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THERMAL ENERGY ANALYSIS OF SOLAR POWERED VAPOUR ABSORPTION COOLING SYSTEM

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ABSTRACT

Solar energy is one of the most efficient, clean and affordable energy alternatives available today. With the current concerns about global warming and ever increasing energy rates, countries are seriously looking for domestic and industrial usage of solar energy. The aim of this work was to evaluate the performance of a 5 kW LiBr-H_2O vapour absorption cooling system driven by 147 m^2 heat pipe evacuated tube collectors, by analyzing the COP. The results from this study showed that actual average COP of the system was 0.49 while the maximum and minimum values were 0.84 and 0.20 respectively. The rate of thermal energy supplied at generator ranged from 30.03 to 59.92 kW, 31.01 to 60.69 kW, 40.99 to 70.91 kW, 35.14 to 57.34 kW, 42.4 to 51.75 kW and 42.80 to 66.19 kW during the months of October, November, December- 2014 and January, February and March- 2015. The refrigerating effect produced by SVAR system in different month ranged 10.9 to 17.86 kW, 11.19 to 22.31 kW, 13.41 to 27.05 kW, 17.89 to 27.88 kW, 17.62 to 33.53 kW and 22.96 to 38.12 kW in respective months. The values of heat rejection rate at condenser ranged from 33.18 to 62.47 kW, 48.28 to 73.79 kW, 59.26 to 93.68 kW, 54.61 to 78.59 kW, 62.30 to 70.94 kW and 71.57 to 93.36 kW during six months of study. These results were obtained based on the average solar collector's efficiency at an ambient temperature of 32 °C.

KEYWORDS: Thermal Energy, Refrigeration Effect, Heat Supplied at Generator, Heat Rejected at Condenser, Vapour Absorption Cooling

INTRODUCTION

The energy shortage and fast increasing energy consumption, there is a need to minimize the use of energy and conserve it in all possible ways. Energy conservation is becoming a slogan of the present decade and new methods to save energy, otherwise being wasted, are being explored. Recovering energy from waste heat and/or utilizing it for system efficiency improvement is fast becoming a common scientific temper and industrial practice now days. The present energy crisis has forced the scientists and engineers all over the world to adopt energy conservation measures in various industries. Reduction of the electric power and thermal energy consumption are not only desirable but unavoidable in view of fast and competitive industrial growth throughout the world. Refrigeration systems form a vital component for the industrial growth and affect the energy problems of the country at large. Therefore, it is desirable to provide a base for energy conservation and energy recovery from vapour absorption cooling system. Although, the investigations undertaken in this work are of applied research nature but certainly can create a base for further R & D activities in the direction of energy conservation and heat recovery options for refrigeration systems and the analysis can be extended further to other refrigeration and air conditioning systems. In recent years, research has been devoted to improvement of vapour absorption refrigeration systems (VARS). Mechanical vapour compression refrigeration requires high grade energy for their operation. Apart from this, recent studies have shown that the conventional working fluids of vapour compression system are causing ozone layer depletion and green house effects.

However, VARS is harmless, inexpensive and waste heat/ solar/ biomass or geothermal energy sources for which the cost of supply is negligible in many cases. Moreover, the working fluids of these systems are envoi mentally friendly (Bennani *et al.,* 1989; Bourseau and Bugarel, 1986; Butz and Stephan, 1989). The overall performance of the VARS in terms of refrigerating effect per unit of energy input generally poor, however, solar heat available from a sun can be used to achieve better overall energy utilization. Ammonia/water (NH_3/H_20) systems are widely used where lower temperature is required. However, lithium bromide/ water ($LiBr/H_20$) system are also widely used where moderate temperatures are required, and the latter system is more efficient than the former (Eisa and Holland, 1986; Sun, 1997; Xu and YQ, 1997). In the present investigation LiBr-water single effect vapour absorption cooling system was operated using heat pipe evacuated collectors.

The objective of this paper is to evaluate thermodynamic analysis and tabulated also heat transfer rate in each components are calculated and tabulated with the help of heat and mass transfer relation. Mass flow rate and heat rate in each components of the system are evaluated and tabulated.

