THERMODYNAMIC COMPARISON OF WATER BASED WORKING FLUID COMBINATIONS FOR VAPOUR ABSORPTION HEAT TRANSFORMERS

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Abstract: Vapour absorption heat transformer (VAHT) is a promising alternative, among various methods used for waste heat up gradation. The performance and cost of the VAHT are strongly dependent on the refrigerant, absorbent and their mixtures. In this paper, thermodynamic comparisons of fifteen water-based working fluids have been made based on both energy and exergy efficiencies. Simulation is carried out with constant waste heat input. It is found that H_2O-(LiCl+$LiNO_3$) system produces the highest absorber heat output for given waste heat input than other working fluid combinations followed by H_2O-LiBr system with a gross temperature lift of 30^oC. The Coefficient of performance and Exergetic efficiency are higher for these combinations compared to other water based combinations. The selection of best working fluid considering various operating conditions has been outlined and conclusions drawn based on performance are presented.

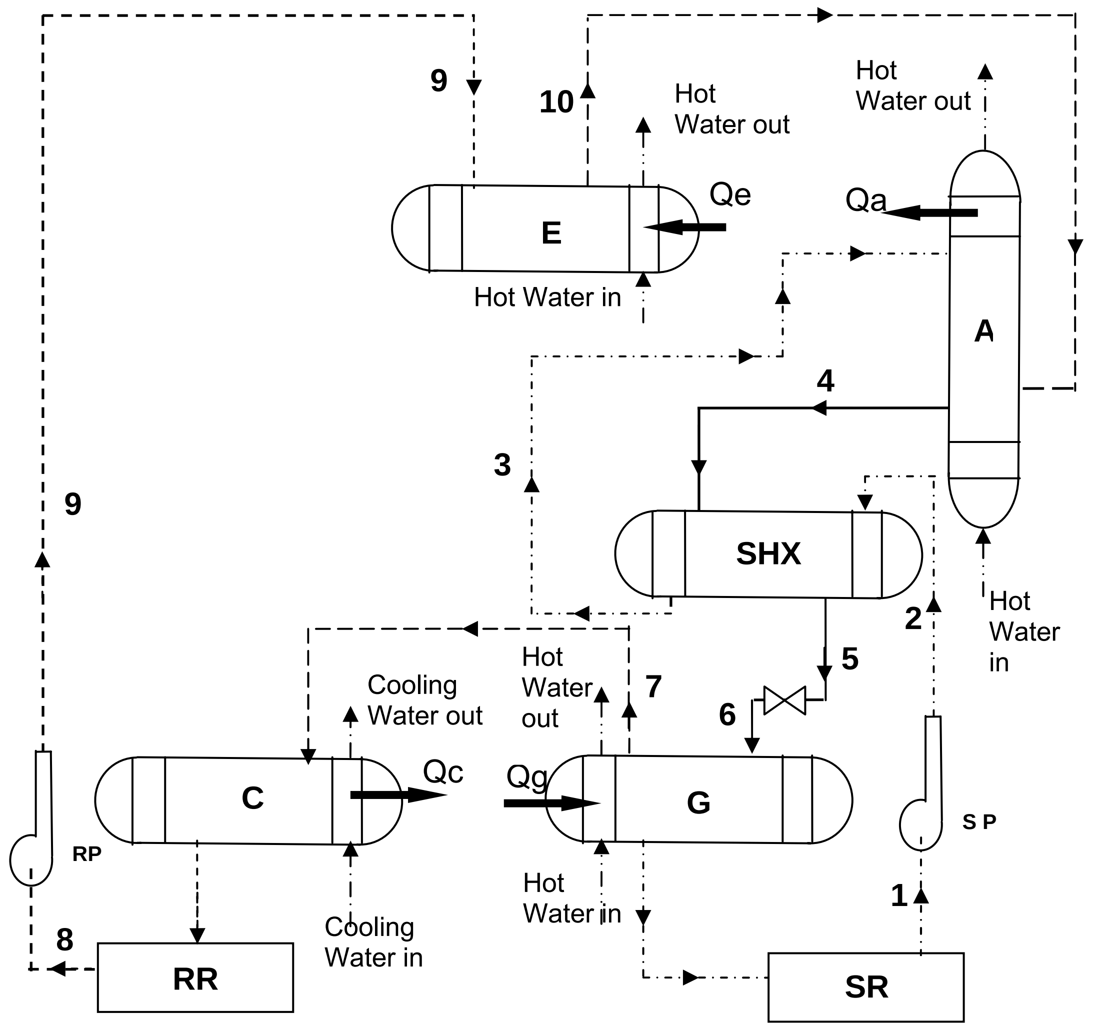
Key Words: ***heat transformers, water based working fluids, exergetic efficiency***

