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Thermodynamic Performance Analysis of a Solar Vapour Absorption Refrigeration System

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Abstract: The air-conditioning and refrigeration systems around the world mostly use the vapor-compression or vapor-absorption type of systems that consumes a huge amount of energy. Using solar energy to power such systems can lead to savings of a large amount of energy. The work presented in this paper is focused on the design of a solar vapor absorption system and the performance analysis of the system. The performance of the system in terms of coefficient of performance (COP) is investigated for absorber temperature, generator temperature and the concentration difference. Also an error analysis has been carried out to investigate the justifications of the outcome of this work. It is found that corresponding to the climatic conditions of Goa, India, the optimal performance of the solar vapor absorption system is obtained for absorber temperature of 40^{o}C and generator temperature of 90^{o}C. Similarly the methodology can be adopted to any place keeping in view the climatic conditions to design and develop a suitable solar absorption system which can lead to optimum use of solar energy and consequently savings of huge amount of electrical energy.

Key-words: Vapor absorption refrigeration; solar energy; absorber; generator; COP; concentration difference.

1. Introduction:

Refrigeration is a thermodynamic process in which external work is provided in order to move heat from one location at lower temperature to other maintained at a higher temperature. It has wide applications industrial and domestic areas including a major impact on agriculture and food production as it allows large scale storage and processing of food and agricultural products. Industrial applications include large scale air conditioning, refrigeration, cooling in manufacturing, liquefaction of gases in chemical and petroleum industry, etc. Continuous refrigeration consists of a refrigeration cycle, where heat is removed from a low-temperature space or source and rejected to a high-temperature sink with the help of external work. Presently most of the cooling produced is by vapour compression or vapour absorption refrigeration system. The compressor of these vapor-compression systems use a huge amount of electrical energy generated by burning fossil fuel. However the scarcity of energy around the world creates the need for the development of a refrigeration system that may run on an alternative source of energy. The traditional absorption refrigeration system has a number of shortcomings that includes the complexity and the high manufacturing cost of the system including the solution pump and the compressor and so on, the strict demand on the heat supply in both quality and quantity.

In recent years, many a number of researchers have carried out research on refrigeration systems driven by renewable source of energy, which achieves conservation of conventional energy and a reduction of environmental pollution. Out of the various renewable sources of energy, solar energy can be considered as the best candidate for Refrigeration and air-conditioning because of the coincidence of the maximum cooling load with the period of greatest solar radiation input (Syed et. al., 2012). Solar energy can be converted into electricity using photovoltaic cells and used to operate a conventional vapor-compression refrigeration system. Also it can be used to heat the working fluid in the generator of a vapor absorption refrigeration system. A refrigeration cycle co-driven by both heat and electrical energy addresses the difficulties associated with the solar-heating system’s long-term operation at a steady state. (Yaxiu et.al., 2008).

Several researchers have studied the utilization of solar energy in the absorption refrigeration process. De Francisco et al. (2002) developed and tested a prototype design of a 2-kW refrigeration equipment with a high level of solar radiation to meet refrigeration requirements. However the COP of the system was determined to be 0.05, which was too low. Sarbu and Sebarchievici (2013) provided a detailed review of different solar refrigeration and cooling methods and presented the theoretical basis and practical applications for cooling systems within various working fluids assisted by solar energy and their recent advances. Kim and Infante Ferreira (2008) presented a state of the art review on solar refrigeration systems.

They made a comparison between solar electric and solar thermal refrigeration systems both from the point of view of energy efficiency and economic feasibility. The comparison showed that solar electric refrigeration systems using photovoltaic appear to be more expensive than solar thermal systems.

The solar absorption systems utilize the thermal energy from a solar collector to separate a refrigerant from the refrigerant/absorbent mixture. The flat plate solar collectors can be used for the single-effect cycle. However, the multi-effect absorption cycles require high temperatures which can be delivered by the evacuated tube or concentrating-type collectors. A single-effect absorption cooling system is simpler than other when the design depends on the types of working fluids. The system shoes better performance with non-volatile absorbents as H_2O/LiBr. If volatile working pair such as NH_3/H_2O is used, then an extra rectifier should be used before the condenser to provide pure refrigerant (Srikhirin et. al., 2001). Nakahara et al. (1977) developed a single-effect H_2O/LiBr absorption chiller of 7 kW nominal cooling capacity, assisted by a 32.2 m^2 array of flat plate solar collectors. In their system, thermal energy produced by the solar collector was stored in a 2.5 m^3 hot-water storage tank. Their experimental results during the summer period showed that the cooling capacity was 6.5 kW. The measured COP of the absorption system was in range of 0.4–0.8 at the generator temperature of 70^{o}C to 100^{o}C. Izquierdo et al. (2004) designed a solar double-stage absorption plant with H_2O/LiBr, which contained flat plate collectors to feed the generator.

