EQUILIBRIUM TEMPERATURES AND PERFORMANCE OF TRIPLE EFFECT SERIES FLOW WATER-LITHIUM BROMIDE ABSORPTION REFRIGERATION SYSTEM

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ABSTRACT

The engineering profession demands more energy efficient systems and the triple effect water-lithium bromide vapour absorption refrigeration system is under active development which is expected to be about 25% more efficient than that of the double effect system. The equilibrium temperatures at low and medium pressure generators are obtained by energy balance and simultaneously the system performance is also predicted. The equilibrium temperatures and performance maps are generated for varying operating conditions. Both the equilibrium temperatures are found to increase with increase in supply heat and condensing temperatures, and decrease in heat exchanger effectiveness. Sub-optimal performances are observed at off-design conditions. The analysis is useful in guiding the absorption system to obtain the best performance at all operating conditions.

KEYWORDS

Absorption refrigeration; Triple effect; Series flow; Water -lithium bromide; Equilibrium temperatures; Performance analysis

1. INTRODUCTION

Water - lithium bromide vapour absorption systems, both single and double effect, are being used extensively for air conditioning purpose. Double effect systems are about 75% more energy efficient than that of the single effect systems. Both series and parallel flow double effect systems have been studied [1-4] suggesting controlling equations to guide the system for the best performance at off-design conditions. Triple effect cycles are expected yield about 25% more efficiency than that of the double effect cycle. However, relatively few works are available on these cycles and the published literatures are silent on the estimation of equilibrium temperatures.

Figure 1 shows the schematic of the triple effect series flow cycle. It consists of an evaporator, an absorber, three condensers, three generators, three heat exchangers, a solution pump, four expansion valves and three pressure reducing valves (PRV). The high pressure (HP) condenser and the medium pressure (MP) generator are coupled and so also the medium pressure (MP) condenser and the low pressure (LP) generator.

In triple effect cycle the vapour is generated thrice. The first generation is by external heat input (supply heat - q_g) at the high pressure (HP) generator as shown in Fig. 1. The second and third generations are accomplished by internal heat exchange at medium pressure (MP) and low pressure (LP) generators respectively. Thus more vapour is generated for a unit heat input as compared to the single and double effect cycles. Vapour generated at the first generator is completely condensed at the HP condenser, thereby utilising all the available heat for second generation. Similarly all the vapour thus generated is condensed at the MP condenser for the third generation. This is achieved in the practical system with a steam trap, which restricts the vapour from escaping the condenser. The MP and LP generators adjust themselves achieving the equilibrium temperatures and facilitating the complete condensation at the HP and MP condensers. The condensate is throttled, which evaporates in the evaporator. The strong solution in the absorber absorbs the vapour thus formed. The weak solution is pumped back to the HP generator through three heat exchangers, which gets stripped off from water sequentially in three generators before entering the absorber.

2. ANALYSIS

The triple effect cycle makes use of the availability of high temperature heat source. The analysis is performed for steady state conditions using known/computed thermodynamic property correlation for high temperatures [5-8] to calculate pressure, temperature, enthalpy, concentrations, etc together with energy, mass and material balance equations.

The mass flow rate of refrigerant is obtained by energy balance at the evaporator and is given as,

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$$m_r = \frac{q_e}{(h_4 - h_3)} \tag{1}$$

Circulation ratio is the ratio of mass flow rate of 'absorbent weak' solution pumped per unit flow of refrigerant and is calculated as