1 INTRODUCTION

The high rate of increase in energy demand, fast depletion of fossil fuels and concern about global warming urge scientists and engineers all over the world to develop cleaner and more energy efficient processes. Most interesting are systems reusing the enormous amounts of waste heat that are presently emitted to the environment by the chemical and refinery industries. Among the various systems used for waste heat recovery, VAHT is attractive one, since it can transfer low-grade heat into high-grade heat consuming very little electrical energy for its operations. It is very simple in configuration and has a higher life expectancy. It can reduce energy loss and the discharge of carbon dioxide thus reducing the greenhouse effect (Lin Shi et al. 2001). In this work, a thermodynamic comparison is made for water based absorption working fluid combinations in VAHT.

2 DESCRIPTION OF THE SYSTEM

VAHT works with two pressure levels and three temperature levels. It has four major components: absorber (A), generator (G), condenser (C) and evaporator (E). Condenser and generator are at lower pressure and absorber and evaporator are at higher pressure. VAHT takes in heat at intermediate temperature at generator and evaporator, rejects heat at lowest temperature at condenser and upgrades heat at highest temperature at absorber as shown in Figure 1. Vapour generated in the generator is transported to the condenser, where it is cooled and condensed. The condensate is stored in the refrigerant reservoir (RR) and is pumped to the evaporator through refrigerant pump (RP). Vapour formed in the evaporator is absorbed in the absorber liberating heat of absorption. Weak solution from absorber is fed



E – Evaporator C – Condenser A – Absorber

G – Generator SHX – Solution Heat Exchanger SR – Solution Reservoir

SP – Solution Pump RR – Refrigerant Reservoir RP – Refrigerant Pump

_ _ _ _ _ Refrigerant — — — — — Refrigerant Vapour

——— Weak Solution -·-·-·-·- Strong Solution

Figure 1: Schematic of VAHT

to the generator. The strong solution that remains after generation of vapour in the generator is stored in solution reservoir (SR) and pressurized to absorber pressure by solution pump (SP). To increase the performance of VAHT, a solution heat exchanger is provided between generator and Absorber. The pressure and temperature levels are as given below:

$$p_g = p_c < p_e = p_a \quad (1)$$

$$t_c < t_e = t_g < t_a \quad (2)$$

3 WORKING FLUIDS

Though VAHT can be used for achieving a heat pumping effect to high temperature levels for industrial applications, suitable working fluids and their relative performances are yet to be established. The performance, operational characteristics and cost of the VAHT are strongly dependent on the properties of the refrigerant, absorbent and their mixtures. Several working fluids both organic and inorganic were surveyed, analyzed and presented by many researchers. Water as a refrigerant has low vapour pressure, high latent heat and low viscosity. In this study fifteen water based working fluid combinations H_2O-LiBr, H_2O-LiI, H_2O-LiCl, H_2O-LiBr+LiI, H_2O-LiCl+$LiNO_3$, H_2O-LiBr+LiSCN, H_2O-LiBr+$ZnBr_2$, H_2O-LiBr+$LiNO_3$, H_2O-LiBr+$ZnBr_2$+LiCl,H_2O-LiBr+$ZnCl_2$+$CaBr_2$,H_2O-LiBr+LiI+$C_2H_6O_2$,H_2O-NaOH+KOH+CsOH, H_2O-LiBr+LiCl+$ZnCl_2$,H_2O-$LiNO_3$+KNO_3+$NaNO_3$ and H_2O-LiCl+$CaCl_2$+$Zn(NO_3)_2$ are considered for thermodynamic analysis and various performance parameters are compared. Thermodynamic (specific heat and heat of mixing) and thermo physical (vapour pressure, density, viscosity, surface tension and solubility) properties of absorption working fluids have been developed by many researchers. Correlations for equilibrium properties giving p-T-X (pressure, temperature, concentration) and h-T-X (enthalpy, temperature, concentration) data have also been obtained for H_2O-LiBr+LiSCN (Iyoki et al, 1981), H_2O-LiCl+$CaCl_2$+$Zn(NO_3)_2$ (Pinchuk et al 1982), H_2O-LiBr (Herold and Morjan, 1987), H_2O-LiCl (Grover and Devotta, 1988), H_2O-LiBr+$ZnBr_2$+LiCl (Iyoki et al, 1989), H_2O-LiBr+$ZnCl_2$+$CaBr_2$ (Iyoki et al, 1989), H_2O-$LiNO_3$+KNO_3+$NaNO_3$ (Ally, 1990), H_2O-LiBr+LiI+$C_2H_6O_2$ (Iizuka et al, 1990), H_2O-LiBr+LiI (Iyoki et al, 1990), H_2O-LiI (Patil et al. 1991), H_2O-LiBr+$ZnBr_2$ (Adegoke et al, 1991),H_2O-LiCl+$LiNO_3$ (Iyoki et al, 1993), H_2O-LiBr+LiCl+$ZnCl_2$ (Iyoki et al, 1993), H_2O-LiBr+$LiNO_3$ (Iyoki et al, 1993), H_2O-NaOH+KOH+CsOH (Rivera and Romero, 1997). These correlations are used to evaluate different properties such as enthalpy, temperature, concentration and flow rates at various state points.