They reported that within a condensation temperature of 50^{o}C, the COP was 0.38 while providing a generation temperature of 80◦C. They also performed an exergetic analysis of this system and conclude that the single-effect system had 22% more exergetic efficiency than the double-stage half-effect system. Triple-effect absorption cooling can be classified as single-loop or dual-loop cycles. Single-loop triple-effect cycles are basically double-effect cycles with an additional generator and condenser. The resulting system with three generators and three condensers operates similarly to the double effect system. Primary heat concentrates absorbent solution in a first-stage generator at about 200–230^{o}C. A fluid pair other than H_2O/LiBr must be used for the high temperature cycle. The refrigerant vapour produced is then used to concentrate additional absorbent solution in a second-stage generator at about 150^{o}C. Finally, the refrigerant vapour produced in the second-stage generator concentrates additional absorbent solution in a third-stage generator at about 93^{o}C. The usual solution heat exchangers can be used to improve cycle efficiency. Theoretically, these triple-effect cycles can obtain COPs of about 1.7 [9]. Besides a number of researchers have put deep insight into the area of solar absorption refrigeration system through their review articles [10,11,12].

2. Detailed Description of the System

The absorption refrigeration cycle is similar to the compression cycle, except for the method of raising the pressure of the refrigerant vapor. In the absorption system, the compressor is replaced by an absorber which dissolves the refrigerant in a suitable liquid, a liquid pump which raises the pressure and a generator which on heat addition drives off the refrigerant vapor from the high-pressure liquid. Some work is needed by the liquid pump but, for a given quantity of refrigerant, it is much smaller than the work required by the compressor in the vapor compression cycle. In an absorption refrigerator, a suitable combination of refrigerant and absorbent is used. The most common combinations are ammonia (refrigerant) with water (absorbent), and water (refrigerant) with lithium bromide (absorbent). However this work is based on absorption refrigeration and cooling system lithium bromide as absorbent in which heat is provided by solar energy using Evacuated tube collector (ETC).

Solar energy is the most widely available renewable energy. The total solar energy absorbed by Earth's atmosphere, oceans and land masses is approximately 3,850,000 exajoules (EJ) per year. The amount of solar energy reaching the surface of the planet is so vast that in one year it is about twice as much as will ever be obtained from all of the Earth's non-renewable resources of coal, oil, natural gas, and mined uranium combined. The major advantages of solar thermal systems include reduced dependency on imported fuel, improved diversity of energy supply, savings in scarce natural resources, savings in CO_2 emission at very low cost.

2.1 Solar Vapour Absorption Refrigeration System:

The solar-powered absorption cycle consists of four major systems namely the generator, condenser, evaporator and absorber. These major components are divided into three parts by one heat exchanger, two expansion valves and a pump. In the generator the solar energy is used to heat a weak solution of Li-Br/H_2O. This heat causes the refrigerant, in this case water, to evaporate. The water vapor that results passes into the condenser section where a cooling medium is used to condense the vapor back to a liquid state. The refrigerant is then expanded to a low pressure region to reduce temperature of saturated liquid (Joule Thompson Expansion). The water then flows down to the evaporator section where it passes over tubes containing the fluid to be cooled, which causes the refrigeration effect. By maintaining a very low pressure in evaporator and absorber, the water boils at a very low temperature. This boiling causes the water to absorb heat from the medium to be cooled, thus, lowering its temperature. Evaporated water then passes into the absorber section where it is mixed with a Li Br/H2O solution that is very low in water content. This strong solution (strong in Li Br) tends to absorb the vapor from the evaporator section to form a weaker solution. This is the absorption process that gives the cycle its name. The weak solution is then pumped to the generator section to repeat the cycle. The limitation on maximum and minimum pressure was determined taking into account the climatic restriction as per climate of Goa. The saturation pressure in the condenser limits the maximum pressure in system. The maximum pressure after condensation was calculated to be 4.5 kPa as minimum temperature that could be attained in condenser was 31^{o}C. The saturation pressure was obtained from the minimum temperature of 5^{o}C required after refrigeration. The minimum pressure was found to be 0.87kPa. The thermodynamic cycle is presented in Figure 1.