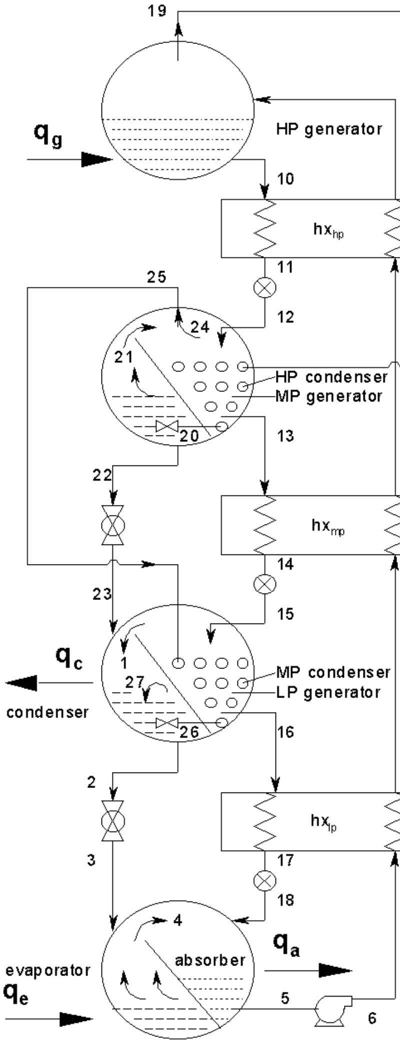

Figure 1 Schematic of triple-effect series-flow water - lithium bromide vapour absorption refrigeration system

$$CR = \frac{m_w}{m_r} = \frac{x_{sl}}{(x_{sl} - x_w)} \tag{2}$$

Mass flow rate of weak solution is then given by

$$m_w = m_r(CR) \tag{3}$$

Mass balance at the high, medium and low pressure generators yields the mass flow rate of strong solutions as given below.

$$m_{sh} = \frac{m_w(x_w)}{x_{sh}} \tag{4}$$

$$m_{sm} = \frac{m_{sh}(x_{sh})}{x_{sm}} \tag{5}$$

$$m_{sl} = m_w - m_r \tag{6}$$

Effectiveness of heat exchanger is defined as the ratio of actual heat transfer to the maximum possible heat transfer. Accordingly, the effectiveness of high, medium and low pressure heat exchangers are respectively given as under.

$$E_h = \frac{(h_{10} - h_{11})}{(h_{10} - h_{11'})} \tag{7}$$

$$E_m = \frac{(h_{13} - h_{14})}{(h_{13} - h_{14'})} \tag{8}$$

$$E_l = \frac{(h_{16} - h_{17})}{(h_{16} - h_{17'})} \tag{9}$$

Where, $h_{11'}$, $h_{14'}$ and $h_{17'}$ represent the enthalpy of minimum heat capacity streams (here, it is hot stream, i.e., strong solution) at the exit of the respective heat exchangers when they are cooled to the temperature of the respective entry cold streams (weak stream). At this condition the terminal temperature difference at the cold end is zero and consequently the effectiveness (E) of heat exchanger is unity. Thus,

$$h_{11'} = f(x_{sh}, t_{11'}) \tag{10}$$

$$h_{14'} = f(x_{sm}, t_{14'}) \tag{11}$$

$$h_{17'} = f(x_{sl}, t_{17'}) \tag{12}$$

If the above enthalpies happen to enter the crystallization region, then the specific heat of solution is assumed constant and the enthalpies in Eqs. (7), (8) and (9) are replaced by the respective temperatures. By energy balance, enthalpies at the exits of the heat exchangers, i.e., at state points 7, 8, 9, 11, 14 and 17 are calculated as under.

$$h_{17} = h_{16} - E_l(h_{16} - h_{17'}) \tag{13}$$

$$h_{14} = h_{13} - E_m(h_{13} - h_{14'}) \tag{14}$$

$$h_{11} = h_{10} - E_h(h_{10} - h_{11'}) \tag{15}$$

$$h_7 = h_6 + \frac{m_{sl}}{m_w}(h_{16} - h_{17}) \tag{16}$$

$$h_8 = h_7 + \frac{m_{sm}}{m_w}(h_{13} - h_{14}) \tag{17}$$

$$h_9 = h_8 + \frac{m_{sh}}{m_w}(h_{10} - h_{11}) \tag{18}$$

Pump work of the solution pump is obtained by,

$$W = m_w \frac{(p_{gh} - p_e)}{\eta_p} v_s \tag{19}$$

Where, V_s is the specific volume of the weak solution and is given by,

$$v_s = f(x_w, t_a) \tag{20}$$

Accordingly, the enthalpy of weak solution at the exit of the pump is calculated as,

$$h_6 = h_5 + \frac{W}{m_w} \tag{21}$$

The energy balance equations for LP, MP and HP generators are given by,

$$q_{lp} = m_{sl}*h_{16}+m_1*h_1-m_{sm}*h_{14}-m_{25}*(h_{25}-h_{26}) = 0$$

$$q_{mp} = m_{sm}*h_{13}+m_{24}*h_{24}-m_{sh}*h_{11}-m_{19}*(h_{19}-h_{20}) = 0$$

$$q_g = m_{19}(h_{19}) + m_{sh}(h_{10}) - m_w(h_9) \tag{24}$$

Apart from mass and material balances, saturated liquid condition is imposed at State 26 for LP generator and at State 20 for MP generator.