4 THERMODYNAMIC ANALYSIS

Thermodynamic analysis has been carried out on VAHT to find the effect of temperature lift on performance parameters of VAHT like COP and Exergetic efficiency. The influence of heat exchanger effectiveness on system performance has also been studied.

4.1 Assumptions

1. The flow through the components is under steady state and thermodynamic equilibrium conditions.
2. The working fluid at the exits of generator and absorber, condenser and the evaporator are all saturated.
3. Heat losses and gains and pressure losses in various components and piping are neglected.
4. The work done by the pumps is considered negligible.
5. The evaporator and generator temperatures are the same.
6. Pure refrigerant is liberated at the generator since the absorbents considered here have much higher boiling points than the generating temperature.

4.2 Heat Loads

Heat loads of various components of VAHT are obtained using the respective energy balance equations (with reference to Figure1).
The generator heat load

$$Qg = m_1h_1 + m_7h_7 - m_6h_6 \quad (3)$$

Condenser: $$Qc = m_7h_7 - m_8h_8 \quad (4)$$

Evaporator: $$Qe = m_{10}h_{10} - m_9h_9 \quad (5)$$

Absorber: $Qa = m_3h_3 + m_{10}h_{10} - m_4h_4$ (6)

4.3 Performance Parameters

The most important design parameters for a VAHT are Circulation Ratio (f), Concentration Differential (dX), Coefficient of Performance (COP), Gross Temperature Lift (GTL), Carnot COP and Exergetic Efficiency.

4.3.1 Circulation ratio

It is an important design and optimizing parameter since it is directly related to the size and cost of the generator, absorber, heat exchanger and pump. It is defined as the ratio of the mass flow rate of the solution leaving the absorber to the generator (m_4) to the mass flow rate of the working fluid (m_7).

$$f = \frac{m_4}{m_7} \tag{7}$$

4.3.2 Concentration differential

It is a measure of difference in the solution concentrations at the generator outlet and the absorber outlet.

$$dX = \frac{Xs - Xw}{Xs}[100] \tag{8}$$

4.3.3 COP

It is equal to the heat load in the absorber per unit heat load in the generator and the evaporator.

$$COP = \frac{Qa}{Qg + Qe} \tag{9}$$

4.3.4 GTL

It is the difference between the useful absorber temperature and generator temperature.

$$GTL = Ta - Tg \tag{10}$$

4.3.5 Carnot COP

It is the maximum possible value of COP. It is for an ideal reversible cycle which is working at the same range of actual cycle and based on only the temperatures.

$$COP_{car} = [Ta/(Ta - Tc)] \times [(Te - Tc)/Te] \tag{11}$$

4.3.6 Exergetic efficiency

It is based on Second Law and is expressed as

$$\eta_{ex} = \frac{Qa[1 - To/Ta]}{Qg[1 - To/Tg] + Qe[1 - To/Te]} \qquad (12)$$

5 RESULTS AND DISCUSSIONS

Thermodynamic analysis for the working fluid combinations was done and performance curves were plotted. Generator temperature was varied form 60°C to 80°C. Figure 2 shows the effect of generator temperature on COP, for the working fluid combinations at a fixed condenser temperature of 30°C with 30°C GTL and a solution heat exchanger effectiveness of 0.75. Increasing generator temperature causes an increase in concentration differential and hence a decrease in circulation ratio. Since the evaporator and absorber pressures are mainly determined by evaporator temperature, a higher Te corresponds to a high pressure, which causes the solution concentration at the absorber outlet to decrease. On the other hand, increasing Tg (keeping generator pressure constant) causes the solution concentration at the generator outlet to increase. These lead to larger concentration differentials and then smaller circulation ratios. As circulation ratio decreases, COP increases. H_2O-LiCl+$LiNO_3$ combination gives maximum COP values followed by H_2O-LiBr.