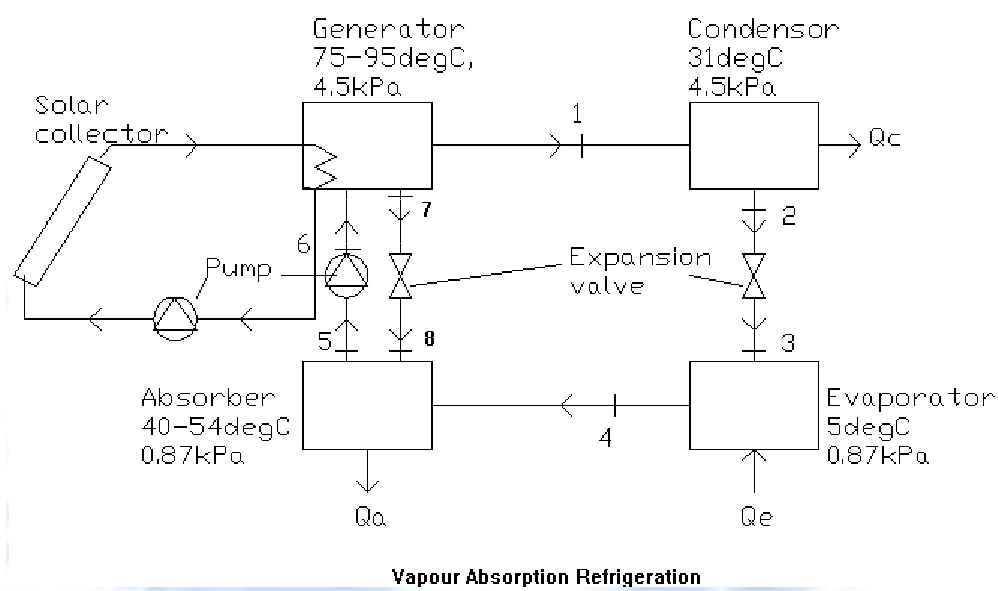

Figure 1: Thermodynamic cycle of solar vapour absorption refrigeration system

2.2 Evacuated Tube Collector (ETC)

The solar energy can be captured with the help of solar collectors. A solar collector is a device for capturing solar radiation. Solar collectors are either non-concentrating or concentrating. In the non-concentrating type, the collector area that intercepts the solar radiation is same as the absorber area absorbing the radiation. The common types of non concentrating collectors are flat-plate and evacuated-tube collectors. Concentrating collectors like parabolic dish and parabolic trough collectors have a bigger interceptor than absorber. As mentioned earlier the Evacuated Tube Collector (ETC) is used in this work for absorption of heat from solar radiation. The ETC collectors absorb heat from solar radiation and convert it into heat output which heats water flowing through the collectors. The ETC collector is filled with vacuum in order to reduce losses due to convection and re-radiation. Evacuated heat pipe tubes (EHPTs) are composed of multiple evacuated glass tubes each containing an absorber plate fused to a heat pipe. The heat is transferred to the transfer fluid (water or an antifreeze mix—typically propylene glycol) of a domestic hot water or hydronic space heating system in a heat exchanger called a "manifold". The manifold is wrapped in insulation and covered by a protective sheet metal or plastic case. The vacuum that surrounds the outside of the tube greatly reduces convection and conduction heat loss, therefore achieving greater efficiency than flat-plate collectors, especially in colder conditions.

The heat requirement from the solar collector is the heat that needs to be supplied to the generator. By considering the Latitude of Goa and the variation of suns position over the year, the average incident solar beam radiation for each month were calculated.

$$I_b = I_{sc}[\cos\Phi.\cos\delta.\cos\omega - \sin\Phi.\sin\delta] \quad (1)$$

Considering an optical efficiency of 0.75 the collector efficiency was calculated for every month. From this we calculated the area of ETC collector required for our objective.

$$\eta_c = \frac{Q_c}{A_c I_{bc}} = \frac{\eta_{opt} - U_{c,e}(T_{in} - T_a)}{A_c I_{bc}} \quad (2)$$

The outlet temperature of the collector was calculated taking into account the mass flow rate and inlet temperature of the collector.

$$Q_c = mC_p(T_{max} - T_{min}) \quad (3)$$

The solar radiation on a horizontal plate collector is given by [13,14].

$$I_0 = I_{sc}(\cos\Phi\cos\delta\cos\omega + \sin\Phi\sin\delta) \quad (4)$$

where I_{sc}= 1367 W/m2

Φ is the latitude location which ranges between -90^0 to 90^0

δ is Sun's declination given by

$$\delta = 23.45[360\,(284 + n)/365] \quad (5)$$

For Goa, Ø = 15^o

For day 10 (n=10) of the year, calculating incident solar radiation at 2pm –

$$\delta = 23.45\,(360(284+n)/365) \quad (6)$$

For n=10, δ = -22.0396

For 2pm, ω = 2*15 = 30

Therefore, I_o was calculated as

$$I_o = 1367\,[\mathrm{Cos}15\ \mathrm{Cos}(-22.0396)\ \mathrm{Cos}30 + \mathrm{Sin}15\ \mathrm{Sin}\,(-22.0396)\,] = 927.6032\ \mathrm{KW/m^2} \quad (7)$$

For a particular month, we take the average of all the values of solar radiation in that month to find Ic. The outlet temperature for different months of a year are tabulated in Table 1.

2.3 Generator

The generator delivers the refrigerant vapour to the rest of the system by separating refrigerant from the solution. In the generator, the solution vertically falls over horizontal tubes with high temperature energy source typically steam or hot water flowing through the tubes [15]. The generator provides sensible heat and latent heat to the weak solution of Li-Br. The sensible heat raises the inlet stream temperature up to the saturation temperature. The heat of Vaporization consists of the heat of vaporization of pure water and the latent heat of mixing of the liquid solution. The solution absorbs heat from the warmer steam or water, causing the refrigerant to boil (vaporize) and separate from the absorbent solution. As the refrigerant is boiled away, the concentration of the absorbent solution becomes more. The concentrated absorbent solution further returns back to the absorber and the refrigerant vapour moves to the condenser. Considering the heat and mass balance across generator, the generator characteristics were found out.