The performance of the cycle is obtained by,

$$COP = \frac{q_e}{(q_g + W)} \tag{25}$$

$$COP_c = \frac{(t_g - t_a)}{t_g} \frac{t_e}{(t_c - t_e)} \tag{26}$$

3. COMPUTATION PROCEDURE

The equilibrium temperatures and concentrations at MP and LP generators are obtained by successive substitution method simultaneously predicting the performance. The computation procedure is as follows.

1. The operating parameters are: evaporator temperature te, condenser temperature tc, absorber temperature ta, HP generator temperature tgh, and effectiveness of heat exchangers.
2. Fixed parameters are: Unit kW of refrigeration (qe), efficiency of the solution pump ˜ p = 60%, generator-condenser temperature differential = 5oC, efficiency of generators and absorber = 100%.
3. Calculate evaporator pressure pe, condenser pressure pc, and the weak solution concentration xw.
4. Estimate minimum LP generator temperature tgl, min, minimum MP generator temperature tgm, min and cut-off temperature tcut-off.
5. Estimate crystallisation temperature tcry, corresponding to pc.
6. Assume initial value of t_{gl} and t_{gm}.
7. Find the HP generator pressure p_{gh} and its strong solution concentration x_{sh}.
8. Find the MP generator pressure p_{gm} and its strong solution concentration x_{sm} and the concentration of strong solution leaving the LP generator x_{sl}.
9. Calculate the circulation ratio CR and mass flow rate of refrigerant m_r.
10. Calculate the mass flow rate of weak solution m_w and mass flow rate of strong solution from LP generator m_{sl}.
11. Calculate the enthalpies at state points 16, 17 and 5.
12. Estimate the pump work W and enthalpy at state points 6 and 7.
13. Calculate the enthalpies at state points at 1, 13, 14, 22 and 25.
14. Estimate the mass flow rate of strong solution from HP and MP generators, i.e., m_{sh} and m_{sm} respectively.
15. Calculate the mass of refrigerant boiled off from the MP generator i.e., m24 and mass of refrigerant vapour flashed off due to throttling of the condensate from the HP generator i.e., m21 and mass of refrigerant boiled off from the HP generator i.e., m19.
16. Find the enthalpy at state point 8 and the mass of refrigerant boiled off from the LP generator.
17. Find t_{gl}, by energy balance across LP generator to the desired accuracy.
18. If energy balance is not occurred to the desired accuracy, increase/decrease t_{gl} as required and repeat steps from (viii) to (xvii) with the new t_{gl}, till energy balance occurs across the LP generator.
19. If energy balance is occurred, across the LP generator, find the enthalpies at state points 24, 19, 10 and 11.
20. Find energy balance across the MP generator.
21. If energy balance is not occurred to the desired accuracy, increase/decrease t_{gm} as required, and repeat steps from (vii) to (xx) with the new t_{gm} and the t_{gl} at which energy balance occurred across the LP generator, till energy balance occurs across the MP generator.
22. If energy balance is occurred, to the desired accuracy, calculate the heat input to the HP generator from the Eq. (24) and the coefficient of performance of the system using Eq. (25).

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Table 1 Operating parameters and their mean values

Sl. No.	Operating parameters	Range	Mean value
1	Evaporator temperature	2.5 to 12.5ºC	5ºC
2	Condenser temperature	25 to 45ºC	30ºC
	Absorber temperature	20 to 40ºC	25ºC
4	Generator temperature	60 to 250ºC	Entire domain
5	Effectiveness of heat exchangers	0 to 100%	50%

4. RESULTS AND DISCUSSION

Analysis of the cycle has been carried out over a judiciously selected range of operating parameters as listed in Table 1. The generator temperature is varied from cut-off temperature to the crystallisation limit for each set of operational parameters.

