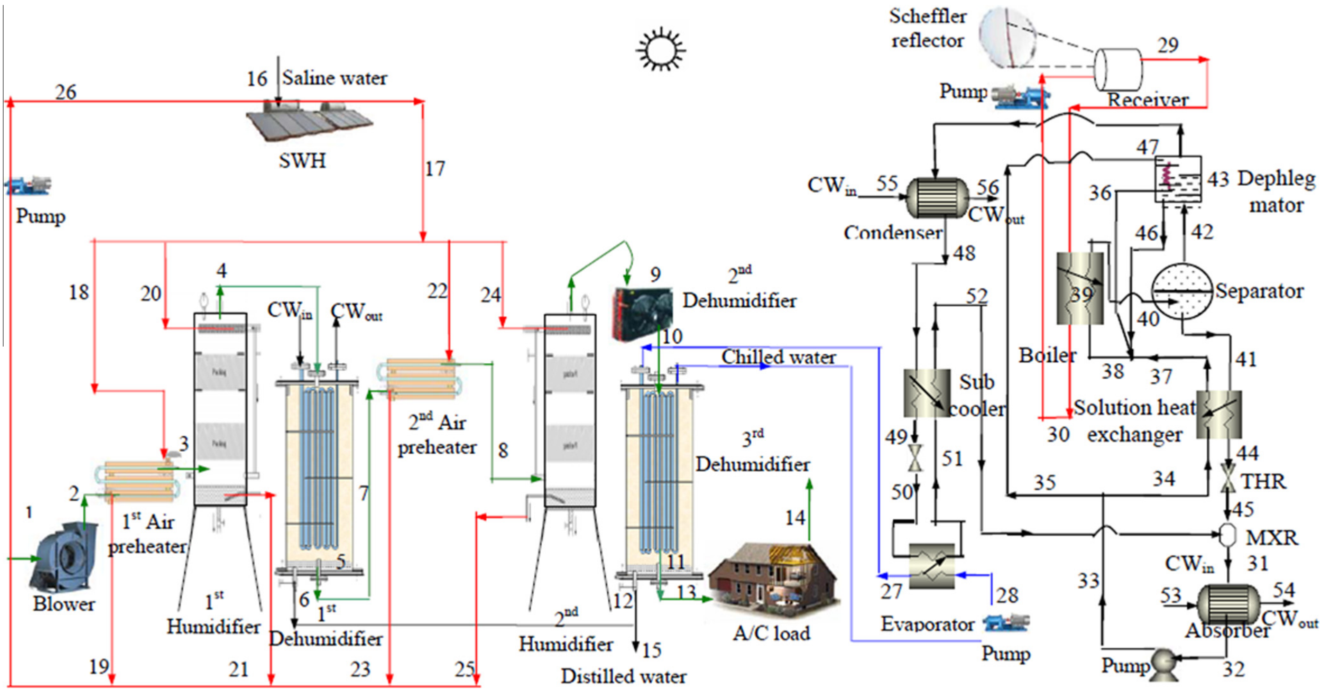

Figure 1 Two stage desalination with integrated VAR cooling.

exchanger increase the internal heat recovery and improve the COP. The VAR plant is solved theoretically with a source from the solar parabolic collector.

The rejection of heat from the dephlegmator condenses the water vapor from the ammonia-water mixture. Due to removal of water from the mixture, the concentration of the vapor increases from x_{in} to x_{exit} as shown in Fig. 2. The maximum limit to reject the heat in the dephlegmator is restricted by 100% ammonia vapor state. Therefore the effectiveness of the dephlegmator can be defined as the ratio of actual concentration rise in the dephlegmator to the maximum concentration rise when the vapor becomes pure ammonia.

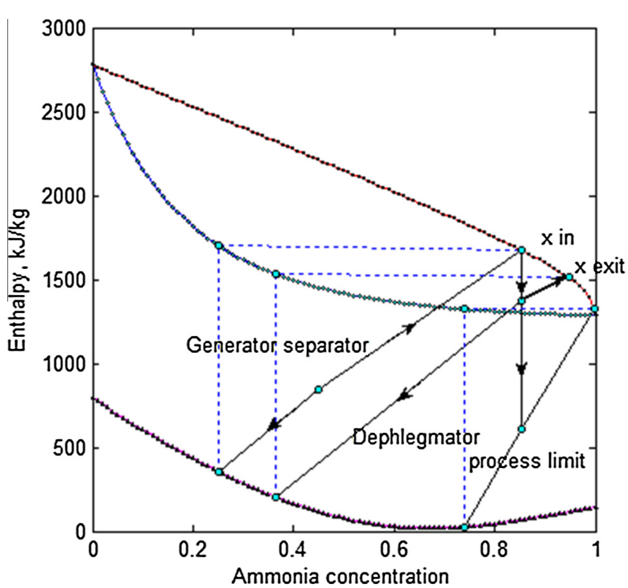

Figure 2 Dephlegmator process to show the effectiveness of distillation.