2.4 Condenser

The purpose of condenser is to condense the refrigerant vapours. In the condenser, heat is extracted from refrigerant at constant pressure [15]. The phase of the refrigerant changes from vapor to liquid state and the temperature of the refrigerant changes from 90 to 31^{o}C. As heat transfers from the refrigerant vapor to the water, refrigerant condenses on the tube surfaces. The condensed liquid refrigerant is collected at the bottom of the condenser before proceeding to the expansion device.

2.5 Evaporator

The evaporator containing a bundle of tubes carry the system of circulating water to be cooled. At a lower pressure in the evaporator, the refrigerant gets evaporated by absorbing heat from the circulating water and the refrigerant vapours thus formed tend to increase the pressure in the vessel [15]. With increase in pressure, the boiling temperature increases and the desired cooling effect is not obtained. Therefore the refrigerant vapours are removed from the vessel into the lower pressure absorber. Most commonly the evaporator and absorber are contained inside the same shell, allowing refrigerant vapours generated in the evaporator to move continuously to the absorber. In the evaporator, phase change of refrigerant takes place at a constant pressure of 0.87kPa. In order to facilitate the heating the evaporator extracts heat from the space or substance to be cooled.

Table 1 : The outlet temperature for different months of a year

	Q_{solar}	η	T_{amb}	Uc	ηc	Ic	A	m	T_{in}	T_{out}
Jan	11.955	0.75	30	1.6	0.733548	486.256	33.5164	0.04	35	106.501
Feb	11.955	0.75	30	1.6	0.73513	538.010	30.2271	0.04	35	106.501
Mar	11.955	0.75	30	1.6	0.73541	548.336	29.6465	0.04	35	106.501
Apr	11.955	0.75	30	1.6	0.735398	547.857	29.6730	0.04	35	106.501
May	11.955	0.75	30	1.6	0.735843	565.072	28.7516	0.04	35	106.501
Jun	11.955	0.75	30	1.6	0.735919	568.154	28.5927	0.04	35	106.501
Jul	11.955	0.75	30	1.6	0.735898	567.293	28.6369	0.04	35	106.501
Aug	11.955	0.75	30	1.6	0.735659	557.840	29.1316	0.04	35	106.501
Sep	11.955	0.75	30	1.6	0.73595	569.407	28.5285	0.04	35	106.501
Oct	11.955	0.75	30	1.6	0.735905	567.581	28.6221	0.04	35	106.501
Nov	11.955	0.75	30	1.6	0.734181	505.736	32.1976	0.04	35	106.501
Dec	11.955	0.75	30	1.6	0.73297	469.752	34.7213	0.04	35	106.501

2.6 Absorber

Inside the absorber of a vapour absorption system, the refrigerant vapour is absorbed by the solution. As the refrigerant vapour is absorbed, it condenses from a vapour to a liquid so that the heat it acquired in the evaporator is being released. The cooling water circulating through the absorber tube bundle carries away the heat released from the condensation of refrigerant vapours by their absorption in the solution. The weak absorbent solution is further pumped to the generator to drive off the refrigerant by supply of heat [15]. The refrigerant vapours formed in the generator migrate to the condenser. In the absorber strong solution of Li-Br absorbs the vapors from the evaporator turning it into a weak solution. The cooling water flows through the absorber in order to extract heat from it.

3. Results and Discussion

The vapour absorption cycle considered in this analysis is presented in Figure 1. The properties at various locations of the cycle were determined taking into account the state of the refrigerant. The various properties at the different locations are listed in Table 2. The pressure was limited by the saturation temperature that was obtained by cooling in condenser and the evaporator temperature. The design in this work is based on evaporator which can cool up to 5^{o}C. Thus the lower pressure and higher pressure in the system was designed to be 0.087 kPa and 4.5 kPa. The absorber temperature and generator temperature were varied to their effect on Coefficient of Performance (COP). The major outcome of this work is the investigation of the variation of COP of the system corresponding to variation in absorber and generator temperature.

Table 2: The properties at different locations

Point	Enthalpy (KJ/Kg)	m (Kg/s)	Pressure (kPa)	T (^{o}C)	% LiBr	Remarks
1	2679	0.003348	4.5	90	0	Superheated steam
2	129.93	0.003348	4.5	31	0	Saturated liquid
3	129.93	0.003348	0.87	5	0	
4	2519	0.003348	0.87	5	0	Saturated vapour
5	106.8	0.024924	0.87	40	0.58	
6	107.54	0.024924	4.5	40	0.58	
7	137.4	0.024924	4.5	58	0.58	
8	246	0.021576	4.5	90	0.67	
9	193.8	0.021576	4.5	62	0.67	
10	176.4	0.021576	4.5	50	0.67	