Figures 2 to 5 show the effect of supply heat temperature on the equilibrium temperatures of LP and MP generators for four operating parameters namely evaporator, absorber and condenser temperatures, and heat exchanger effectiveness respectively. It is seen that the equilibrium temperatures increase linearly as the supply heat temperature increases. When t_{gh} increases, more vapour tends to boil out at the HP generator. Since all the vapour has to be condensed, more heat will be available at the MP generator, which in turn tends to generate more vapor at the MP generator. Similarly, as all the vapour generated in the MP generator, including the vapour flashed due to throttling of the condensate from the HP generator, has to be condensed, more heat will be available at the LP generator, which further tends to generate more vapour at the LP generator, which is not possible for a given unit refrigeration. More over, the degassing width at the MP and LP generators should also increase proportionately to that of vapour boils out, which is also not possible. This would lead to an imbalance between the heat energy available and that required at the generators, and the balance vapour from the HP and LP generators tend to escape, which the practical system do not allow. Thus, a new equilibrium t_{gm} and t_{gl} with new pressure p_{gh} and p_{gm} respectively will be reached, opposing the generation of vapour in the immediate high pressure generator, on one hand and facilitating the condensation of that vapour and consequent generation of vapour in the respective generators, on the other hand. Thus, the increase of HP generator temperature causes a chain of action and reaction to strike energy and mass balances, resulting in an increase of t_{gm} and t_{gl} linearly.

Figure 2 also shows the effect of evaporator temperature on the equilibrium temperatures. It is seen that the two equilibrium temperatures increase with the evaporator temperature. Increase in t_e decreases the concentration of weak solution for a given absorber temperature. The decrease in concentration increases the boiling width at the HP generator for a constant supply heat temperature. This causes the equilibrium temperatures to increase as explained in the preceding paragraph. The effect of increase of t_a is the same as that of decrease of t_e. Thus, as Fig. 3 indicates, both the equilibrium temperatures decrease when the absorber temperature increases. The increase in condenser temperature increases the t_{gl} which in turn increases the t_{gm} marginally (Fig. 4). The increase of t_{gl} is more pronounced than that of t_{gm} as the increase of t_{gm} is due to indirect effect of the increase of the t_{gl}.

Figure 5 shows that the increase in effectiveness of all the three heat exchangers, decreases the equilibrium temperatures. Increase in effectiveness reduces both the terminal temperature differentials. Consequently, the enthalpy of solution entering MP and LP generators are low and that of weak solution entering the HP generator is high. Therefore, more heat is required to sustain the same amount of boiling rate at the MP and LP generators. This is possible either by increase of vapour generated at the HP generator or by decrease of temperature at these generators. Though the boiling rate of HP generator increases slightly due to increase in enthalpy of weak solution entering the HP generator, it alone cannot nullify the effect of enthalpy reduction of strong solutions entering the MP and LP generators. Thus, the equilibrium temperatures decrease marginally to assist the generation rate of vapour at both the generators and thereby, striking a balanced state.

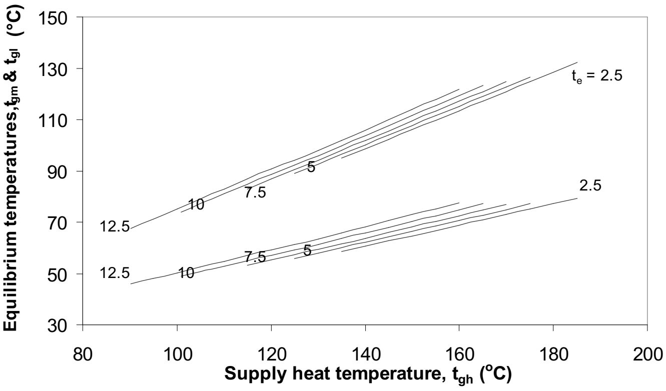

Figure 2 Effect of supply heat temperature on equilibrium temperatures for various evaporator temperatures