The effectiveness of dephlegmator is function of refrigerant concentration (x) as follows:

$$\varepsilon_{dephlegmator} = \frac{x_{exit} - x_{in}}{1 - x_{in}} \tag{1}$$

Following are the assumptions taken for thermodynamic evaluation:

(a) Air flow rate in the desalination plant at normal condition is 15 N m^3/h = 19.31 kg/h (m, kg/h = m, N m^3/h × 28.84/22.4).
(b) Saline water temperature at the inlet of air preheaters and humidifiers is 60 °C.
(c) For condenser and absorber, the circulating water inlet temperature is 30 °C.
(d) The separator or generator temperature in VAR is 105 °C.
(e) The dephlegmator effectiveness is assumed as 50%.
(f) The liquid vapor mixture temperature at the exit of evaporator is 10 °C [13].

The chilled water temperature at the inlet and outlet of the evaporator is determined from the exit temperature of evaporator.

$$T_{28} = T_{evaporator} + \mathrm{TTD} \tag{2}$$

In the above equation, the terminal temperature difference (TTD) in the evaporator is 4 °C.

The chilled water temperature is

$$T_{27} = T_{28} - \mathrm{TD} \tag{3}$$

In the above equation, the temperature difference (TD) in chilled water is considered at 5 °C.

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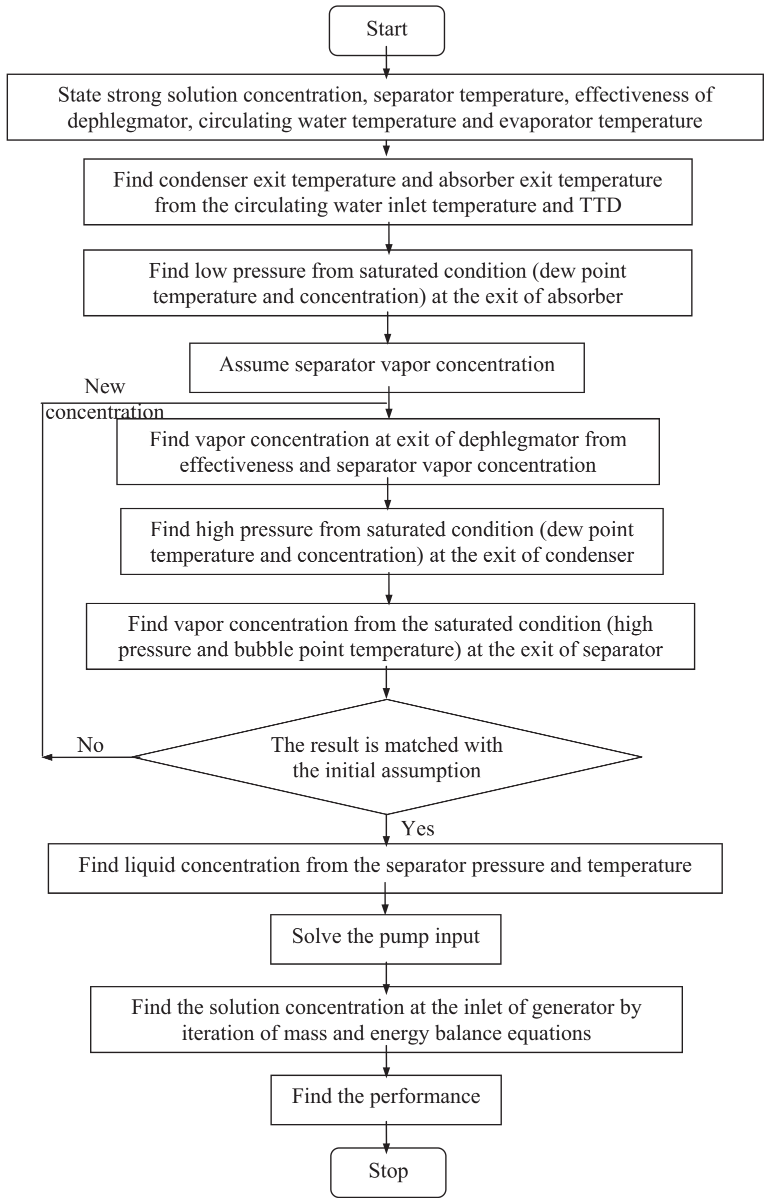

Figure 3 Representation of methodology in flowchart to solve the VAR.

