Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage:
https://semarakilmu.com.my/journals/index.php/fluid_mechanics_thermal_sciences/index
ISSN: 2811-3950

Area Optimization of a Flat Plate Collector for Meeting the Air Conditioning Load of an Office Building Using a Solar Vapor Absorption System

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ARTICLE INFO

Article history:
Received 17 September 2021
Received in revised form 25 December 2021
Accepted 6 January 2022
Available online 4 February 2022

Keywords:
Solar flat plate collector; absorption refrigeration; cooling load profile; solar insolation profile; optimization

ABSTRACT

A solar single effect vapor absorption system is designed to meet the cooling demand of an office building having a floor area of 100 m^2. The absorption system operating parameters are optimized using Genetic algorithm to maximize the coefficient of performance (COP). The solar insolation at a location is used as the heat source for the absorption refrigeration generator heat input. The monthly total global radiation at the location for a particular year is found. The insolation profile of a representative day of the year is the input source for the sizing of the solar flat plate collector. Also, the ambient temperature variation profile is used to dynamically simulate the system performance. The refrigeration system is integrated with the solar collector and storage tank to meet the varying cooling load. The total generator load required to meet the cooling load profile of the building is found from the vapor absorption system model in Matlab. The solar flat plate collector system is modelled in such a way that the energy output from the solar collector matches the generator load required. The hot water temperature to generator (heat supplied) is kept constant at 85°C. The generator load required to meet the varying cooling load is achieved by controlling the solution pump flow rate in absorption system. The optimal area of the collector required for meeting the total generator load is found as 14.6 m^2. The storage volume required in the storage tank is 0.48 m^3. In the solar collector, a variable water flow system profile is used to maintain the constant temperature required in the generator.

1. Introduction

The use of solar energy in Refrigeration and Air Conditioning applications are increasing. This helps the reduction in the fossil fuel consumption and reduce the greenhouse gas emissions. Conventional Air conditioning systems consumes electricity for the operation. Environmentally friendly and energy efficient technologies are the need of the hour to replace conventional air conditioning and refrigeration systems. A solar assisted absorption air conditioning system is considered as a sustainable solution for cooling and heating of a building.

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https://doi.org/10.37934/arfmts.92.1.134148

Florides *et al.,* [1] presented the modelling and simulation of a 11 kW solar absorption cooling machine to meet the air-conditioning load a well-insulated domestic building. The system needed 15 m^2 compound parabolic collector tilted at 30° and 600 l hot water storage for its optimum performance. Florides *et al.,* [2] presented a numerical model of a single stage LiBr-water absorption refrigeration system and analyzed its performance and characteristics. The study focused on the effect of LiBr percentage ratio at absorber exit on the absorber outlet temperature. The effect of generator temperature and solution heat exchanger effectiveness on COP of the system were studied. It was found that the solution heat exchanger increases the performance of the system. The cost analysis of a nominal 10 kW capacity absorption chiller compared to a similar capacity conventional system was also done and the cost of absorption was found to be around three times higher than the conventional one. Assilzadeh *et al.,* [3] conducted a numerical analysis to model and simulate Li-Br water absorption for Malaysia weather conditions. Evacuated tube solar collector with a tilt angle of 20° were used to generate the heat required for the system. Mittal *et al.,* [4] presented the modelling and simulation of a 10.5 kW solar assisted LiBr-water absorption system for Bahal, India. The effect of hot water temperature on performance of the system and flow ratio was found. The study concluded that surface area of the system components is affected by the hot water inlet temperature. The surface area of the absorber and solution heat exchanger is decreased when the inlet hot water temperature is increased. The dimensions of the other components remained constant. Pongtornkulpanich *et al.,* [5] developed and installed a 10 ton solar assisted LiBr-water absorption system at Phitsanulok, Thailand. An evacuated tube collector area of 72 m^2 was required for getting solar fraction of 81% yearly. The remaining 19% was met by LPG fired heating unit. B. Bakhtiari *et al.,* [6] developed a model for the analysis of LiBr-water absorption system based on a 14 kW prototype built at Montreal. It was found that the simulations results were in good agreement with the experimental results. The performance of the machine was measured at different hot water, cooling water and chilled water flow rates and temperatures. Siddiqui and Said [7] described different methods for solar cooling along with experimental and numerical studies. The study revealed that direct cooling by absorption refrigeration using solar energy is more efficient than refrigeration system using electricity generated by photo voltaic technology. Ochoa *et al.,* [8] presented a dynamic model of a LiBr-water absorption system to predict the variations of pressure, temperature and concentration when disruptions in thermal load and power supply occur. The model was implemented on Matlab platform. Shirazi *et al.,* [9] conducted a multi objective optimization of a single- effect, double-effect and triple-effect solar absorption cooling systems to find the technological and economical potential of these systems for large scale applications. It was concluded that the triple effect system was the most energy efficient, double effect system achieved the lowest economic payback period and the single effect system achieved the lowest annual cost. Zaidan *et al.,* [10] presented a numerical analysis of a solar cooling system for a building with hot and cold storage tanks. A single effect absorption system of 7 kW cooling capacity is used. It has been found that for maximum working hours of the system using a solar parabolic collector, a minimum hot storage tank volume of 0.23 m^3 and cold tank volume of 0.65 m^3 is required. Bellos and Tzivanidis [11] employed a cu/water-based Nano fluid as working fluid for his solar LiBr-water absorption system and compared its performance with pure water-LiBr absorption system. The thermal efficiency of the system was reported to be increased by 2.5%. The model was developed in Engineering equation solver.

