Energy and Exergy Analysis of a Hybrid Refrigeration System

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Abstract

This paper investigates the performance of a hybrid refrigeration system (HRS) with pair of LiBr-H_2O as working fluid (Absorbent-Refrigerant) based on an exclusive thermodynamic analysis. The HRS in the study is a form of integrated compression-absorption system which works like a single effect absorption refrigeration system with the exception that pump is replaced by compressor and generator works as an evaporator in the system. This hybrid refrigeration system possesses the advantage of obtaining high COP like a vapor compression refrigeration system and using ecofriendly working fluid in the cycle like a vapor absorption refrigeration system. The effect of various parameters has been studied on the COP and exergetic efficiency of the system. The maximum value of COP of the system have been observed to be as high as 7.7 and exergetic efficiency is computed as 32% for a given condition. Further, it is observed that COP decreases but exergetic efficiency increases with the increase in pressure ratio whereas both the COP and exergetic efficiency increases with the increase in the generator temperature.
Keywords: Hybrid refrigeration system, LiBr-H_2O, COP, exergetic efficiency.

INTRODUCTION

Due to the growing concern for environment in view of global warming and ozone depletion potential apart from energy efficient refrigeration system, the idea of a hybrid refrigeration system which is an integrated compression-absorption system was presented by merging the compressor to a vapor absorption refrigeration system [1]. A thermodynamic analysis of a compression-absorption heat pump was performed and COP and circulation ration was calculated at different compression ratio and operating temperatures [2]. The basic analysis of single and double effect hybrid compression-absorption system with LiBr-H_2O mixture was done [3]. An optimization study of compression-absorption cycle with NH_3-H_2O mixture was done for maximum allowed pressure and different temperature gradient [4]. A study on similar system was carried out for the feasibility investigation of a compression absorption refrigeration system with NH_3-H_2O as fluid pair which predicted a better performance under certain conditions for such a system when compared with a simple vapor compression system [5]. A similar configuration of a hybrid or integrated

refrigeration system named as absorption recompression system was suggested [6] where the condenser in single effect vapor absorption refrigeration system was replaced by a compressor while the superheated refrigerant leaving the compressor was utilized in generator as a source of heat. The thermodynamic feasibility of a hybrid compression absorption refrigeration system was analyzed by using it as a heat pump under the various operating condition by taking working fluid pair of NH_3-H_2O and predicted the COP to be 5.39 for certain operating conditions [7]. The exclusive simulation work of a 400 kW ammonia water hybrid refrigeration system used for water chilling application was carried out for three different configurations of solution heat exchanger areas [8]. Some encouraging results were obtained by the thermodynamic analysis of a single stage absorption/compression heat pump using ternary working fluid Trifluoroethanol+ Water+ Tetraethylen-glycol dimethyl-ether for upgrading the waste heat coming out from any system [9].

In this paper a detail energy and exergy analysis has been carried out on a hybrid refrigeration system considering LiBr-H_2O as working fluid pair of absorbent-refrigerant.

SYSTEM DESCRIPTION

The HRS in the proposed study also known as compression absorption refrigeration system has been described schematically in the Figure 1. In this system the absorber operates at high pressure and the generator functions as an evaporator operates at low pressure. The generator works like a desorber in the system absorbs heat from the space to be cooled and the superheated refrigerant (water) is compressed by the compressor from it to absorber pressure. The refrigerant absorbent solution leaves the generator at state point 1 and is pumped via the solution heat exchanger to the absorber where mixing of the strong and weak solutions takes place. The refrigerant absorbent mixture absorbs the refrigerant (water) becomes rich and passes through the solution heat exchanger where heat exchange takes place between cold solution coming from the pump and hot solution coming from the absorber. The strong solution (rich in refrigerant) throttled to the generator pressure thus completing the cycle.
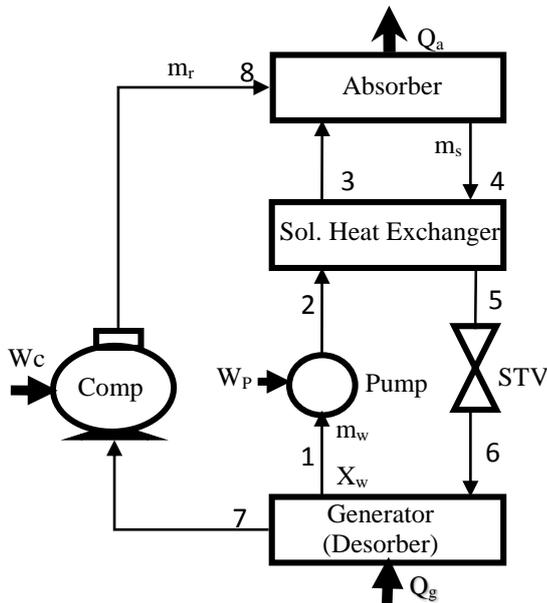
Figure1. Schematic diagram of a Hybrid Refrigeration system