The methodology to solve the VAR is outlined in the flowchart as shown in Fig. 3. The independent variables in the VAR cycle are strong solution concentration, separator temperature, effectiveness of dephlegmator, circulating water temperature and evaporator temperature. The constraints in the state of working fluid are saturated liquid condition at the absorber exit, saturated liquid condition at the condenser exit and saturated vapor condition at the exit of separator. From these conditions, cycle low pressure and high pressure can be solved. Since three constraints are available, in addition to low pressure and high pressure generator's vapor concentration can be determined instead of its fixation. The iteration is developed as shown in the flowchart to determine the separator vapor concentration. Now the degree of freedom is restricted with the five variables listed. To find the best operational process parameters (strong solution concentration, separator temperature, effectiveness of dephlegmator, circulating water temperature and evaporator temperature), two variables are changed together. The EUF of cycle and plant is studied under the specified range of these variables (parameters). Four plots are generated to identify the area of operation for the maximum energy conversion. Some of the variables to be selected are at the border level and some may be at optimum (maximum or minimum) i.e. in between the low and upper limits which are concave or convex in shape. The selected variables at the upper or lower edge of specified range can be fixed in the subsequent parametric optimization process. Initially, the analysis has been conducted to the variables where the optimum is resulting at the extreme ends in the range as it has no concave or convex nature. In the final stage of optimization, the concave or convex shaped functions are analyzed with the other variables kept constant.

The cooling output from the plant is

$$Q_{cooling} = m_{da}(h_{ambient} - h_{11}) \quad (4)$$

The performance of the desalination plant is solved with the energy utilization factor (EUF) for two stage desalination cycle. The area of solar flat plate collector for hot water and parabolic collector for VAR plant is determined from the sizing of solar collector [14].

The EUF of two stage desalination cycle with cooling effect is

$$EUF_{ts\ cycle} = \frac{m_{ts\ desalination}h_{fg} + Q_{cooling}}{Q_{APH,1} + Q_{APH,2} + Q_{humidifier,1} + Q_{humidifier,2} + Q_{VAR} + W_{pump,hw} + W_{VAR} + W_{pump,chw}} \quad (5)$$

The EUF of two stage desalination plant with cooling effect is

$$EUF_{ts\ plant} = \frac{m_{ts\ desalination}h_{fg} + Q_{cooling}}{G_{global}A_{SWH} + G_{global}A_{PC} + W_{pump,hw} + W_{VAR} + W_{pump,chw}} \quad (6)$$

3. Results and discussions

The influence of VAR plant conditions is studied on the overall performance of integrated desalination and cooling cycle and plant. Strong solution concentration has been selected as a key operational parameter which can be controlled during charging of the working fluid in VAR plant. The role of separator or generator temperature, effectiveness of dephlegmator, circulating water inlet temperature and evaporator temperature is studied with the strong solution concentration. The results are aimed to maximize the EUF for cycle and plant by controlling the VAR operational conditions.

Fig. 4 shows the influence of strong solution concentration (0.36–0.5) with separator temperature (100–110 °C) on (a) cycle and (b) plant EUF. In vapor generator (boiler) heat transfer and the liquid vapor separation can be made in a single drum. The generator temperature is equal to the separator temperature. In theoretical work, the chilled water inlet and outlet temperature are fixed according to the evaporator temperature. The chilled water requirement is determined from the last stage of dehumidifier's heat load. While changing the strong solution concentration and separator temperature, the evaporator temperature is kept constant. Therefore the desalination and cooling generation from the plant are constant and do not vary with the changes in strong solution concentration and separator temperature. The results show that an increase in separator temperature is not favoring the performance of the integrated (desalination + cooling) plant. The drop in source temperature improves the COP of the cooling system with a penalty in cooling quantity. Therefore a lower feasible limit of separator temperature can be selected from the specified range. The optimum strong solution concentration decreases with increase in the separator temperature. The combination of low separator temperature and high strong solution concentration generates better results. The strong solution can be optimized after completion of all the variables. This study recommends a separator temperature of 100 °C in generator. In other parametric variations, the separator temperature can be fixed at the lower limit of range. Out of five variables, the separator temperature can be fixed as a boundary in the rest of the analysis.