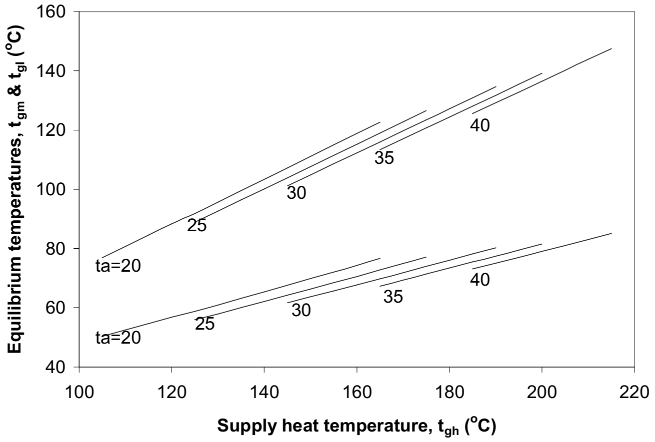

Figure 3 Effect of supply heat temperature on equilibrium

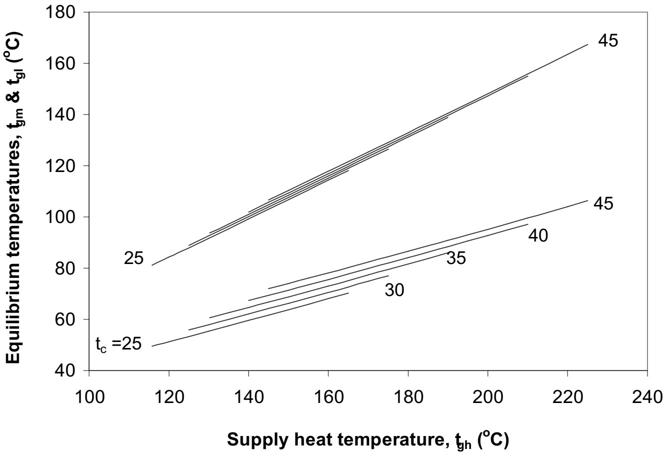

Figure 4 Effect of supply heat temperature on equilibrium temperatures for various condenser temperatures

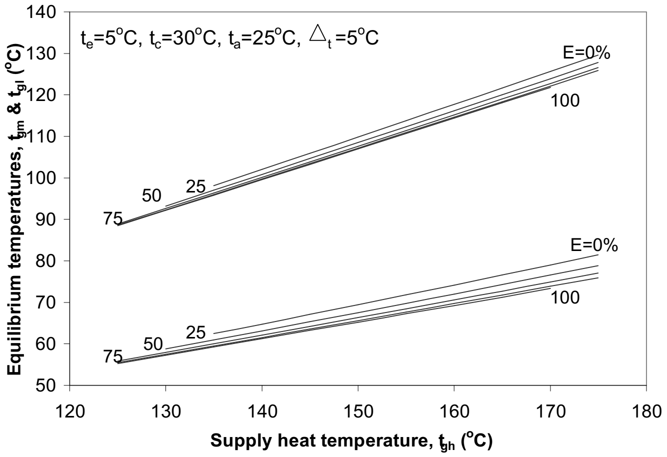

Figure 5 Effect of supply heat temperature on equilibrium temperatures for various heat exchanger effectiveness

Figures 6 to 9 show the effect of supply heat temperature on the COP for four operating parameters namely evaporator, absorber and condenser temperatures, and heat exchanger effectiveness respectively. The COP increases sharply from zero at some minimum temperature, then levels off to some constant value at a higher temperature, and decreases slightly with a further increase in the temperature. This variation is typical of any absorption refrigeration system. The initial sharp increase is due to the corresponding exponential decrease in the circulation ratio (Fig. 10), which reduces the un-recovered heat in the heat exchangers. The subsequent marginal decrease is essentially due to the variation of solution property. At constant temperature its enthalpy increases with the increase in concentration and hence at high generator temperatures enthalpy of solution entering the absorber is more. This means less heat transfer (per kg solution) in the heat exchangers and less COP.

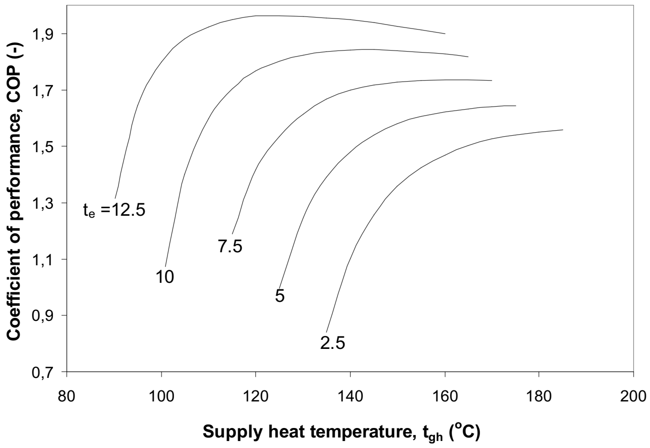

Figure 6 Effect of supply heat temperature on coefficient of performance for various evaporator temperatures