DESCRIPTION OF SOLAR COOLING SYSTEM

The solar cooling system which was studied is LiBr - H_2O absorption system having rated installed capacity of 5 TR (17.5 kW) installed at Department of Post-Harvest Engineering and Technology, College of Food Processing Technology and Bio energy, Anand was used for the study. The basic energy flows of a solar-powered vapour absorption cooling system are shown schematically in Figure 1. The experimental LiBr-water cooling system is consisted of four main parts generator, condenser, absorber and evaporator. Start with, heat pipe evacuated tube solar collector converted solar energy to thermal energy (hot water) and accumulated in the hot water storage tank. The hot water is supplied to the generator by electricity pump to boil off water vapor from a solution of LiBr-H2O. At the condenser, water vapor is cooled down and then passed to the evaporator wherein it again gets evaporated at low pressure, thereby providing cooling to the cold rooms to be cooled. This system employs an evaluated heat pipe solar collector (HP-ETC) of area 147 m^2, a hot water and a cold water storage tank, a 15 kW cooling tower and a 17.5 kW nominal cooling capacity LiBr-H_2O absorption chiller. There are generating the water flow rate via the components of the external circuits as follow; the water flow rate value via the HP-ETC and hot storage tank are set at, 5500 and 6000 lit per hour (LPH), while the flow rate in the cooling tower and the fan coils are 8500 LPH, respectively.

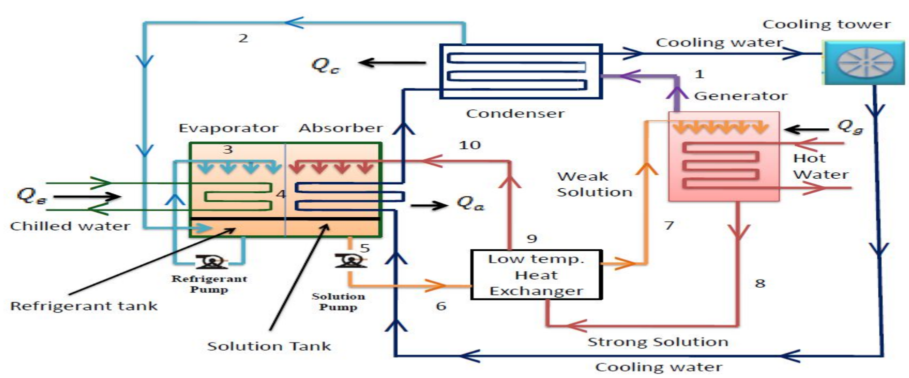

Figure 1: Schematic Diagram of Solar Heat Assisted Single Effect LiBr-Water VAR System

METHODOLOGY AND THERMAL ENERGY ANALYSIS OF VAPOUR ABSORPTION COOLING SYSTEM

In the present solar absorption cooling system, the rate of energy balance at evaporator, condenser, generator, and absorber is estimated by using standard heat and mass transfer equations. The rate of energy balance at evaporator, condenser, generator, and absorber is calculated as under.

The analysis of the system is carried out assuming negligible changes in potential and kinetic energies across each component and no pressure drops due to friction. The schematic diagram of various components of solar heat assisted single effect LiBr-water vapour absorption refrigeration system indicating points of energy input and output is shown in Figure. 1. The trials were conducted in the month of October, November, December- 2014 and January, February and March- 2015, for evaluation of thermal performance of solar cooling system.

The main parameters that define the performance of solar cooling system can be determined by applying the first and the second law of thermodynamics, with refer to Figure 1. The heat balance can be established (Soraya *et al.,* 2007).

$QA + QC = QG + QE$

The mass flow rates of refrigerant and LiBr solution are given below.

m = mass flow rate of refrigerant, kg/s = $\frac{Qe}{h4-h3} = \frac{17.5}{2512.6-210} = 0.0076$

m_{SS} = mass flow rate of strong solution (rich in LiBr), kg/s

$= \lambda m = 11 \times 0.076 = 0.0083$ kg/s

m_{WS} = mass flow rate of weak solution (weak in LiBr), kg/s =

$= (\lambda+1)\ m = 12 \times 0.076 = 0.0091$ kg/s

The circulation ratio (λ) is defined as the ratio of strong solution flow rate to refrigerant flow rate. It is given by:

$\lambda = m_{SS}/m = \xi_{WS}/ (\xi_{SS}-\xi_{WS}) = \frac{55}{60-55} = 11$

ξ_{WS} = mass fraction of weak solution

ξ_{SS} = mass fraction of strong solution

Table 1: Temperature, Pressure, Mass Fraction and Enthalpy of LiBr-Water at Various State Points

State Point	Temperature at Various State Point	Temperature (°c)	Mass Fraction	Enthalpy (kJ/kg)
1	Vapor temperature	90	-	2660.1
2	Condensing temperature	40	-	167.5
3	Liquid refrigerant	6	-	210
4	Vapor refrigerant	6	-	2512.6
5	Weak LiBr	40	0.5587	-150
6	Weak refrigerant	40	0.5587	-150
7	LiBr-$H_2$0 Con. after LTHE	60	0.5587	-110
8	Generator temperature	90	0.60	-60

Table 1: Contd.,				
9	Outlet temp. Of LTHE	40	0.60	-140
10	Strong solution (LiBr-H_20)	40	0.60	-140