Fig. 5 results the influence of strong solution concentration and dephlegmator effectiveness on (a) cycle and (b) plant

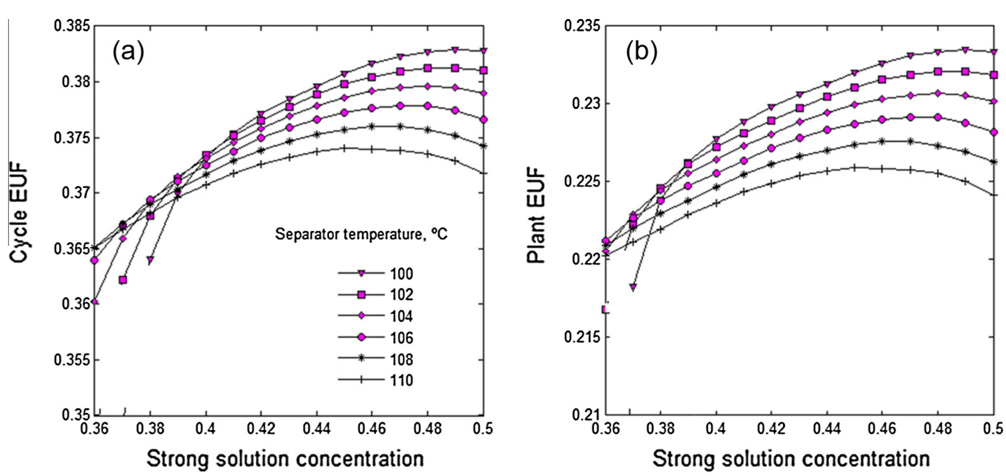

Figure 4 Influence of VAR's strong solution concentration with separator temperature on (a) cycle EUF and (b) plant EUF.

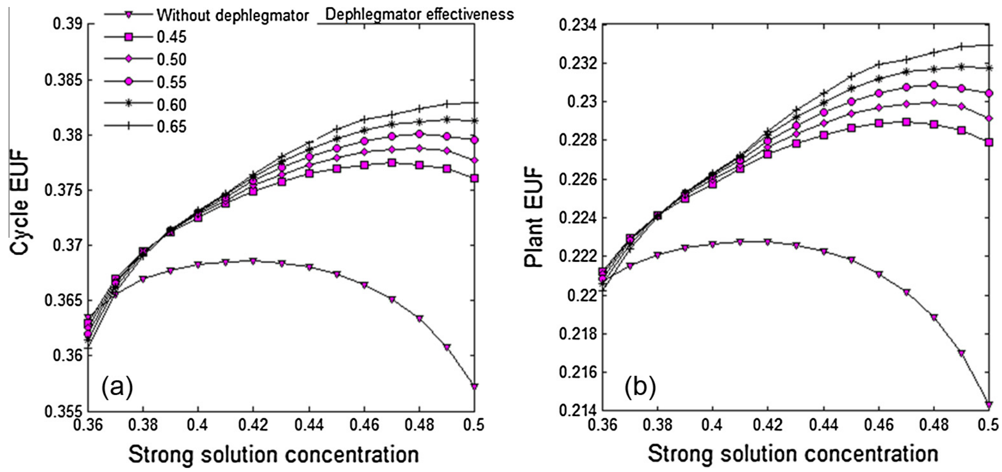

Figure 5 Influence of VAR's strong solution concentration with dephlegmator effectiveness on (a) cycle EUF and (b) plant EUF.