Though the solar air conditioning reduces greenhouse gases, the COP of the system is low. New optimization strategies and improvement in the properties of working fluids have to be employed to enhance the performance of solar cooling technologies [12,13].

One of the main disadvantages of solar absorption systems compared to conventional air-conditioning systems is high initial cost for the setup. The initial cost of solar absorption system mostly depends on the size of collector. The size of the required solar collector depends on the available solar radiation in the area, the cooling load and collector efficiency.

From the literature review it is understood that most of the studies in modelling and optimization of solar assisted absorption systems are conducted based on a fixed cooling load capacity. In this paper a methodology is presented to design and optimize a solar absorption refrigeration system operating parameter. The optimized system is integrated with a solar collector and it is utilized to dynamically match the load requirement considering the solar flux changes and ambient temperature. The system simultaneously considers the changes in the ambient conditions and solar flux variation which in turn affect the cooling load requirements. The present study aims at finding the optimum collector area required for running an air conditioning system of an office building in accordance with the cooling load profile of the building and its geographical location.

2. Vapor Absorption Refrigeration System Description

A single effect LiBr-water vapor absorption refrigeration system is used to meet the cooling load requirement. The collector used is a flat plate collector in which water is used as the fluid medium to transport the heat. A single effect absorption system can use the low temperature hot water (70°C to 95°C) from the solar flat plate collector. The vapor absorption system and solar collector system, are modelled thermodynamically and analyzed in Matlab. A single objective optimization is done for the absorption system by considering COP as the objective function and the temperatures of the generator and evaporator as variables.

In a solar integrated refrigeration system, the heat required in the generator is supplied by the solar collector. Hot water storage is used in this system to meet the varying cooling load requirement and solar heat flux. Water is used as the refrigerant and LiBr salt as the absorbent. The schematic diagram of the system is shown in Figure 1. The system main components are generator, condenser, evaporator, absorber and solution heat exchanger. The weak solution (weak in LiBr and rich in water) from the absorber is pumped to the generator and is heated in the generator by the hot water from the storage tank. Due to the difference in the boiling temperature between water and lithium bromide salt, a portion of the water is converted to steam and is condensed in the condenser. The hot strong solution (rich in LiBr) thus formed in the generator is returned to the absorber through a solution heat exchanger. In the solution heat exchanger, the strong solution exchanges heat with the weak solution going to the generator. The condensed refrigerant (water) then passes to the evaporator through an expansion valve and the pressure is reduced. The low pressure water vaporizes in the evaporator by absorbing heat from the cooling space and is passed to the absorber. In the absorber, the vapor coming from the evaporator is absorbed by the strong solution coming from the generator. The weak solution thus formed in the absorber is pumped back to the generator and the cycle is repeated. A chilled water circuit is maintained in the evaporator for cooling applications.