Where,

h_1= Enthalpy of superheated water vapors before entering to condenser

h_2 = Enthalpy of water after living to condenser

h_3 = Enthalpy of water refrigerant to entering the evaporator

h_4 = Enthalpy of vapour refrigerant in evaporator

h_5= Enthalpy of weak refrigerant (LiBr-water) mixture at after evaporator

h_6 = Enthalpy of weak refrigerant at outlet of pump

h_7 = Enthalpy of weak solution at the exit of solution LTHE

h_8 = Enthalpy of strong solution at the exit of generator

h_9 = Enthalpy at outlet temperature of heat exchanger

h_{10}= Enthalpy of strong solution (H2O- LiBr) mixture spray to absorber

λ = Circulation ratio

m = mass flow rate of refrigerant (kg/s)

ξ_{WS} = mass fraction of weak solution

ξ_{SS} = mass fraction of strong solution

m_{SS} = mass flow rate of strong solution (kg/s)

m_{WS}= mass flow rate of weak solution (kg/s)

Thermal Energy Analysis of Evaporator

In the SVAR system operation, the evaporator's energy analysis is carried out by applying mass and energy balance equation.

$\therefore$ Qe = $m(h4 - h3)$

= 0.0076 (kg/s) $\times$ (2660.1 – 167.5 kJ/kg)

= 18.94 kW

Thermal Energy Analysis of Condenser

Condenser is a heat exchanger where the refrigerant rejects the heat to a cooling medium and it becomes liquid refrigerant. The condenser energy analysis is carried out by applying mass and energy balance equation.

$\therefore m_1 = m_2 = m$

$\therefore Q_c = m\,(h_1 - h_2)$

= 0.0076 (kg/h) × (2512.6- 210 kJ/kg)

= 17.49 kW

Thermal Energy Analysis of Absorber

Absorber is a component of SVAR system where water vapour is absorbed into strong solution of LiBr. The absorber energy analysis is carried out by applying mass and energy balance equation.

∴For total mass balance

$\therefore m + m_{ss} = m_{ws}$

$\therefore m + \lambda_m = m_{ws}\ (m_{ss}/m = \lambda)$

Mass balance of pure water

$\therefore m + (1 - \xi_{ss})\, m_{ss} = (1 - \xi_{ws})\, m_{ws}$

$\therefore \lambda = \frac{\xi_{ws}}{\xi_{ss} - \xi_{ws}}$

$\therefore Q_a = mh_4 + \lambda m h_{10} - (1+\lambda) m h_5$

$\therefore Q_a = \text{m}\ \{(h_4 - h_5) + \lambda\,(h_{10} - h_5)\}$

= 0.0076 {(2512.6+150) +11 (-140+150)}

= 0.0076 {(2662.6 +110)}

= 0.0076 × 2772.6 = **21.07 kW**

Thermal Energy Analysis of Generator

The purpose of the generator is to deliver the refrigerant vapour to the rest of the system. It accomplishes this by separating refrigerant from the solution. The generator energy analysis is carried out by applying mass and energy balance equation.

$\therefore m_7 = m_8 + m_1$

∴Heat input to the generator is given by

$\therefore Q_g = mh_1 + \lambda m h_8 - (1+\lambda) m h_7$

$\therefore Q_g = \text{m}\ \{(h_1 - h_7) + \lambda\,(h_8 - h_7)\}$

= 0.076 {(2660.1 + 110) + 11 (-60 + 110)}

= 0.076 {(2770.1 + 550)}

= 25.23 kW

Thermal Energy Analysis of Low Temperature Heat Exchanger

Efficiency of heat exchanger is a play major role to increase the performance of the SVAR system. Using of solution heat exchanger the temperature of cold fluid increases before entering to the generator, so there is less heat input required in the generator for rejection of heat from diluted LiBr solution and hence COP of system is increases.

∴$Q_{LTHE} = (1+\lambda)m(h_7 - h_6) = \lambda m(h_8 - h_9)$

= 11 × 0.076 (-60 + 140)

= 6.68 kW

Thermal Performance of HP-ETC

Heat supplied by the HP-ETC is presented by (Rittidech and Wannapakne, 2007; Kim, 2012).

∴ Solar collector efficiency (η) $= \frac{Q_W}{A_C G_T} = \frac{m_w C_{pw} \ (T_{ow} - T_{iw})}{A_C G_T}$

Where,

A_c= Solar collecting area (m^2)

G_T= Solar radiation (W/m^2)

Q_W = Quantity of heat transferred to the water in the tank (kg/h)

m_w = Water flow rate (kg/h)

C_{pw}= Specific heat of water (kJ/kg. K)

T_{ow} = Water outlet temperature (°C)

T_{iw} = Water inlet temperature (°C)

For Example, the value of parameters for a particular day and its calculations is given as under.