The variation of COP with respect to absorber temperature within a range of 35°C to 55°C for three different values of generator temperature is presented in Figure 2. Similarly the variation of COP with respect to generator temperature for four different values of absorber temperature is presented in Figure 3. The general trend from these figures indicates that the COP decreases as absorber temperature decreases. This can be attributed to the fact that the concentration of most of the solution, falls as temperature increases which satisfies the Raoult's law [16]. The more is the concentration of weak solution the more is the refrigerant evaporated giving more cooling thus more COP. But the nature of curve also tells another story. The COP attains a maximum. Going by these curves one can predict that after certain temperature of absorber the COP won't show considerable increase. In this work the absorber temperature is focused within a range of 35°C to 40°C which is determined by hit and trial method. The optimum point lies close to 40°C. The Figure 3 showing relation between COP and generator temperature clearly shows that the COP attains a maximum after the optimum point, after which there is no considerable increase in COP. The point lies close to 90°C. Clearly the absorber temperature being close to 40°C and simultaneously generator temperature being close to 90°C may give a maximum value of COP. A further increase in generator temperature and decrease in absorber temperature won't increase the COP considerably.

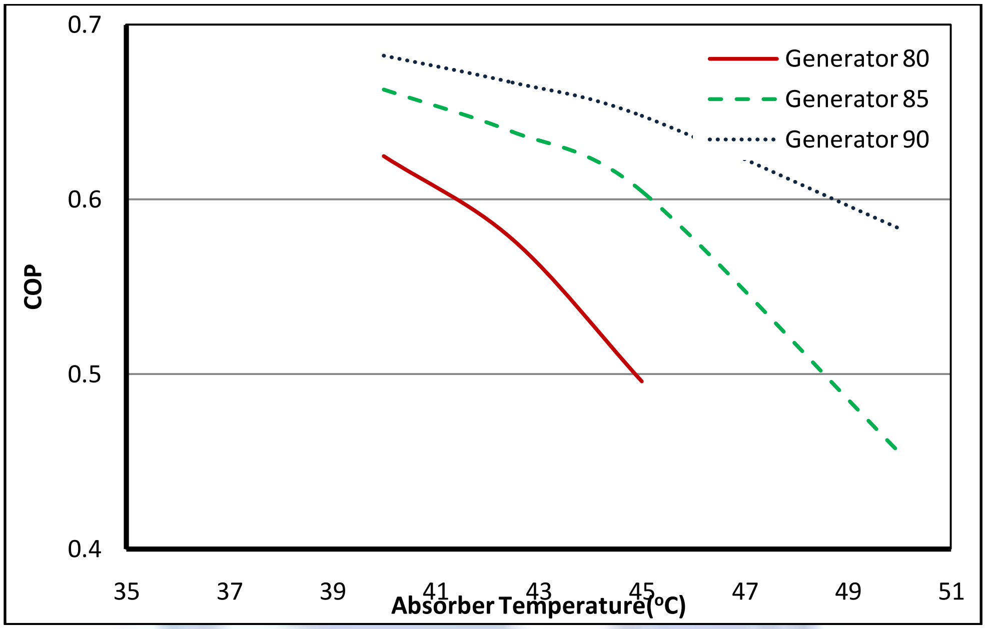

Figure 2 - The variation of COP with respect to absorber temperature

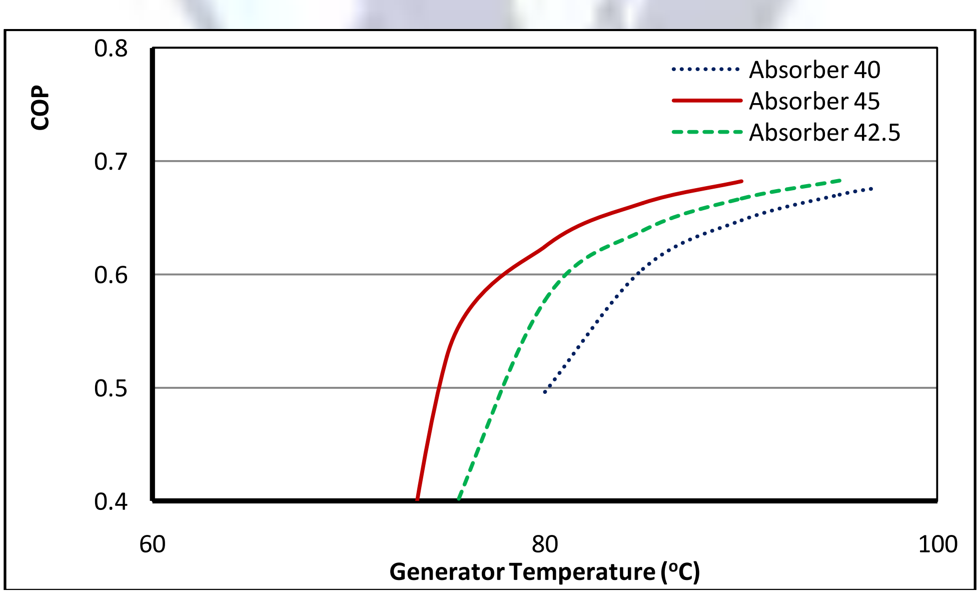

Figure 3 - The variation of COP with respect to generator temperature