THERMODYNAMIC ANALYSIS OF HRS

The thermodynamic analysis of HRS comprises the principles of mass conservation, energy conservation and exergy balance. A computational model has been formulated and the system analysis has been carried out using Engineering Equation Solver (EES) software [10]. The thermodynamic properties of water and steam are taken from built-in functions in EES. The properties of water-lithium bromide solution are taken from [11].

Mass balance
Mass balance at the absorber or desorber is given by the equation (1).

$$\dot{m}_s = \dot{m}_r + \dot{m}_w \qquad (1)$$

Mass flow rate through the compressor is $\dot{m}_r$.

Energy Balance
The energy balance in each component of a single effect compression absorption refrigeration system is given by the following equations:

$$\dot{Q}_a = \dot{m}_r h_8 + \dot{m}_w h_3 - \dot{m}_s h_4 \qquad (2)$$

$$\dot{Q}_g = \dot{m}_r h_7 + \dot{m}_w h_1 - \dot{m}_s h_6 \qquad (3)$$

$$\dot{W}_{comp} = \dot{m}_r (h_8 - h_7) \qquad (4)$$

$$\dot{Q}_{she} = \dot{m}_w (h_3 - h_2) = \dot{m}_s (h_4 - h_5) \qquad (5)$$

$$\dot{W}_p = \dot{m}_w (h_2 - h_1) \qquad (6)$$

$$Energy\ in = \dot{W}_{comp} + \dot{W}_p \qquad (7)$$

$$Energy\ out = \dot{Q}_a \qquad (8)$$

The coefficient of performance (COP) of the single effect compression absorption refrigeration system is defined as the ratio of the cooling capacity attained at the evaporator to the sum of energy input into the compressor and pump. From this definition of the hybrid cycle COP is given as:

$$COP = \frac{\dot{Q}_g}{\dot{W}_{comp} + \dot{W}_p} \qquad (9)$$

Exergy Balance
Exergetic efficiency is given by:

$$\eta_{e_x} = \frac{\dot{Q}_g \left| \left(1 - \frac{T_0}{T_r}\right) \right|}{\dot{W}_{comp} + \dot{W}_p} = COP \left| \left(1 - \frac{T_0}{T_r}\right) \right| \qquad (10)$$

RESULTS AND DISCUSSION
In this study the EES software code developed for obtaining the results has been validated by comparing the results with Kaushik et al [12]. At a generator temperature of 11^0C (T_a = 30°C, X_w = 40%) and pressure ratio of 5 the COP computed by Kaushik et al is 7.46 whereas in the present study the COP computed is 7.7 for the same parameters except for X_w i.e. weak concentration ratio taken as 39%. The parameters used for computing the results in the present study are mentioned below:

1. Pressure ratio across compressor and pump: 5-10

2. Isentropic efficiency of compressor, (η_{comp}):85 %

3. Generator temperature (T_g): 2-11°C

4. Absorber temperature (T_a): 25-35°C

5. Effectiveness of solution heat exchanger, ($\in_{she}$): 0.7

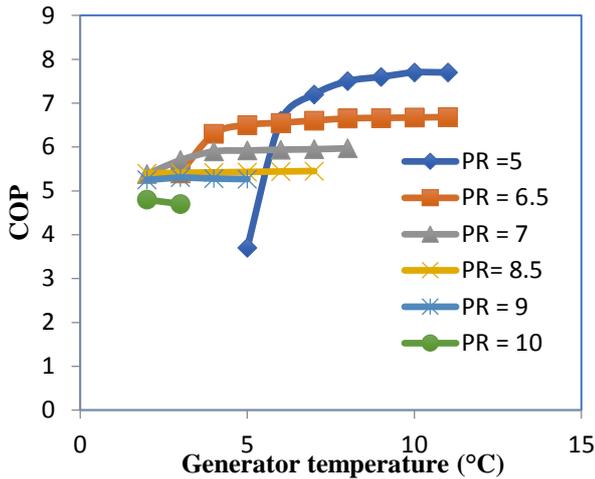6. Mass flow rate of the refrigerant through the evaporator: 1 kg/s

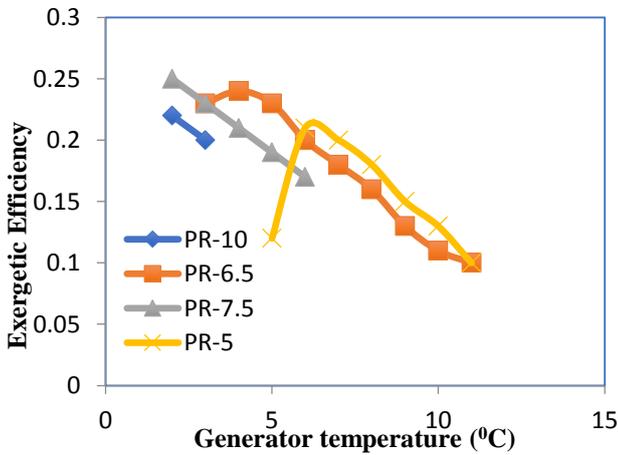**Figure 2.** COP vs Generator temperature for varying pressure ratio ($T_a = 30°C$, $X_w = 39.5\%$)

Figure 3. Exergetic Efficiency vs Generator temperature for varying pressure ratio ($T_a = 30°C$, $Xw = 39.5\%$)

Figure 2 and 3 shows the variation of COP and exergetic efficiency with generator temperature at varying pressure ratio. The decrease in pressure ratio from 10 to 5 results in increase in the COP from 4.9 to 7.7 and it is also observed that the system seizes to function at higher values of generator temperature when the pressure ratio increases. At higher pressure ratio exergetic efficiency decreases with increase in generator temperature but at lower pressure ratio there is a sharp increase initially and then sharp decrease in exergetic efficiency with increase in generator temperature. The highest value of exergetic efficiency of 25% occurs at a pressure ratio of 7.5 corresponding to a generator temperature of $2°C$.
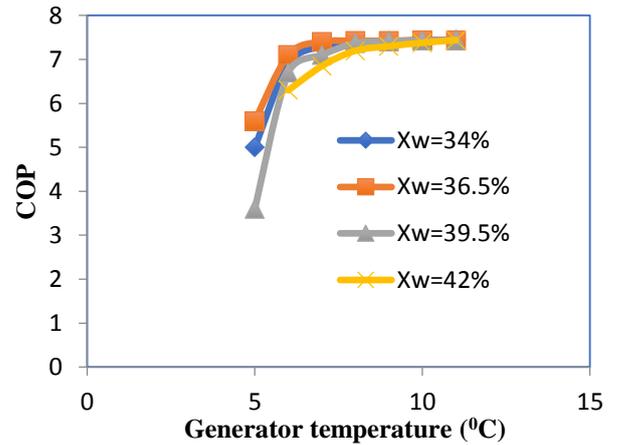

Figure 4. COP vs Generator temperature at varying weak solution concentration ($T_a = 30°C$, pressure ratio = 5)