∴ Solar collector efficiency (η) $= \frac{m_w C_{pw} \ (T_{ow} - T_{iw})}{A_C G_T}$

$= \frac{5481.83 \text{ (LPH)} * 4.186 \text{ (kJ/kgk)} * (99.04 - 88.37 \ ^{\circ}\text{C}) * 1000}{961.27 \text{ (W/m2)} * 88.14 \text{ (m2)} * 3600}$

= 80.25

Thermal Performance of Solar Cooling System

The thermal performance of solar vapour absorption cooling system is expressed in terms of co-efficient of performance (COP).The COP of the absorption chiller can be written as below (Khurmi and Gupta, 2011; Domkundvar and Arora, 2011).

$$COP_{act} \therefore \frac{Q_e}{Q_g} = \frac{18.94\ kW}{25.23\ kW} = 0.74$$

EXPERIMENTAL RESULTS

Intensity of Solar Radiation

Figure 2 illustrates the variation of the average daily solar irradiation that strikes on the HP-ETC surface by the season and time. It could receive a maximum solar irradiation at 13:30 in summer of about 961 W/m^2 in the month of March- 2015 during the experimental study period. The minimum value during experimental trials appears at 17:00

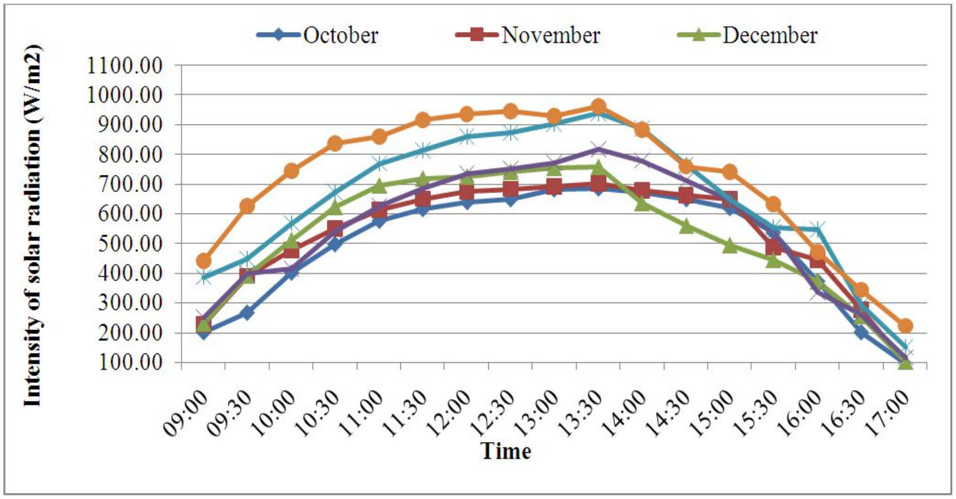

Figure 2: Month Wise Average Solar Radiation on Surface of HP-ETC

Efficiency of a Heat Pipe Evacuated Tube Solar Collectors (HP-ETC)

The heat transfer takes place from the collectors to the water. There is a primary cause of feeding energy through the chiller that measurement in term of solar collector efficiency. Figure 3 demonstrates that the increase of efficiency depends on the solar radiation; thus the energy gains of a solar thermal collector will be increased more than proportional to the solar radiation. The highest value of efficiency of HP-ETC obtained during experimental months was 80.25 % in the month of March, 2015.