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The figure 4 shows the variation between the difference in concentration of weak and strong solutions and their effect on COP. Unlike the traditional view it was found that after a particular difference in the concentrations of weak and strong solutions, the COP remained fairly constant giving the impression that there is not much improvement in COP even though we increase the concentration difference between the weak and strong solutions. The plot also shows that higher generator temperature requires high concentration difference between the concentrations to attain higher COP. The optimum difference lies within a range between 0.07 to 0.09. When the concentration ratio was plotted with respect to the generator and absorber temperature it was found to vary almost linearly. This can be correlated to Raoult's law [16]. The curve may seem linear because of short domain of consideration.

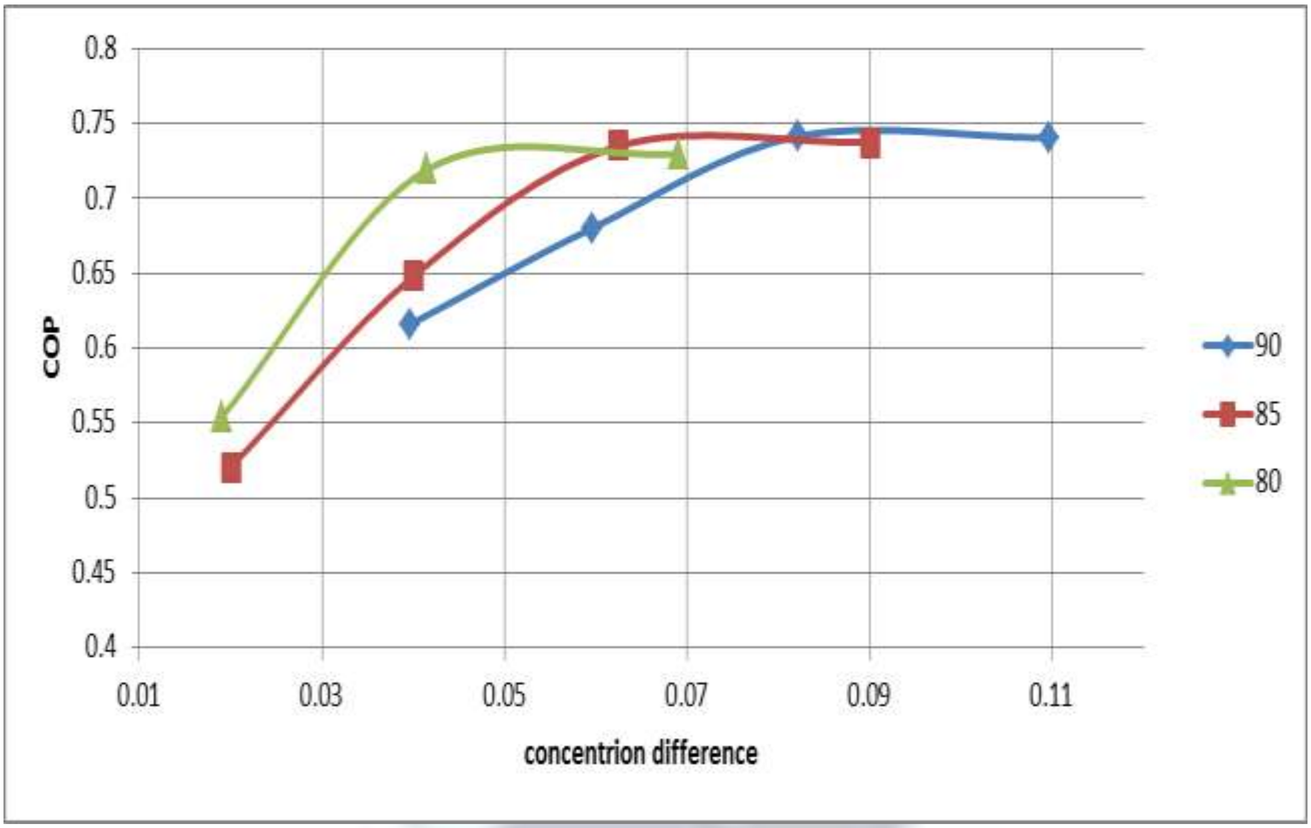

Figure 4 - The variation of concentration difference with respect to COP

The variation of concentration difference with generator temperature and absorber temperature are illustrated in Figures 5 and 6. As observed in Figure 5, within a same range of absorber temperature within 40°C to 55°C, the concentration difference increases with generator temperature. The variation of concentration difference is almost linear with generator temperature and the concentration difference increases by 0.02 for increase in generator temperature by 5°C. Similarly a linear increase in concentration difference is observed with generator temperature for a particular value of absorber temperature. Similarly the heat given out during absorber was analyzed and it was found that the less is the absorber temp the more is the heat given out. For a specific value of absorber temperature, the heat absorbed in the absorber does not have much variation with generator temperature. The generator temperature has hardly any impact on the heat given out in the absorber. However the heat absorbed in the absorber decreases with absorber temperature. It remains almost invariable within absorber temperature of 45°C to 50°C while beyond that it decreases more steeply.