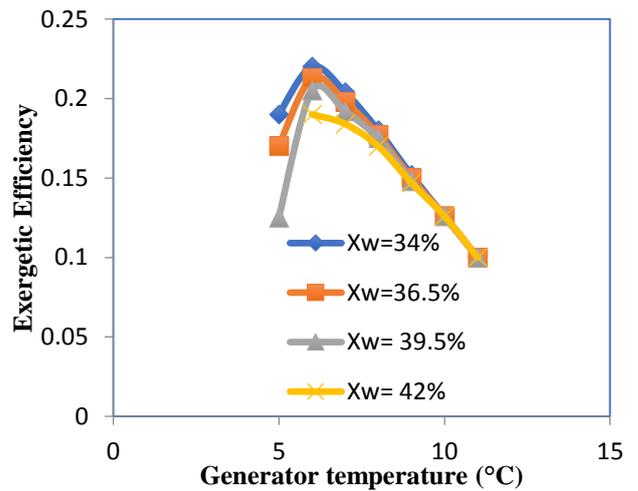**Figure 5.** Exergetic Efficiency vs Generator temperature at varying weak solution concentration ($T_a = 30°C$, pressure ratio = 5)

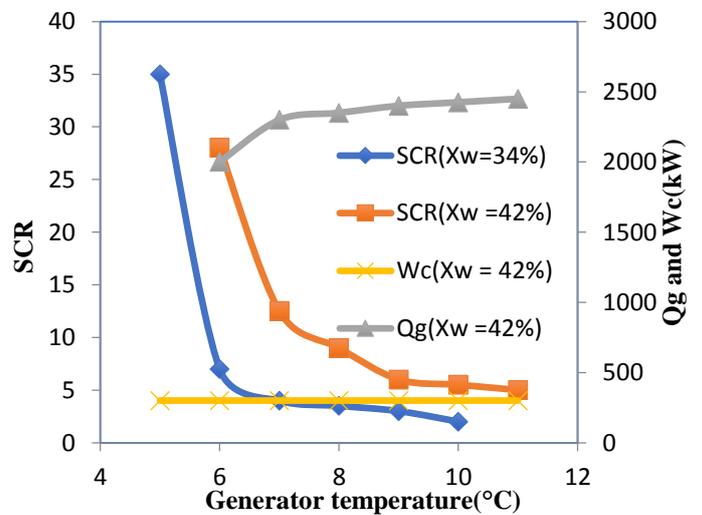**Figure 6.** Effect of solution concentration leaving the generator on SCR, cooling effect and compressor power ($Ta = 30°C$, pressure ratio = 5, compressor efficiency = 85%)

Figure 4 and 5 show the effect of generator temperature on COP and exergetic efficiency respectively at varying weak solution concentration (X_w). It is observed that the value of COP increases sharply with the increase in generator temperature from 5^0C to 6^0C and thereafter this increase is too meagre to have almost a horizontal curve at each value of weak solution concentration. Exergetic efficiency also increases sharply with the increase in generator temperature from 5^0C to 6^0C and thereafter it decreases suddenly with the further increase in generator temperature.

Figure 6 shows that a large drop in solution circulation ratio (SCR) occurs as the generator temperature increases from 5^0C to 6^0C, resulting in sharp rise in COP and cooling effect (Qg). With further rise in generator temperature the increase in above parameters are very nominal. The variation in solution circulation ratio results for large change in COP. It is observed that at lower values of generator temperature, the compressor discharge pressure (for a fixed pressure ratio) is low and hence the strong solution concentration (X_s) leaving the absorber is high. This accounts for higher values of solution circulation ratio ($SCR = Xw/(Xw-Xs)$). The cooling effect produced at the generator is low and it increases when the solution circulation reduces higher solution circulation ratios. However, the compressor power input is dependent on pressure ratio and mass flow rate of refrigerant remains constant and is unaffected with variations in solution circulation ratio. Since the pressure ratio is assumed constant, hence the no variation in compressor power input is observed. It is observed that rate of rise in COP increases with increase in concentration of the weak solution.
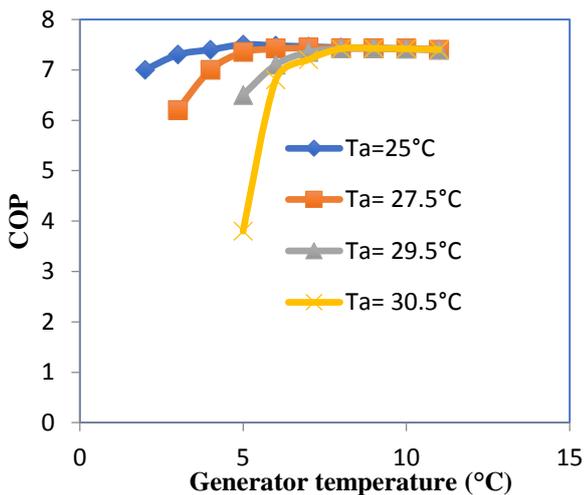