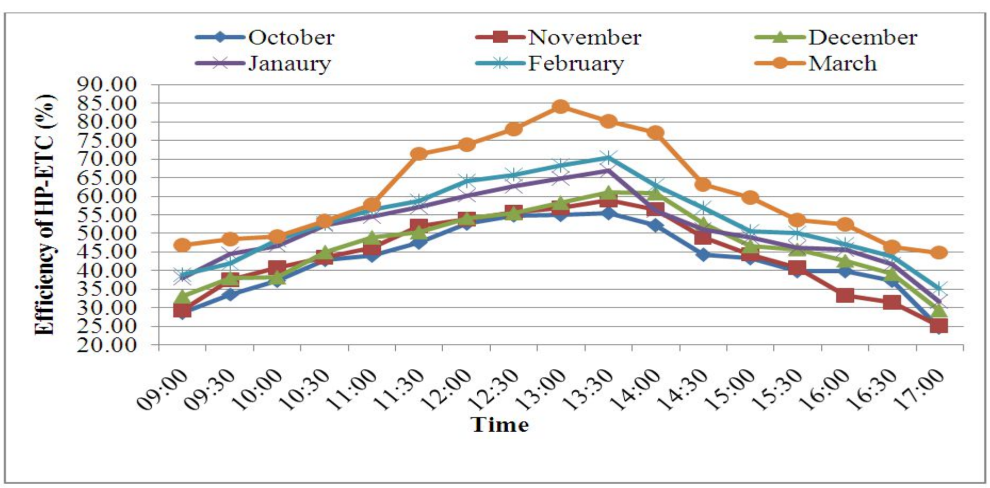

Figure 3: Month Wise Average Efficiency of HP-ETC

Actual COP of Solar Cooling System

The effect of month of operation and time on actual COP obtained is shown in Table 1. The statistical analysis revealed that there is significant effect of month of operation and operating time on actual COP of the plant. The interaction effect of operating time and month was also significant. The highest value of actual COP obtained during the experimental months was 0.84 (M_6T_9) in the month of March, 2015. The month wise actual COP of solar cooling system is depicted in Figure 4

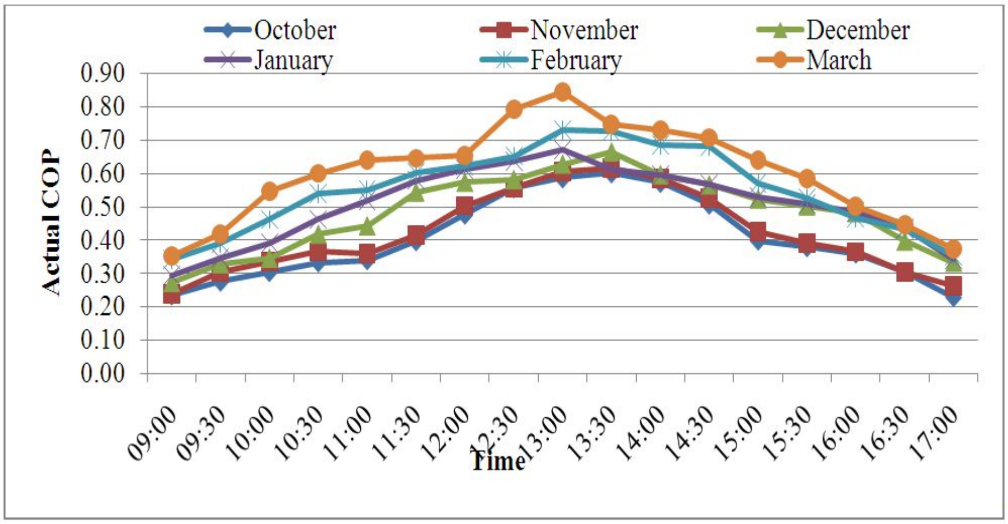

Figure 4: Month Wise Actual COP of SVAR System

Table 1: Effect of Operating Month and Time on Actual COP of Solar Vapour Absorption Cooling System

MT Mean Table for Actual COP																		
	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17	M
M_1	0.23	0.27	0.30	0.33	0.34	0.40	0.48	0.55	0.58	0.60	0.57	0.51	0.40	0.38	0.36	0.30	0.23	0.40
M_2	0.24	0.30	0.34	0.36	0.36	0.42	0.50	0.56	0.61	0.62	0.58	0.53	0.42	0.39	0.36	0.30	0.26	0.42
M_3	0.27	0.33	0.35	0.42	0.44	0.54	0.57	0.58	0.63	0.66	0.60	0.57	0.52	0.50	0.48	0.40	0.33	0.48
M_4	0.29	0.35	0.39	0.46	0.52	0.58	0.61	0.64	0.67	0.61	0.60	0.57	0.53	0.51	0.48	0.43	0.34	0.50
M_5	0.34	0.39	0.46	0.54	0.55	0.60	0.62	0.65	0.73	0.72	0.68	0.68	0.57	0.52	0.47	0.43	0.35	0.54
M_6	0.35	0.42	0.55	0.60	0.64	0.64	0.65	0.79	0.84	0.74	0.73	0.71	0.64	0.58	0.50	0.45	0.37	0.60
T	0.28	0.34	0.39	0.45	0.47	0.53	0.57	0.62	0.67	0.65	0.62	0.59	0.51	0.48	0.44	0.38	0.31	0.49

Treatment	SEm	CD	Test
Month (M)	0.01	0.02	*
Time (T)	0.01	0.03	*
Month (M) * Time (T)	0.03	0.08	*
CV %= 10.59			

$M_{1=}$ October, $M_{2=}$ November, M_3= December, M_4= January, $M_{5=}$ February and $M_{6=}$ March

T_1=9:00, T_2=9:30……………T_{17}=17:00

RATE OF THERMAL ENERGY INPUT AND OUTPUT OF MAJOR COMPONENTS OF SOLAR VAPOUR ABSORPTION COOLING SYSTEM

Energy analysis is the most important decisive to generate information for proper balancing of various components of solar cooling system for better performance of the plant. Thermal energy analysis at condenser, absorber, generator, and evaporator is a complex phenomenon, which is influenced by several factors such as properties of refrigerant and absorbent, processing load of chilled water, environmental conditions, as well as operating variables of the solar cooling system. In the present investigation, the energy analysis of evaporator, generator, absorber, and condenser was carried out under the various operating conditions of system. The cooling load as well as rate of heat transfer greatly influences the energy balance of condenser, evaporator, and generator.