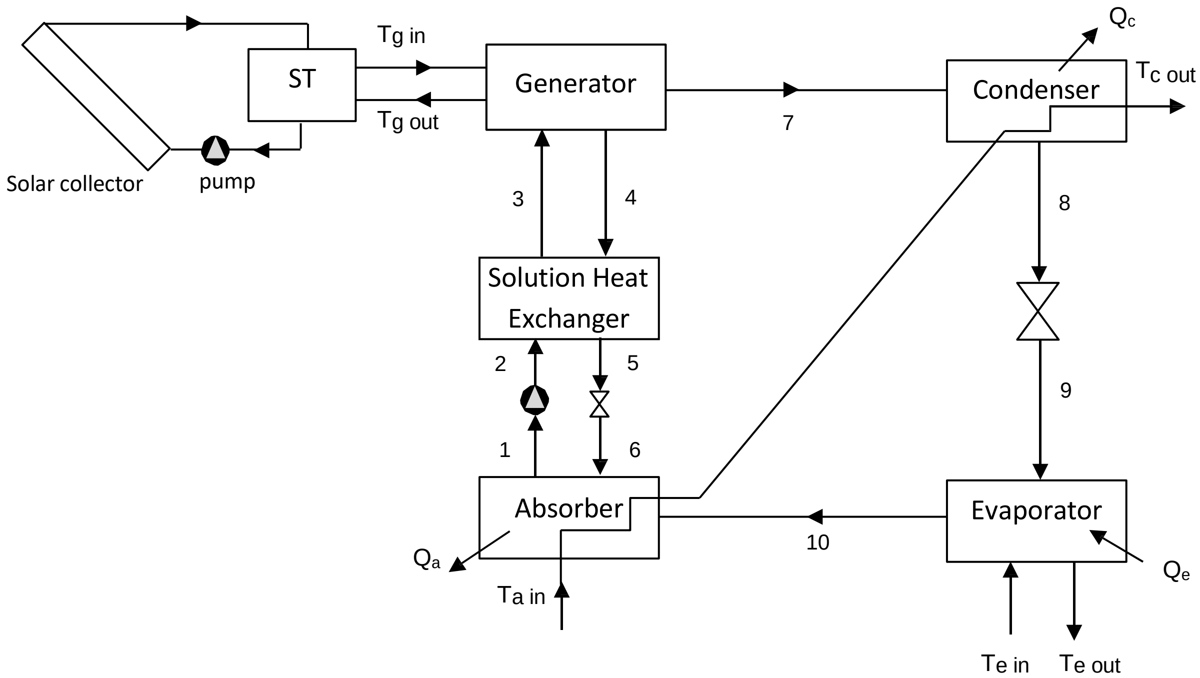

Fig. 1. Solar Absorption refrigeration cycle

3. Thermodynamic Analysis of the System Based on Mass and Energy Balance

The simulation is based on mass and energy balance for each component of the cycle under steady state conditions. Considering the mass balance in the generator

$$\dot{m}_w = \dot{m}_s + \dot{m}_r \tag{1}$$

$$\dot{m}_w x_w = \dot{m}_s x_s \tag{2}$$

$$\dot{m}_s = \frac{x_w}{x_s - x_w} \cdot \dot{m}_r \tag{3}$$

$$\dot{m}_w = \frac{x_s}{x_s - x_w} \cdot \dot{m}_r \tag{4}$$

Circulation ratio, CR = $\frac{\dot{m}_s}{\dot{m}_r}$ (5)

Considering the energy balances in generator, condenser, absorber and evaporator

Generator load, Q_g = $\dot{m}_r h_7 + \dot{m}_s h_4 - \dot{m}_w h_3$ (6)

Condenser load, Q_c = $\dot{m}_r (h_7 - h_8)$ (7)

Absorber load, Q_a = $\dot{m}_s h_6 + \dot{m}_r h_{10} - \dot{m}_w h_1$ (8)

Evaporator load, Q_e = $\dot{m}_r(h_{10} - h_9)$ (9)

Solution heat exchanger energy balance;

$$\dot{m}_w(h_3 - h_2) = \dot{m}_s(h_4 - h_5) \tag{10}$$

Heat exchanger effectiveness, $\varepsilon_{Hex} = \dfrac{T_G - T_5}{T_G - T_A}$ (11)

Coefficient of performance of the Absorption system;

$$COP = \frac{Q_e}{Q_g + W_p} = \frac{Q_e}{Q_g} \tag{12}$$

(Pump work negligible)

Energy balance on absorber Plate;

$$Q_u = A_p S - Q_l \tag{13}$$

Collector thermal efficiency, $\eta_c = \dfrac{Q_u}{A_p I_T}$ (14)

Heat loss from collector;

$$Q_l = U_l A_p (T_{pm} - T_a) \tag{15}$$

Overall heat transfer coefficient, $U_l = U_t + U_b + U_s$ (16)