Figure 3 shows the effect of condenser temperature on COP for the working fluid combinations at a fixed generator temperature of 65°C, with 30°C GTL and a solution heat exchanger effectiveness of 0.75. Condenser temperature was varied form 20°C to 35°C. With increasing Tc, the circulation ratio increases and the concentration differential decreases. Since the condenser and the generator pressures are mainly determined by Tc, a higher Tc corresponds to a higher generator pressure. As a result of this, less water vapour is generated in the generator. So the solution concentration at the generator outlet decreases, which leads to smaller concentration differentials and larger circulation ratios. Since circulation ratio increases, COP decreases. The effect of GTL on COP, at a fixed condenser temperature of 30°C, generator temperature of 60°C and effectiveness of solution heat exchanger 0.75 is shown in Figure 4. As temperature lift increases for fixed temperatures of the condenser, evaporator and generator, the concentration of strong solution decreases while the concentration of weak solution remains constant. Hence the concentration spread decreases. This decrease in concentration spread causes an increase of circulation ratio. This increase in circulation ratio in turn causes a decrease in COP.

Figure 5 shows the effect of GTL on exergetic efficiency at condenser temperature of 30°C, evaporator and generator temperature of 70°C and solution heat exchanger effectiveness of 0.75. For all the fluids except H_2O-LiCl+$CaCl_2$+$Zn(NO_3)_2$, exergetic efficiency increases as GTL increases. Quality of energy is considered in the definition of exergetic efficiency. When GTL increases, Ta increases. The term (1 - To/Ta) also increases with an increase of Ta since To is constant. Hence the exergetic efficiency increases with temperature lift. H_2O-LiCl+$LiNO_3$ combination gives maximum exergetic efficiency, followed by H_2O-LiBr. Figure 6 shows the effect of solution heat exchanger effectiveness on COP at condenser temperature at 30°C, generator and evaporator temperatures at 60°C and GTL 30°C. The circulation ratio depends on the solution concentration differential in the cycle. However, low circulation ratios are desirable to maximize the heat transformer performance since the solution irreversibly carries heat from the absorber to the generator. The irreversible heat transfer can be minimized using the solution heat exchanger. Increasing effectiveness causes COP to increase almost linearly. The absorption heat transformer performance obviously improves with the solution heat exchanger.