The energy analysis of the solar cooling system involves heat and mass transfer operations in various components of the system. The refrigerating effect produced and generator work are the energy input while heat rejected at the condenser is the heat output of the system. Rate of thermal energy input and output of major components of solar vapour absorption cooling system is depicted in Fig. 5, 6, 7, 8, 9 and 10 for the months of October, November, December- 2014 and January, February and March- 2015.

Generator Work

Thermal energy is required at the generator to liberate refrigerant (water) from the strong LiBr-water mixture. The thermal energy supplied to the generator ranged from 30.03 to 59.92 kW, 31.01 to 60.69 kW, 40.99 to 70.91 kW, 35.14 to 57.34 kW, 42.4 to 51.75 kW and 42.80 to 66.19 kW for the months of October, November, December- 2014 and January, February and March- 2015 respectively depending on the rate of chilling effect produced and the temperature of hot water used at generator. The thermal energy supplied to generator is in form of hot water generated by using the solar collectors and hence, there is no any cost incurred for the generator work.

Refrigerating Effect Produced

It was noticed that the inlet-temperature of chilled water did not remain constant during operation of the system as it depends on the cooling load in the cold storage. The outlet chilled water temperature ranged from 6.9 to 16.3 °C, 6.39 to 15.11 °C, 6.3 to 15.50 °C, 6.15 to 16.74 °C, 5.37 to 17.00 °C and 5.76 to 19.84 °C in the month of October, November, December- 2014 and January, February and March-2015 respectively.

The refrigerating effect produced by solar cooling system in different month ranged from 10.9 to 17.86 kW, 11.19 to 22.31 kW, 13.41 to 27.05 kW, 17.89 to 27.88 kW, 17.62 to 33.53 kW and 22.96 to 38.12 kW in the month of October, November, December- 2014 and January, February and March- 2015 respectively.

The variation in refrigerating effect is mainly due to the multi parametric effects such as inlet temperature of water, generator temperature and condensing temperature. It was not possible to keep these parameters constant during the operation of the system.

Condenser Load

The condenser load is dependents on the values of condensing temperature. The values of heat rejection rate at condenser ranged from 33.18 to 62.47 kW, 48.28 to 73.79 kW, 59.26 to 93.68 kW, 54.61 to 78.59 kW, 62.30 to 70.94 kW and 71.57 to 93.36 kW for month of October, November, December- 2014 and January, February and March-2015respectively. It is found that when the condensing load increased, the refrigeration effect produced by system is also increased. It is obvious the condenser absorb more heat from the refrigerant (water).

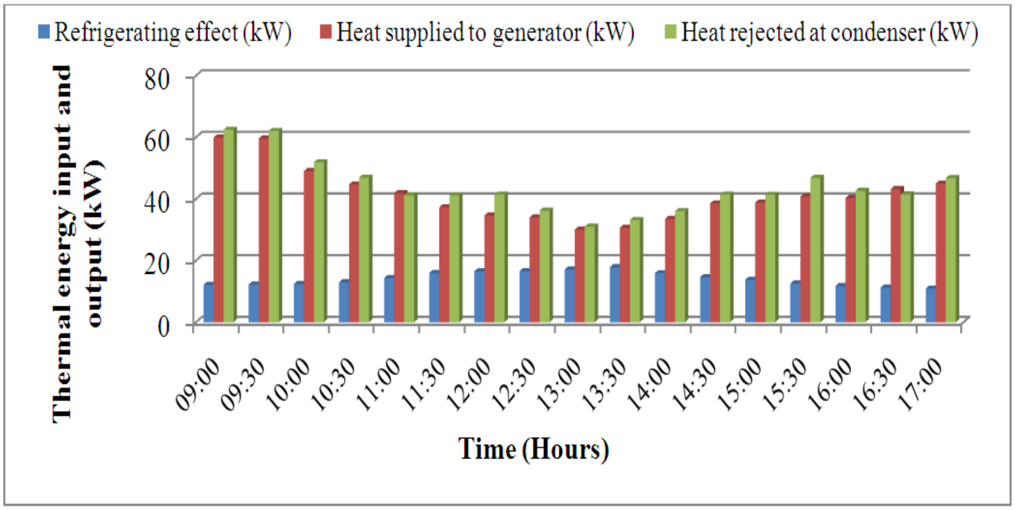

Figure 5: Rate of Thermal Energy Input and Output of Major Componenets of SVAR System in the Month of October, 2014