Collector heat removal factor [20];

$$F_R = \frac{\dot{m}\ C_p}{U_l A_p}[1 - \exp(-\frac{F'U_l A_p}{\dot{m}_s C_p})] \tag{17}$$

Useful heat gains for the collector;

$$Q_u = \dot{m}_s C_p (T_{co} - T_{ci}) \tag{18}$$

$$= F_R A_p [S - U_l (T_{ci} - T_a)] \tag{19}$$

4. Vapor Absorption Refrigeration System Modelling

The thermodynamic modelling of the solar absorption refrigeration system is done in Matlab using the empirical relations for LiBr-water solution [14,15]. The input parameters required for the system model are temperatures of the generator, condenser, evaporator, absorber and effectiveness of heat exchanger. The main output parameter of the model is COP. For validating the model, the input parameters from Arora and Kaushik [16] are used. The results of the simulation are presented for different temperature inputs. (Table 1). It is found that the results are comparable.

Table 1
Comparison of results between Arora and Kaushik and the present study

T_G	T_C	T_E	T_A	COP (Kaushik and Arora, 2009)	COP (present study)	Deviation %
85	40	7.2	40	0.7173	0.7180	-0.09
80	37.8	7.2	37.8	0.7340	0.7355	-0.024
75	35	7.2	35	0.7688	0.7683	0.06
70	30	7.2	30	0.8243	0.8203	0.485
90	40	7.2	40	0.7428	0.7485	-0.76
85	37.8	7.2	37.8	0.7578	0.7629	-0.67
80	35	7.2	35	0.7797	0.7845	-0.61
75	30	7.2	30	0.8161	0.8191	-0.36

5. Optimizing the Absorption Refrigeration System

The optimization of the system is done by maximizing the COP of the system (energy method). The purpose of optimization is to get an optimum generator-evaporator temperature combination required for running the system efficiently. From the parametric study of the effect of operating conditions on COP, it is understood that the COP of the system increases as evaporator temperature increases. A high evaporator temperature enables the system to use a low generator temperature which is ideal for a flat plate collector. The cooling water circuit for absorber and condenser is arranged in series so that the water leaving the absorber enters the condenser where it absorbs the latent heat rejected from the hot water vapor in condenser. Since the cooling water temperature entering the absorber is taken as 25°C, the condenser and absorber temperature is fixed as 35°C. Higher condenser and absorber temperatures reduces the COP of the system. The variation of generator-evaporator temperature for two different condenser temperatures (35°C and 40°C) is shown in Figure 2. The absorber temperature is kept constant at 35°C. Higher condenser temperature demands high generator temperature for the optimum performance of the system. For example, at condenser temperature 35°C and evaporator temperature 10°C, the generator temperature required is 80°C, whereas at condenser temperature 45°C, the generator temperature is increased to 95°C for the same evaporator temperature. Flat plate collector is suitable for only generator temperatures between 70°C to 95°C.

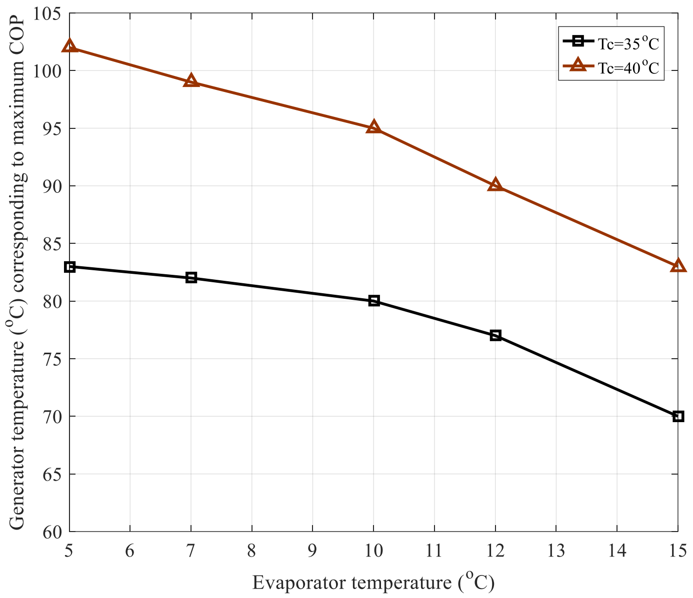

Fig. 2. Variation of generator temperature with evaporator temperature for different condenser temperatures

The absorption system is optimized using Genetic Algorithm (GA) tool in Matlab to maximize the coefficient of performance (COP) by varying the temperatures of generator (75°C to 90°C), evaporator (7°C to 12°C). The condenser and absorber temperature are kept constant (35°C). The operating conditions are chosen in such a way that the temperature of the strong solution from the generator to absorber through the heat exchanger does not fall in the crystallization region. Crystallization occurs normally at hot water temperature above 95°C and cooling water temperature below 25°C [17,18].