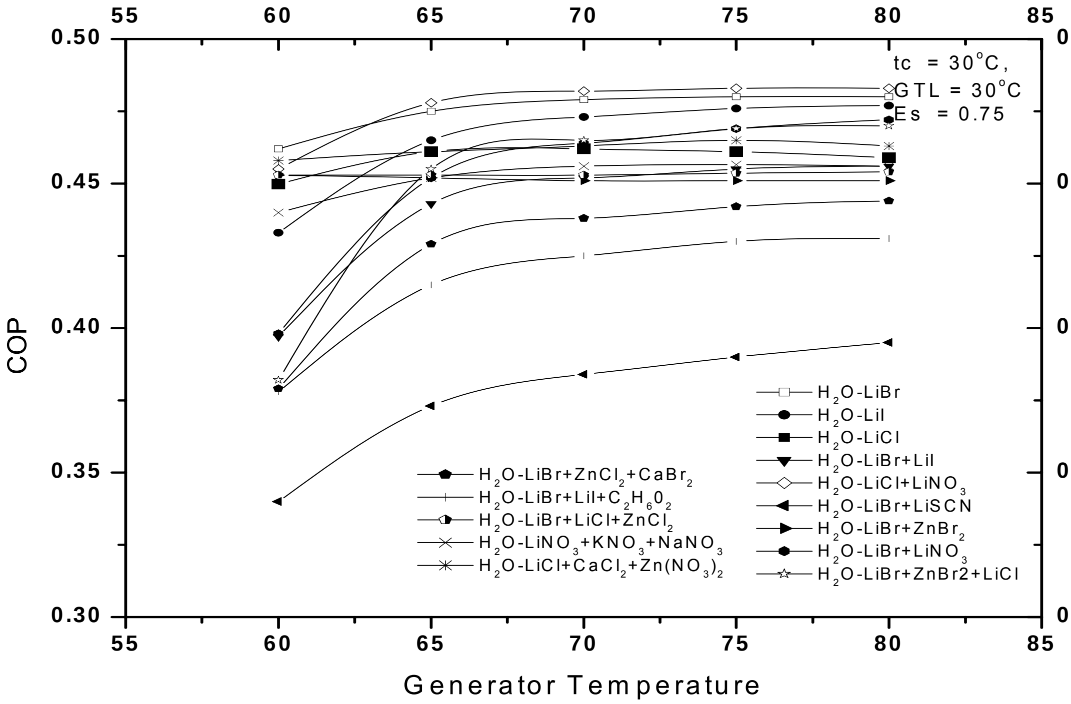


Figure 2: Effect of Generator temperature on COP

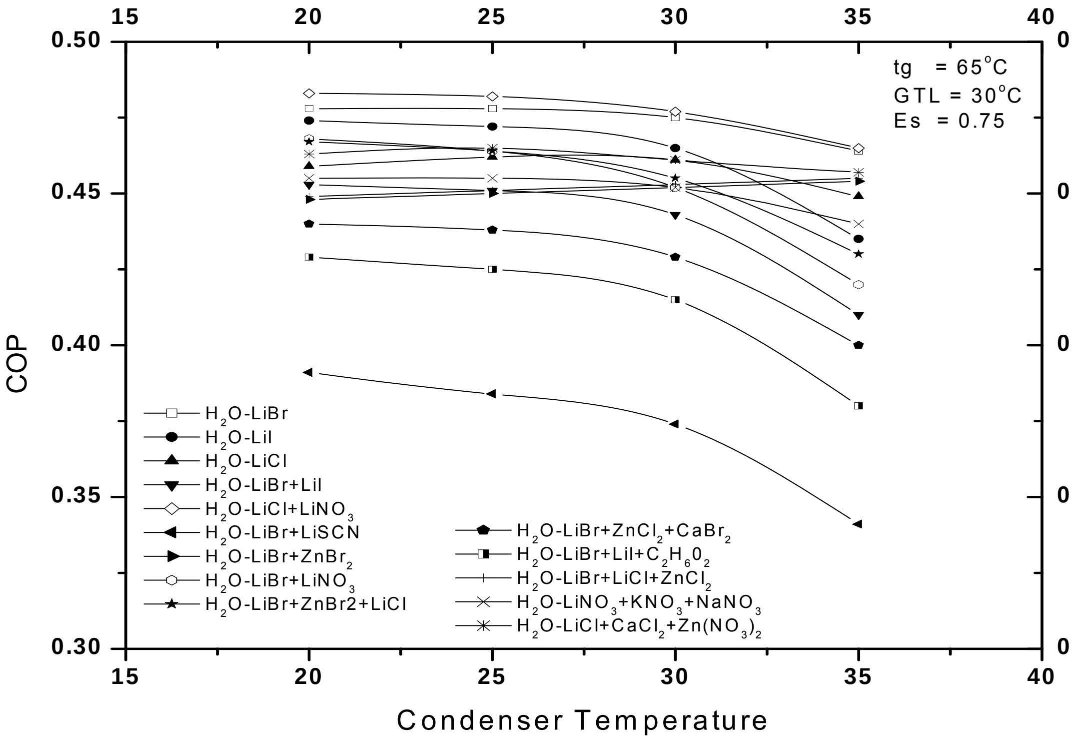


Figure 3: Effect of Condenser temperature on COP