Figure 7. COP vs Generator temperature for varying absorber temperature (pressure ratio = 5, Xw = 39.5%)
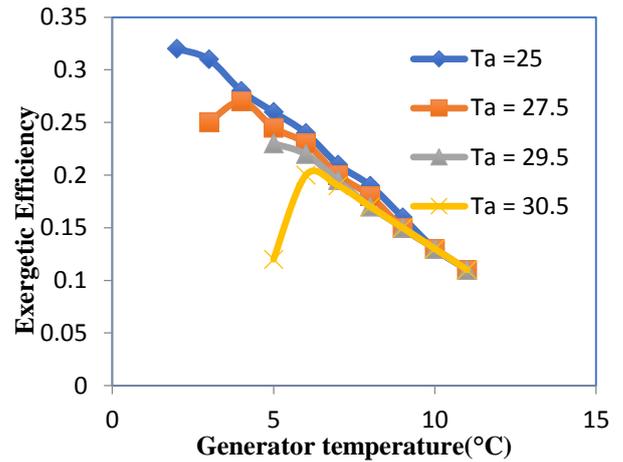

Figure 8. Exergetic Efficiency vs Generator temperature for varying absorber temperature (pressure ratio = 5, Xw = 39.5%)
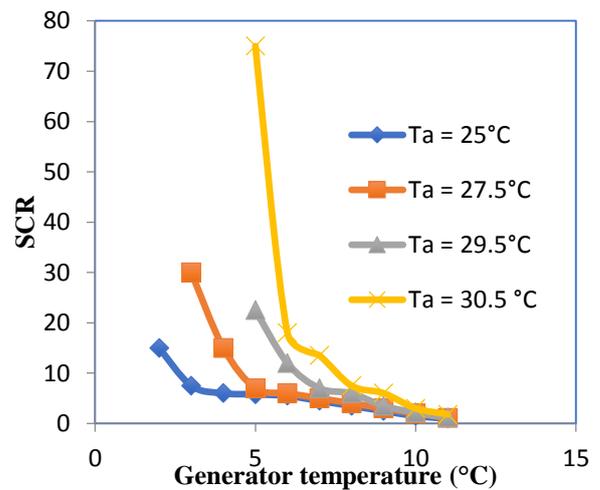

Figure 9. SCR vs Generator temperature for varying absorber temperature (pressure ratio =5, Xw = 39.5%)

Figure 7, 8 and 9 demonstrate the effect of generator temperature on COP, exergetic efficiency and solution circulation ratio for varying absorber temperature. It is observed that there is a sharp increase in COP initially and then it is almost constant with the increase in generator temperature whose trend already discussed. Similar trend is also observed for exergetic efficiency. At higher absorber temperature COP and exergetic efficiency is low and it is very significant at low generator temperature. At an absorber temperature of 25^0C, exergetic efficiency is found to be highest value of about 32.5% (at a generator temperature of 2^0C) whereas the COP after initial increase with increase in generator temperature becomes constant having value of about 7.7 at a generator temperature of 11^0C. It is observed that with the increase in absorber temperature with the corresponding decrease in generator temperature, SCR increases. It can be predicted that with increase in SCR the cooling effect decreases.
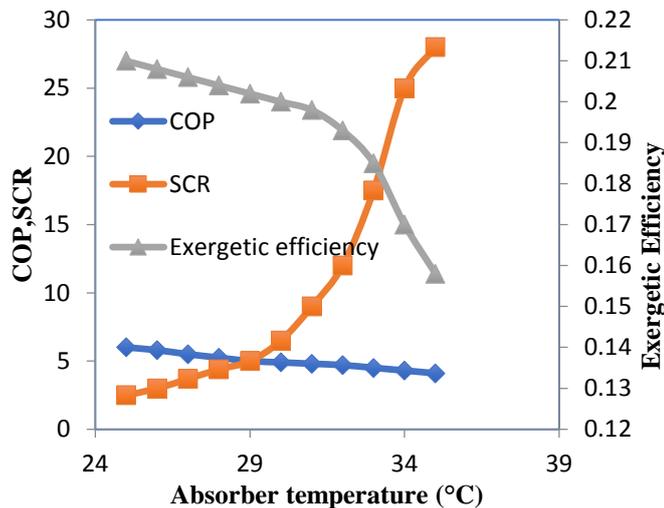
Figure 10. COP, SCR and exergetic efficiency vs T_a (Generator temperature = 5°C, Xw = 42%, Pressure ratio = 6.5, Effectiveness of solution heat exchanger = 0.7 and efficiency of compressor = 0.85)