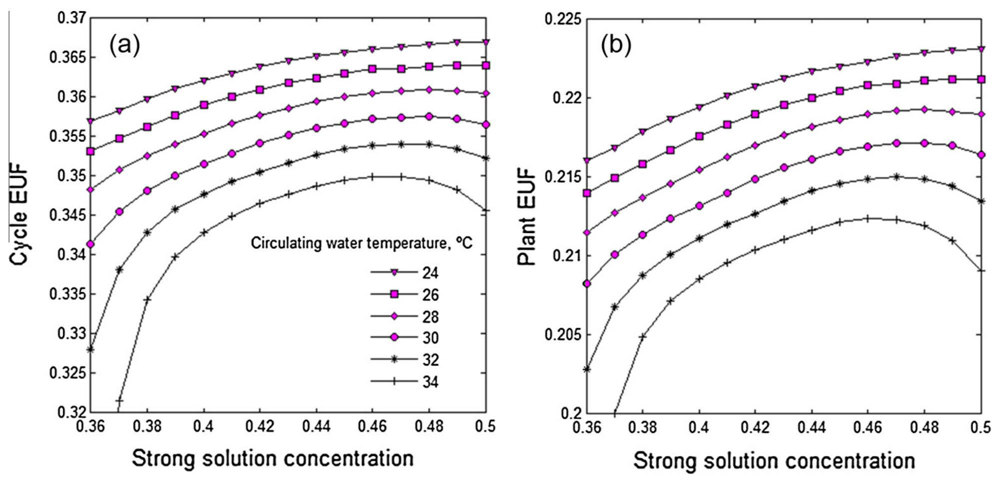

Figure 6 Influence of VAR's strong solution concentration with circulation water inlet temperature on (a) cycle EUF and (b) plant EUF.

EUF. In dephlegmator, the vapor is cooled by rejecting heat and so distilled vapor for the cooling plant. The integrated plant is demanding high dephlegmator effectiveness as it increases the cooling and hence desalination. More heat rejection in dephlegmator increases the ammonia concentration available for the cooling. The effectiveness has a limit up to the pure ammonia generation at the end of dephlegmator. In the current work, the maximum possible side of dephlegmation is adopted to gain the EUF advantage. But practically, it is not possible to reach the pure ammonia stage in the cooling plant and so it is limited to 65% according to the constraints in the operational conditions. The dephlegmator effectiveness is optimized at the upper limit of the specified range. Therefore, in the rest of the analysis, the separator temperature can be fixed at the lower limit and the dephlegmator effectiveness can be fixed at the upper limit. The optimum strong solution concentration is increasing with increase in dephlegmator effectiveness.

Fig. 6 shows the influence of strong solution along with the circulating water inlet temperature (24–34 °C) on (a) cycle EUF and (b) plant EUF. Since the cooling is fixed based on desalination load, the cooling will not effect with the changes in concentration and cooling water temperature. The desalination yield increases by dropping the circulating water temperature. Therefore the cycle EUF and plant EUF are maximized at the lower water temperature. Water temperature changes seasonally and not be controlled by the operator. Therefore a feasible water temperature of 30 °C is selected and fixed in the rest of the analysis. The optimum strong solution concentration is increasing with increase in circulating water temperature.

After fixing the separator temperature (lower limit), dephlegmator effectiveness (upper limit) and circulating water temperature (lower limit), the balanced variables to be optimized are strong solution concentration and evaporator exit temperature. These two variables can be varied simultaneously while others are fixed. Fig. 7 shows the influence of strong solution concentration (0.36–0.50) and evaporator temperature (6–16 °C) on (a) cycle EUF and (b) plant EUF. After throttling and at the inlet of evaporator, the refrigerant temperature is below 0 °C. In the analysis, the chilled water flow rate is to be selected without dropping its temperature below 0 °C. The outlet temperature of the evaporator can be fixed while designing the evaporator size. A low evaporator temperature increases the desalination and cooling outputs. But COP gets maximized at a particular evaporator temperature; hence,

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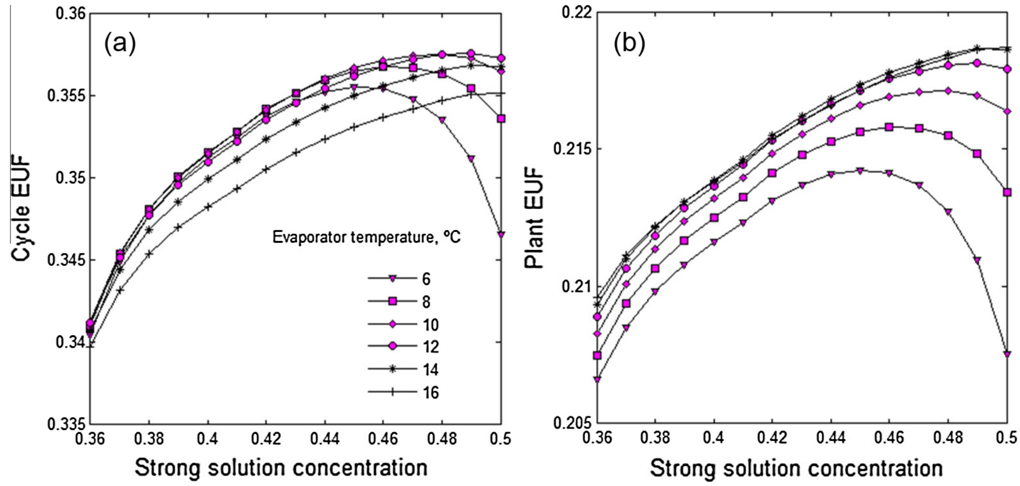

Figure 7 Influence of VAR's strong solution concentration with evaporator temperature on (a) cycle EUF and (b) plant EUF.