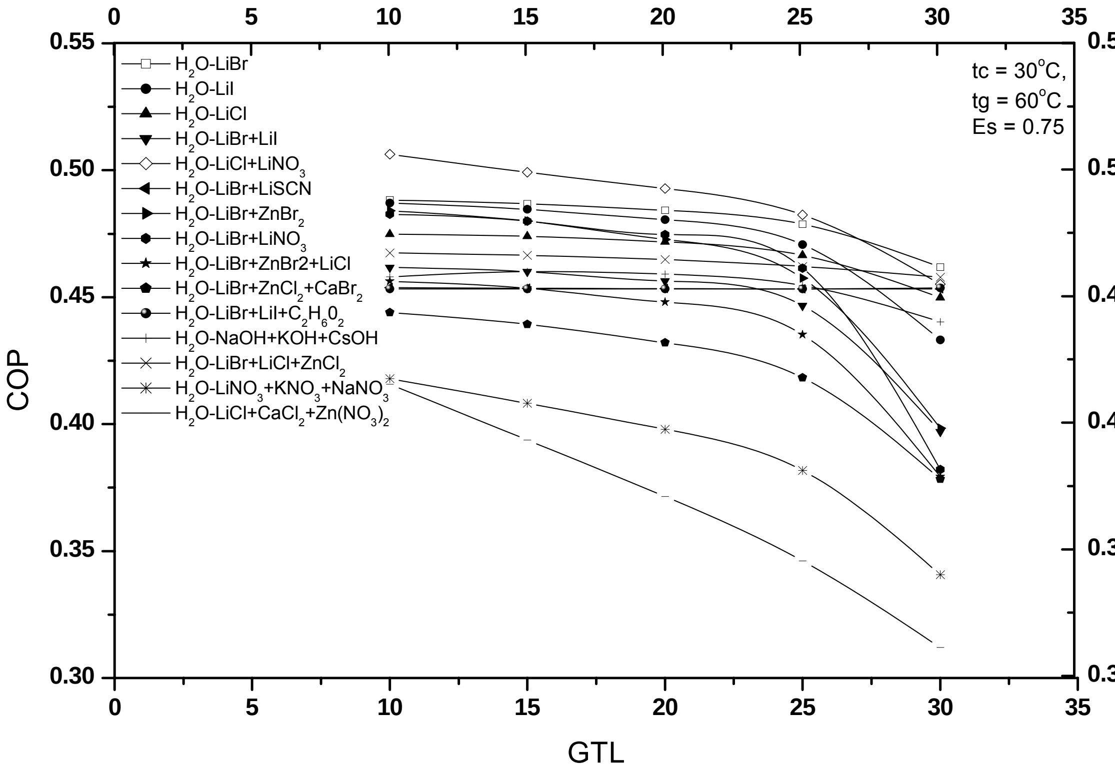


Figure 4: Effect of GTL on COP

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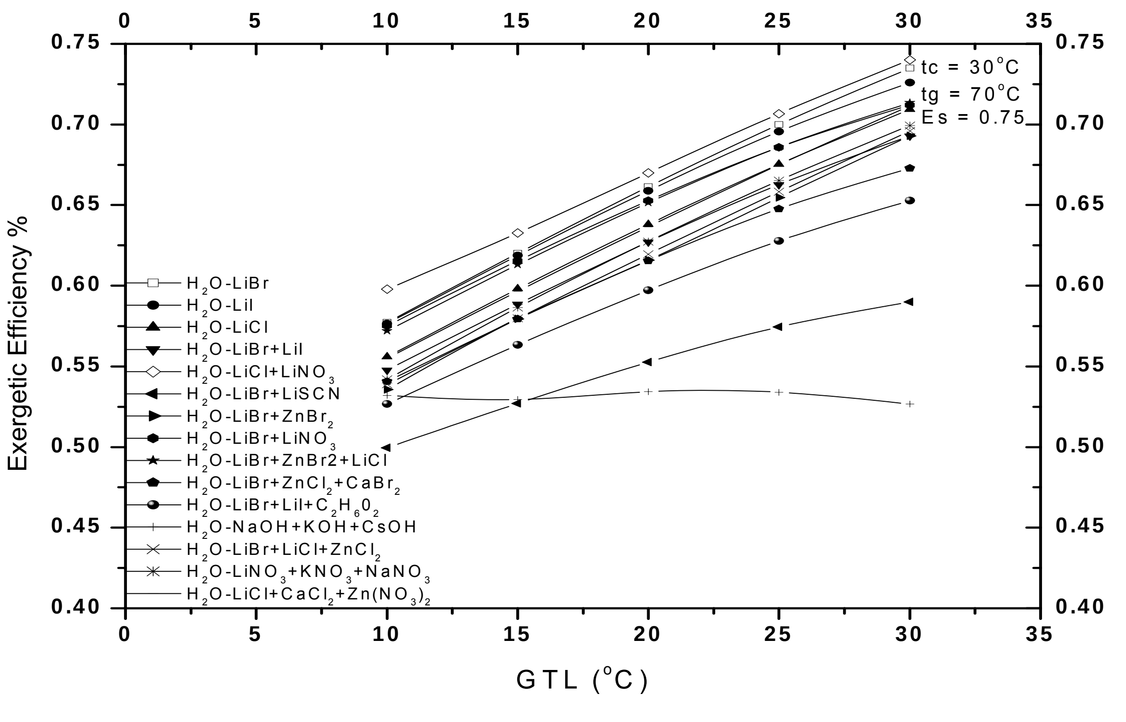