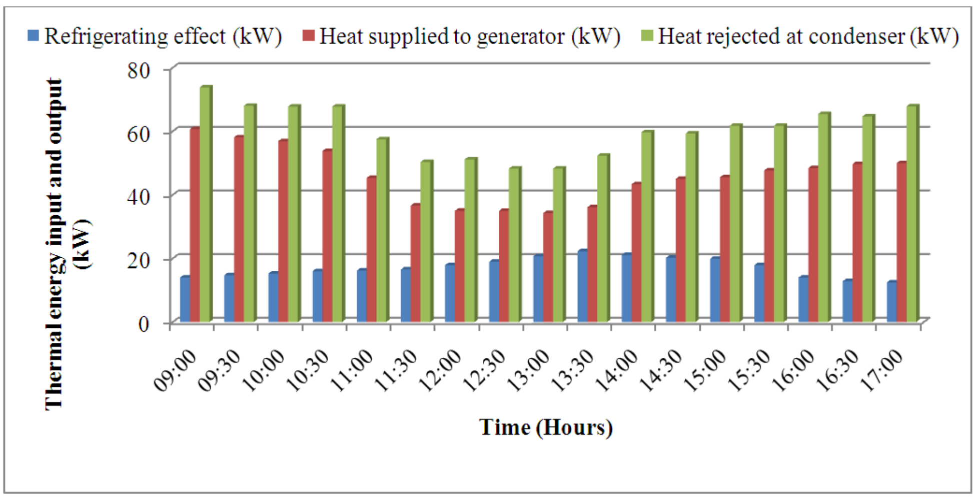

Figure 6: Rate of Thermal Energy Input and Output of Major Componenets of SVAR System in the Month of November, 2014

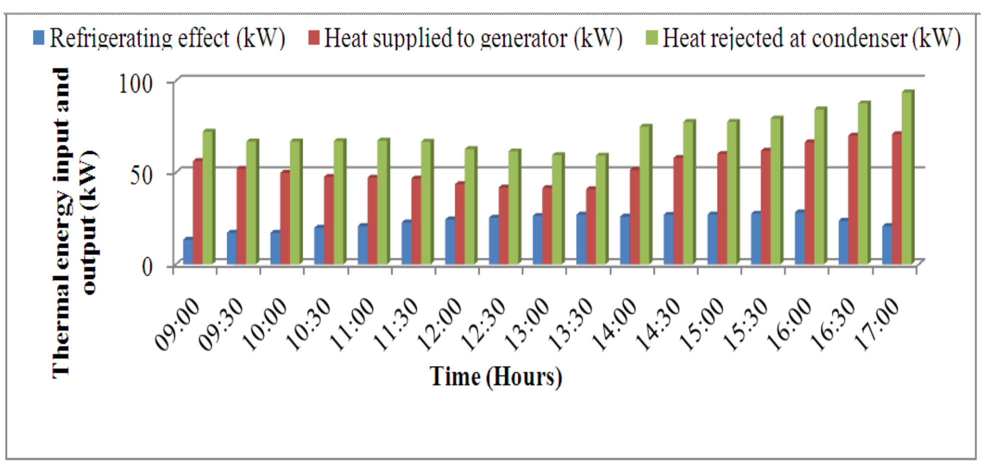

Figure 7: Rate of Thermal Energy Input and Output of Major Componenets of SVAR System in the Month of December, 2014

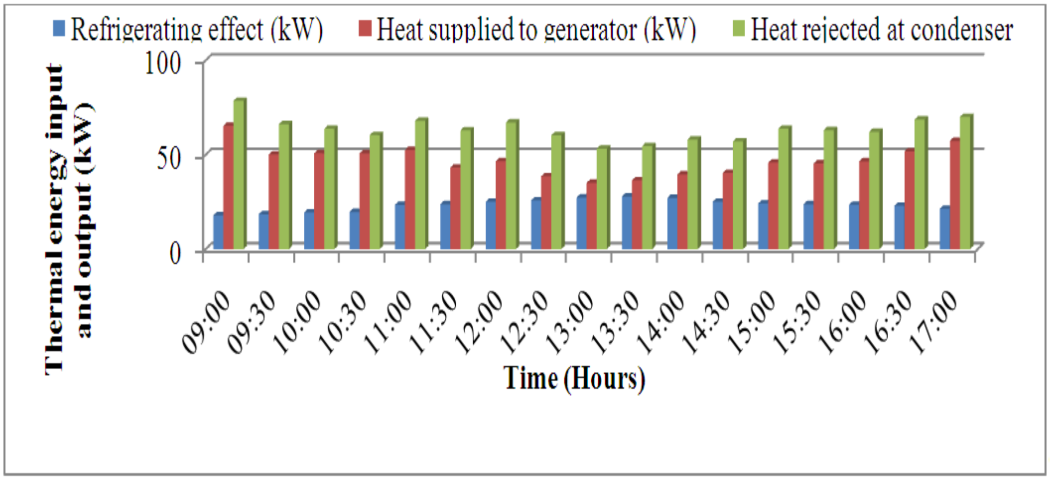

Figure 8: Rate of Thermal Energy Input and Output of Major Componenets of SVAR System in the Month of January, 2015