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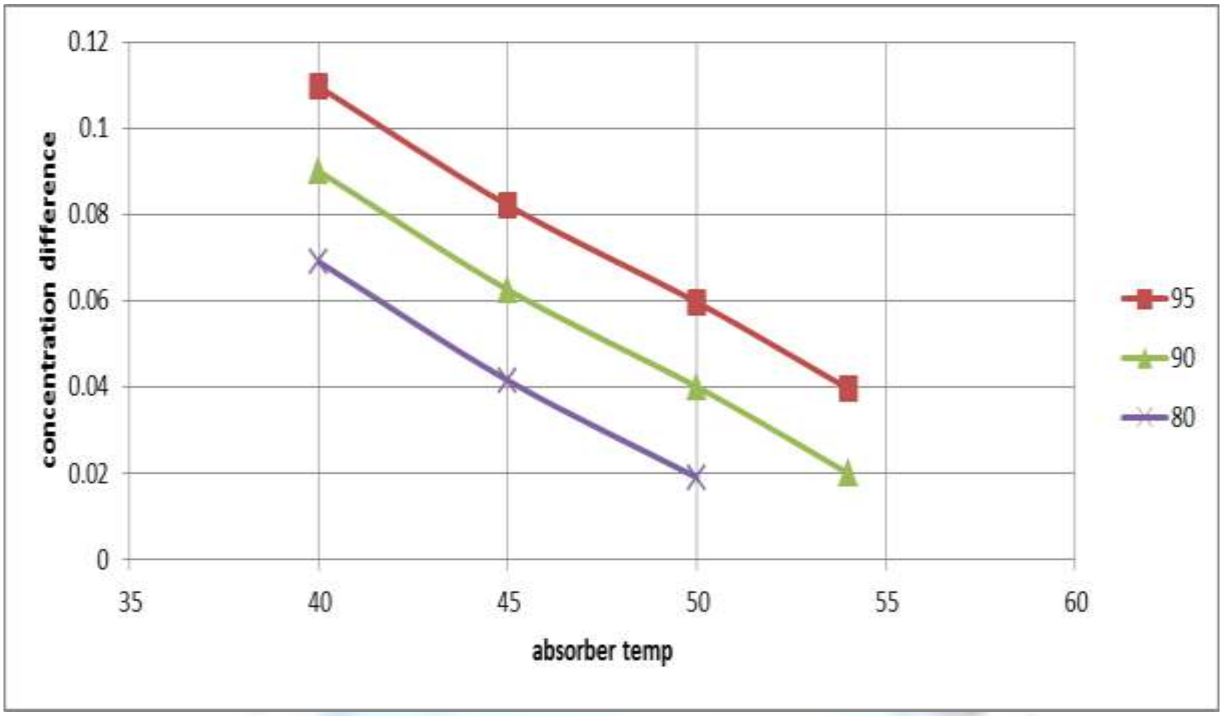