Figure 5: Effect of GTL on exergetic efficiency

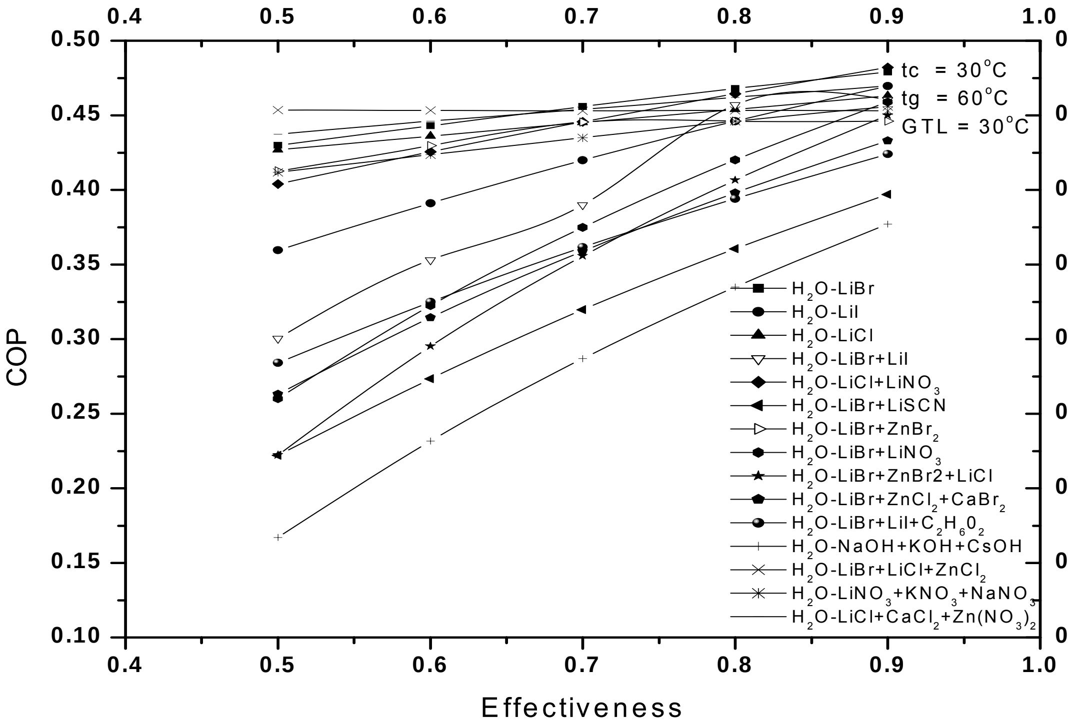

Figure 6: Effect of Effectiveness of solution heat exchanger on COP

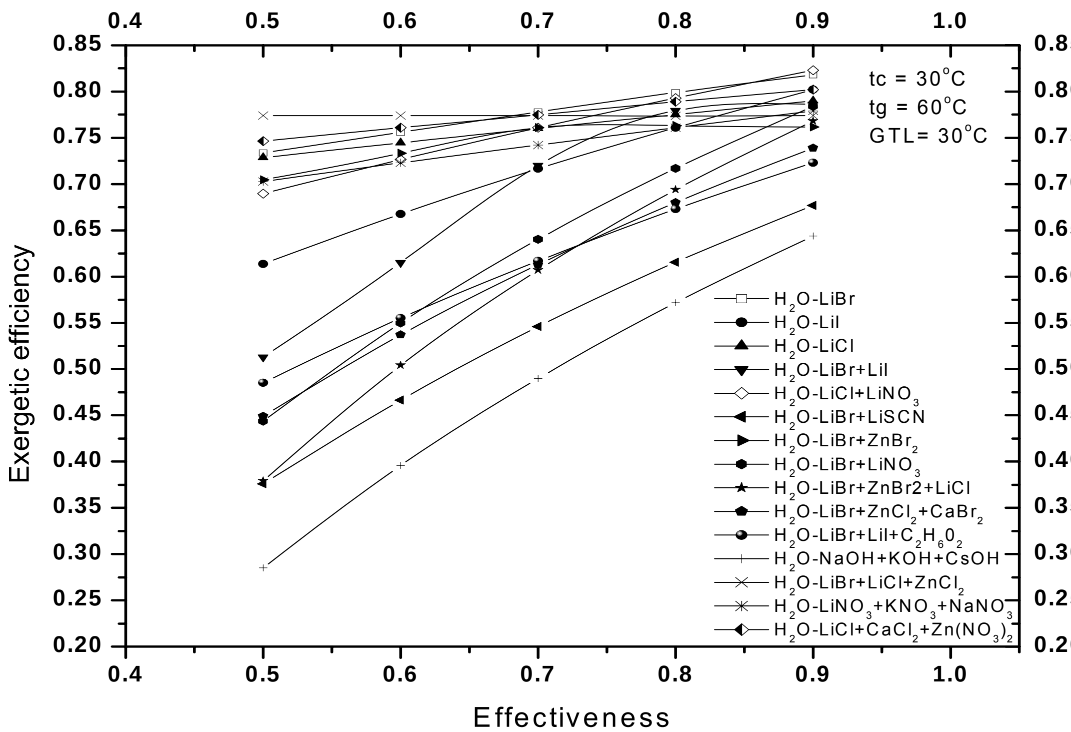

Figure 7: Effect of Effectiveness of solution heat exchanger on exergetic efficiency