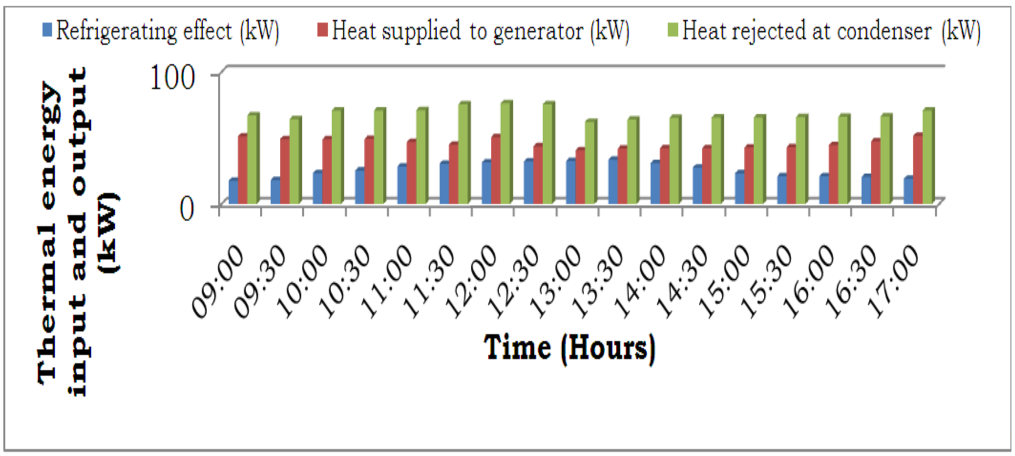

Figure 9: Rate of Thermal Energy Input and Output of Major Componenets of SVAR System in the Month of February, 2015

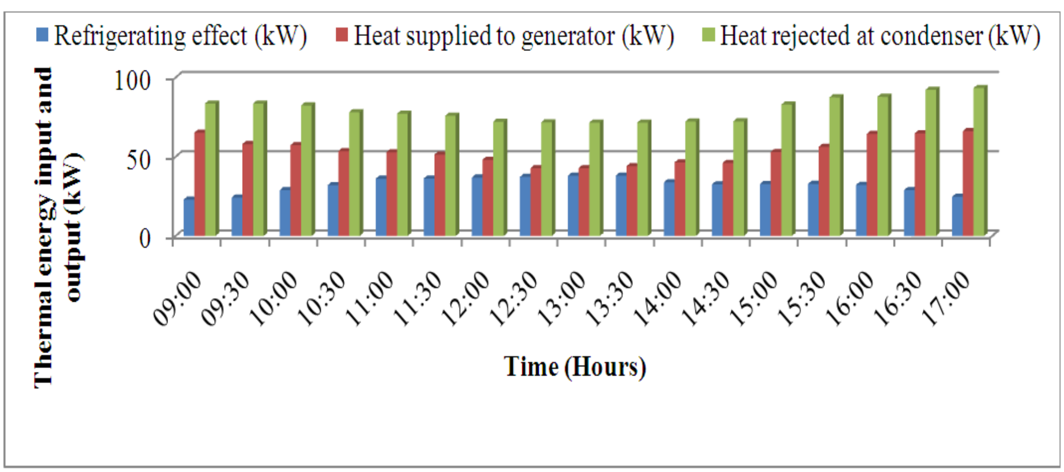

Figure 10: Rate of Thermal Energy Input and Output of Major Componenets of SVAR System in the Month of MARCH, 2015

CONCLUSIONS

An experimental study was carried out to evaluate the real performance of a 5 kW LiBr-H_2O solar absorption cooling system that was installed at Department of Post Harvest Engineering and Technology, AAU, Anand. This work was done focusing on the actual COP and thermal energy analysis of major component of system. When the solar irradiation that struck the solar collector was increased, the cooling capacity and the COP were noticeably increased and no variation of the solar fraction was detected when the water flow rate via the chiller was fixed. It is presently not operating under optimized conditions as it is experiencing some energy losses. In the future development of this study, the research will focus on the optimization of COP by adjusting the water flow rate for energy balancing to attain the highest COP of the system.

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