EUF is also maximized at the evaporator temperature of 12 °C. The higher side of evaporator exit temperature allows more heat transfer or cooling in the evaporator. But a high evaporator temperature generates high chilled water temperature and air temperature in the air conditioning plant. Therefore the evaporator temperature is restricted to 10 °C. At this evaporator temperature, the optimum strong solution concentration is 47%.

4. Conclusions

The influence of VAR's operational conditions (strong solution concentration, separator temperature, dephlegmator's effectiveness, circulating water inlet temperature and evaporator temperature) is studied on EUF of integrated cycle and plant. The optimum strong solution concentration is decreasing with increasing separator temperature, increasing with increase in dephlegmator effectiveness and increasing with increase in circulating water temperature. To result the maximum EUF, a lower limit of separator temperature (100 °C), higher limit of dephlegmator effectiveness (65%) and lower possible circulating water temperature (30 °C) are fixed. Finally the performance is optimized at 0.47 strong solution concentration and 10 °C evaporator temperature for combined desalination and cooling plant.

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References

[1] C. Chiranjeevi, T. Srinivas, Combined two stage desalination and cooling plant, Desalination 345 (16) (2014) 56–63.
[2] C. Chiranjeevi, T. Srinivas, Experimental and simulation studies on two stage humidification-dehumidification desalination and cooling plant, Desalination 376 (15) (2015) 9–16.
[3] P. Colonna, S. Gabrielli, Industrial trigeneration using ammonia–water absorption refrigeration systems (AAR), Appl. Therm. Eng. 23 (2003) 381–396.
[4] R. Shankar, T. Srinivas, Investigation on operating processes for a new solar cooling cogeneration plant, ASME J. Sol. Energy Eng. 136 (3) (2014) 1–10.
[5] T. Tsoutsos, E. Aloumpi, Z. Gkouskos, M. Karagiorgas, Design of a solar absorption cooling system in a Greek hospital, Energy Build. 42 (2010) 265–272.
[6] O. Kaynakli, M. Kilic, Theoretical study on the effect of operating conditions on performance of absorption refrigeration system, Energy Convers. Manage. 48 (2007) 599–607.
[7] J. Sieres, J. Fernández-Seara, Experimental investigation of mass transfer performance with some random packings for ammonia rectification in ammonia–water absorption refrigeration systems, Int. J. Therm. Sci. 46 (2007) 699–706.
[8] Horuz, T.M.S. Callander, Experimental investigation of a vapor absorption refrigeration system, Int. J. Refrig. 27 (2004) 10–16.
[9] V. Muthu, R. Saravanan, S. Renganarayanan, Experimental studies on R134a-DMAC hot water based vapour absorption refrigeration systems, Int. J. Therm. Sci. 47 (2008) 175–181.
[10] J. Fernandez-Seara, A. Vales, M. Vazquez, Heat recovery system to power an onboard NH_3-H_2O absorption refrigeration plant in trawler chiller fishing vessels, Appl. Therm. Eng. 18 (1998) 1189–1205.
[11] T. Berlitz, H. Plank, F. Ziegler, R. Kahn, An ammonia-water absorption refrigerator with a large temperature lift for combined heating and cooling, Int J. Refrig. 21 (3) (1998) 219–229.
[12] Horuz, A comparison between ammonia-water and water-lithium bromide solutions in vapor absorption refrigeration systems, Int. Commun. Heat Mass Transf. 25 (5) (1998) 711–721.
[13] A. Kececiler Hi Acar, A. Dogan, Thermodynamic analysis of the absorption refrigeration system with geothermal energy: an experimental study, Energy Convers. Manage. 41 (1) (2000) 37–48.
[14] John A. Duffie, William A. Beckman, Solar Engineering of Thermal Process, fourth ed., John Wiley & Sons, 2013.

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