Figure 10 exhibits the variation of COP, SCR and Exergetic efficiency with absorber temperature. The SCR increases with increase in absorber temperature resulting in decrease in cooling effect at the generator whereas COP and exergetic efficiency decrease as a result of absorber temperature increase.
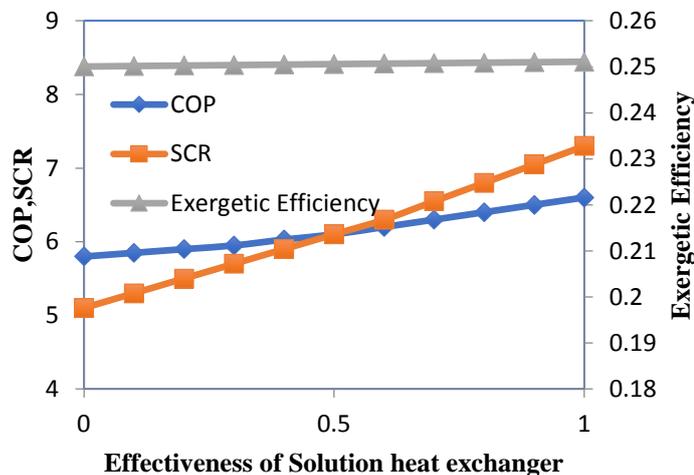

Figure 11. COP, SCR and Exergetic Efficiency versus Effectiveness of Solution heat exchanger (T_g = 6°C, T_a = 28 °C, Xw = 42%, Pressure ratio = 6.5)

Figure 11 demonstrates the variation of COP, SCR and Exergetic efficiency with Effectiveness of solution heat exchanger. It is observed that SCR has no effect with change in effectiveness of solution heat exchanger. As the effectiveness increases, the temperature of strong solution decreases resulting in decrease in enthalpy and hence increasing the cooling effect. Thus, COP increases with increase in effectiveness of solution heat exchanger also causing the increase in exergetic efficiency.

CONCLUSION

In the present study the energy and exergy analysis of a hybrid refrigeration system working with LiBr-H₂O as fluid pair has been conducted. The effect of various parameters has been studied in detail and observation has been made as follows: -

1. The decrease in absorber temperature results in increase in COP along with increase in exergetic efficiency of the system. At different absorber temperature with the increase in generator temperature, COP of the system increases and finally converges to a value of about 7.7 at a generator temperature of 11^0C irrespective of absorber temperature. The maximum exergetic efficiency of 32.5% occurs at a generator temperature of 2^0C and absorber temperature of 25^0C.

2. COP increases with the increase in generator temperature. This rise in COP is significantly large between 5-6^0C of generator temperature and with further increase in generator temperature the rise in COP becomes nominal resulting in almost a flat curve. The exergetic efficiency also increases with increase in generator temperature reaches its maximum at 6^0C and then a sharp decrease is observed. The COP and exergetic efficiency obtained are higher at lower value of weak solution concentration.

3. The decrease in pressure ratio from 10 to 5 results in increase in the COP from 4.9 to 7.7 and it is also detected that the system seizes to run at higher values of generator temperature when the pressure ratio increases. At higher pressure ratio exergetic efficiency decreases with increase in generator temperature. However, at lower pressure ratio there is a sharp increase initially and then sharp decrease in exergetic efficiency is observed with increase in generator temperature. Both the COP and exergetic efficiency increases with increase in effectiveness of solution heat exchanger.

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