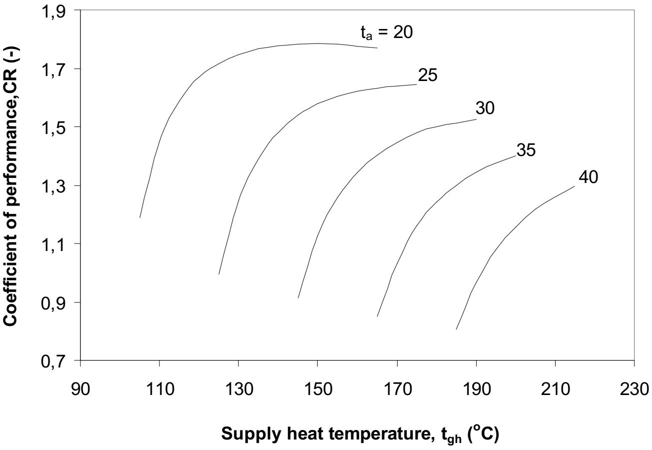

Figure 7 Effect of supply heat temperature on coefficient of performance for various absorber temperatures

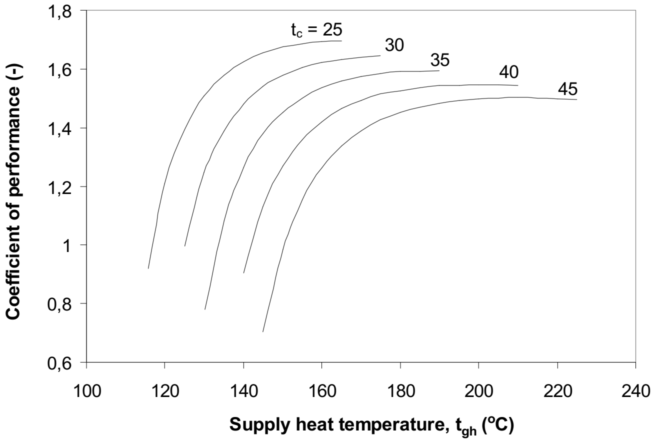

Figure 8 Effect of supply heat temperature on coefficient of performance for various condenser temperatures

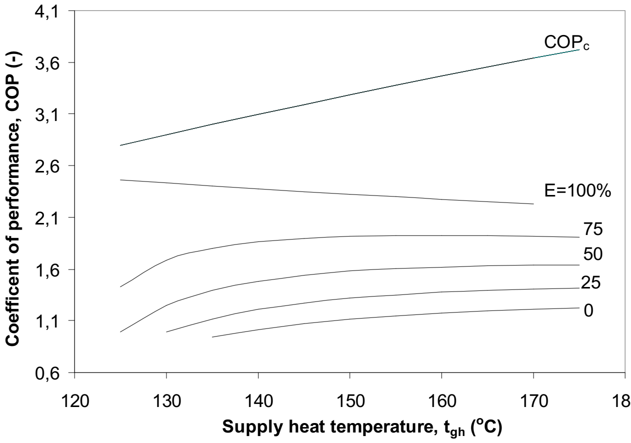

Figure 9 Effect of supply heat temperature on coefficient of performance for various effectiveness of heat exchangers