Figure 5 – The variation of concentration difference with generator temperature

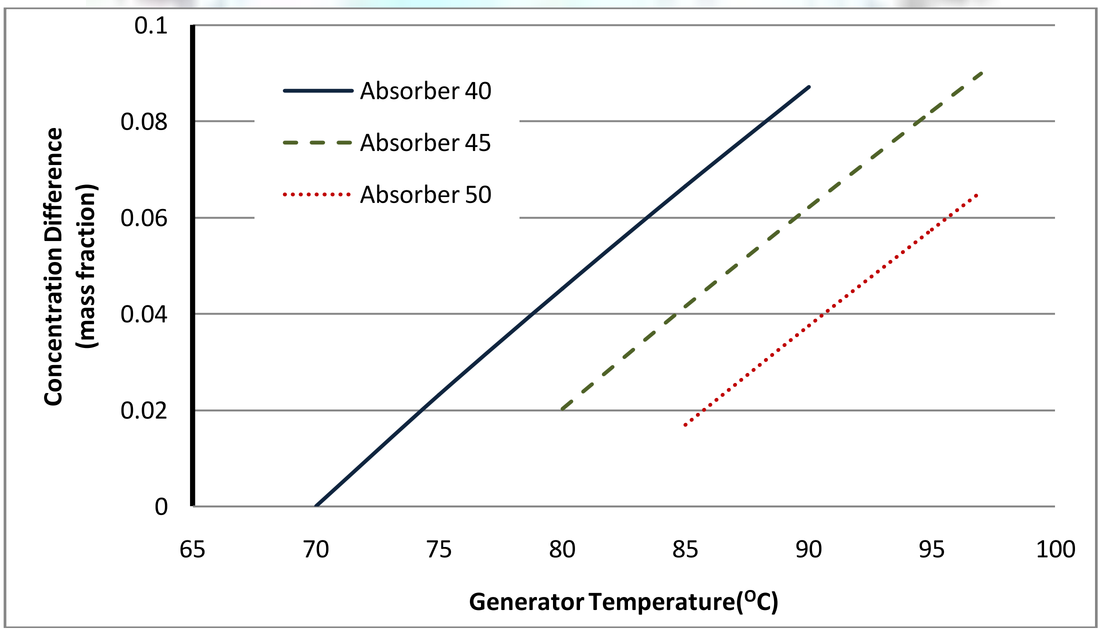

Figure 6 – The variation of concentration difference with absorber temperature

More over to test the accuracy of the interpolation code used for this analysis, the error analysis was carried out. The error is computed as

$$\text{Error} = Q_g + Q_e - Q_c - Q_a \qquad (8)$$

where, (heat absorbed in Generator is Q_g, heat taken out by evaporator is Q_e, heat given out in condenser is Q_c and the heat given out by absorber is Q_a. It was found that the error is low for low absorber temperature and high generator temperature. The error was found to increase with absorber temperature while it decreases with the generator temperature. The variation of error with absorber temperature for different magnitudes of generator temperature is presented in Figure 7. The minimal error was observed to be at absorber temperature of 40^{o}C and generator temperature of around 90^{o}C.

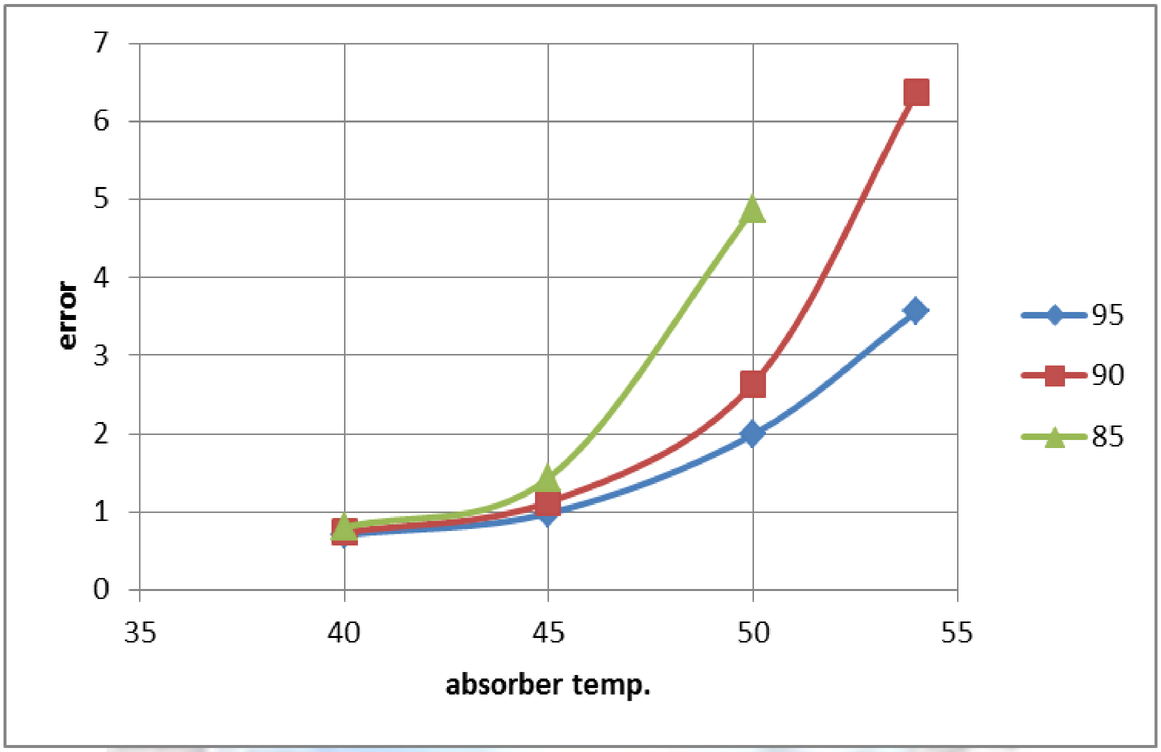

Figure 7 –The variation of error with absorber temperature

Conclusion

The temperatures, pressures and concentration ratio at different points were calculated. Further the generation and absorber temperature were varied to determine the optimum temperatures. The generation, solution, condenser and evaporation heat exchangers were designed. The solar collector area required to power such a vapor absorption system was also calculated. It was found that the least error was obtained at absorber temperature of 40^{o}C and generator temperature of 90^{o}C. Thus the results indicate that a suitable solar vapour absorption refrigeration system can be designed keeping in view the climatic condition of a particular location. Keeping in view the climatic conditions of temperature, the methodology described in this work can be adopted to design and develop a suitable system that can be most effectively and efficiently used maximum utilization of the solar power.

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