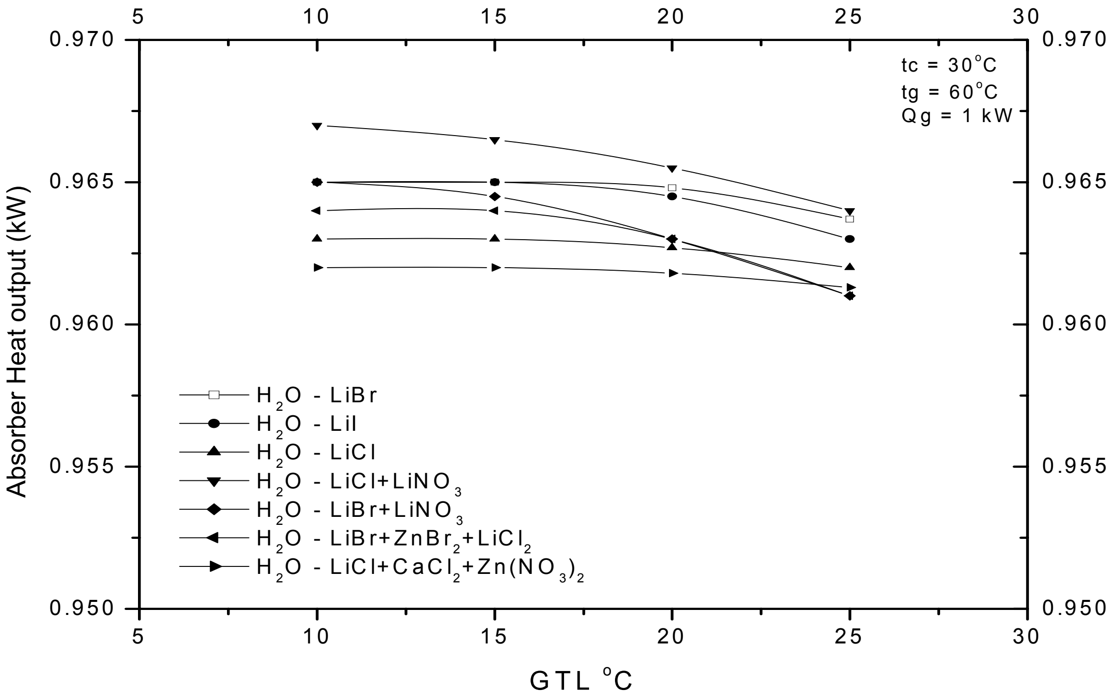

Figure 8: Effect of GTL on Absorber heat output for selected working fluids.

Figure 7 shows the effect of solution heat exchanger effectiveness on exergetic efficiency at Condenser Temperature at 30°C, Generator and Evaporator Temperatures at 60°C and GTL 30°C. Exergetic efficiency shows same trend of COP.

Among the fifteen fluid combinations examined, H_2O-LiBr, H_2O-LiI, H_2O-LiCl, H_2O-LiCl+$LiNO_3$, H_2O-LiBr+$LiNO_3$, H_2O-LiBr+$ZnBr_2$+LiCl and H_2O-LiCl+$CaCl_2$+$Zn(NO_3)_2$ fluids are having better performance than the other fluids. These seven combinations are compared for the effect of GTL on Absorber heat output for the fixed generator, evaporator and condenser temperatures and the result is shown in figure 8. In general for all the fluids, absorber heat output decreases with increase in GTL. H_2O-LiCl+$LiNO_3$ gives the highest absorber heat output followed by H_2O-LiBr.

6 CONCLUSIONS

Thermodynamic analysis of vapour absorption heat transformer with fifteen water based working fluid combinations was done and comparisons made for performance parameters. COP increases with increase in generator temperature and decreases with increase in condenser temperature and GTL. However at higher GTL, exergetic efficiency is better. Increase in solution heat exchanger effectiveness is found to have a positive effect on the performance of the system based on both first and second laws. Among the working fluids examined H_2O- LiCl+$LiNO_3$ gives superior performance in terms of COP, Exergetic efficiency and absorber output followed by H_2O-LiBr.

Acknowledgements

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Nomenclature

h	Specific enthalpy (kJ/kg)
m	Mass flow rate (kg/s)
Q	Heat transfer rate (kW)
t	Temperature (^{o}C)
T	Temperature (K)
X	Concentration (kg / kg of solution)
f	Circulation ratio
dX	Concentration Differential (%)
Es	Effectiveness of Solution Heat Exchanger

Subscripts

a	Absorber
c	Condenser
e	Evaporator
g	Generator
o	Ambient
car	Carnot
r	Refrigerant
s	Strong Solution
w	Weak solution
1-10	State points in the system with reference to Figure 1.

Symbols

η_{ex}	Exergetic Efficiency

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