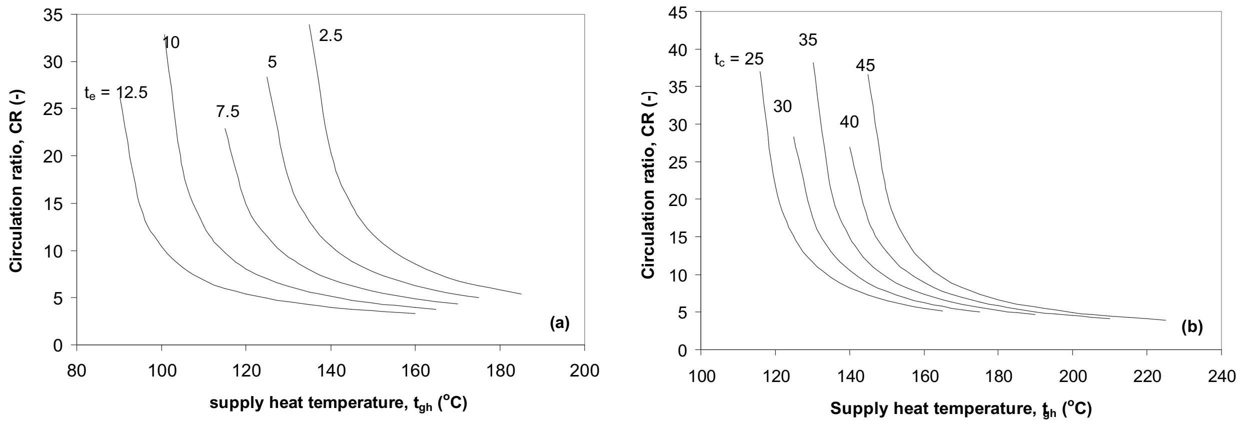

Figure 10 Effect of supply heat temperature on circulation ratio for various evaporator (a) and condenser (b) temperatures

Increase of evaporator temperature increases the COP (Fig. 6). The evaporator and absorber pressures increase with the evaporator temperature. The x_w decreases and so also the CR thereby increasing the COP. For similar reasons, COP also increases with decrease in the absorber temperature (Fig. 7). The increase in condenser temperature increases the solution flow rate (Fig. 10b) and hence reduces the COP (Fig. 8). As shown in Fig. 9, increase in effectiveness of all the three heat exchangers will lead to increase in COP. This is primarily due to reduction in the un-recovered heat in the heat exchangers.

5. PRACTICAL IMPLICATIONS

It is clear, from the above, that there exists a unique equilibrium temperature at MP and LP generators for a given set of operating parameters. The thermodynamic analysis of the triple effect cycle presented here is based on the above fact. It not only gives the true and realistic thermodynamic analysis but also gives the design data for the MP and LP generators.

It can be observed from Figs. 6 to 9 that for a given set of operating parameters, there exists an optimum temperature of HP generator at which the COP of the cycle reaches maximum. Examining together with Fig. 10, it can be observed that, the COP peaks when the CR begins to level up. By and large, only sub-optimal condition exists at the off design conditions arising due to less cooling load or variation of ambient conditions. The solution flow rate, which is governed by resistance to flow and the prevailing pressure differential between the generators and absorber, will not be at optimal level. The analysis not only finds the maximum COP at varied operating conditions but also generates useful inputs needed to build a tailor-made control system for guiding the refrigeration system to operate at these conditions yielding the maximum performance at all operating conditions.

6. CONCLUSIONS

A triple-effect series-flow water-lithium bromide vapour absorption refrigeration system is analysed

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finding the equilibrium temperatures at low and medium pressure generators. The two equilibrium temperatures increase with evaporator, condenser and supply heat temperatures. There exists an optimum supply heat temperature at which the coefficient of performance is maximum for each set of operating parameters. The present analysis is useful in generating the design data for medium and low pressure generators and devising a control system for guiding the refrigeration system to yield the best performance at all operating conditions.

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NOMENCLATURE

COP	Coefficient of performance (-)
CR	Circulation ratio (-)
E	Effectiveness of heat exchanger (-)
HP	High pressure
h	Specific enthalpy (kJ kg^{-1})
LP	Low pressure
MP	Medium pressure
m	Mass flow rate (kg s^{-1})
P	Pressure (Pa)
q	Heat transfer (kW)
t	Temperature (^{o}C)
W	Pump work (kW)
x	Solution concentration (mass of absorbent/mass of solution) (-)
v	Specific volume (m^3 kg^{-1})

<u>Subscripts</u>

a	Absorber
c	Condenser
cut-off	Cut-off value
e	Evaporator
g	Generator
gh	High pressure generator
gm	Medium pressure generator
gl	Low pressure generator
liq	Liquid
min	Minimum
r	Refrigerant
s	Solution
sh	Solution leaving high pressure generator
sl	Solution leaving low pressure generator
sm	Solution leaving medium pressure generator
tl	Temperature at low pressure generator
tm	Temperature at medium pressure generator
w	Weak
1,2,3...	State points as in Figure 1

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