The optimized temperatures obtained for the Generator, Condenser, Evaporator and Absorber are T_G=79.89°C, T_C=35°C, T_E=10°C, T_A=35°C. The optimized COP of the system is 0.801. The effect of generator temperature on COP of the system is shown in Figure 3.

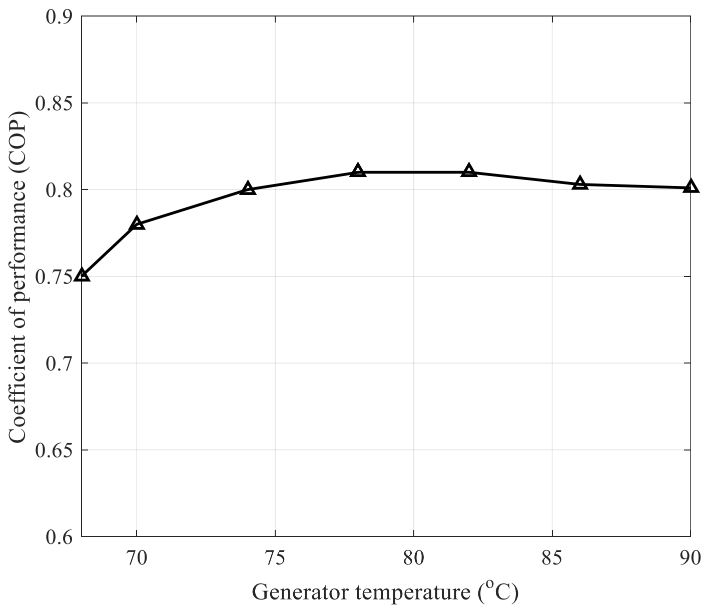

Fig. 3. Variation of COP with generator temperature (T_C=35°C, T_A=35°C, T_E=10°C, ε_{HEX}=0.7)

At high generator temperature, solution concentration leaving the generator increases and the circulation ratio decreases. The enthalpy of the weak solution is increased by heat exchange with the strong solution in the solution heat exchanger. Therefore, the thermal load in the generator is decreased. Hence the COP increases. Condenser thermal load is also increased since the enthalpy of super-heated vapor leaving the generator increases.

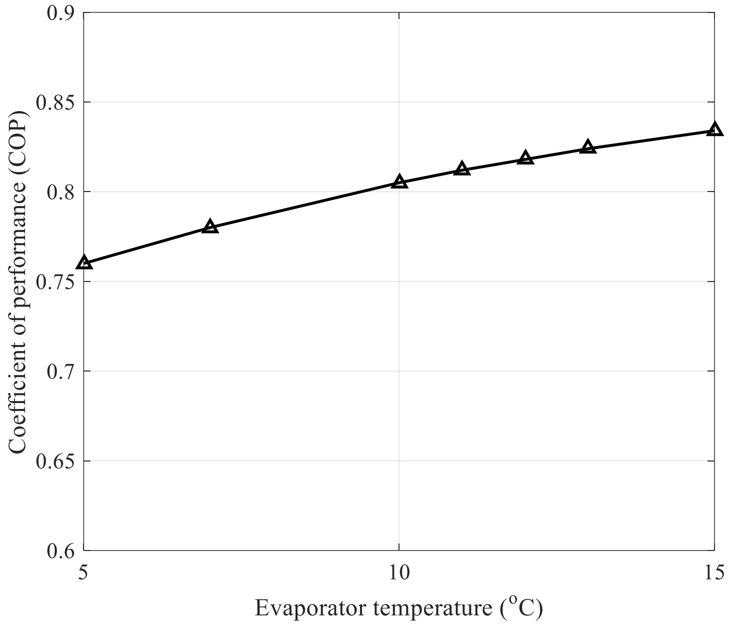

Fig. 4. Variation of COP with evaporator temperature (T_G=80°C, T_C=35°C, T_A=35°C, ε_{HEX}=0.7)

At higher evaporator temperature, the weak solution concentration and circulation ratio decreases which again decreases generator load. Hence the COP increases. This is shown in Figure 4. The absorber thermal load is also reduced.

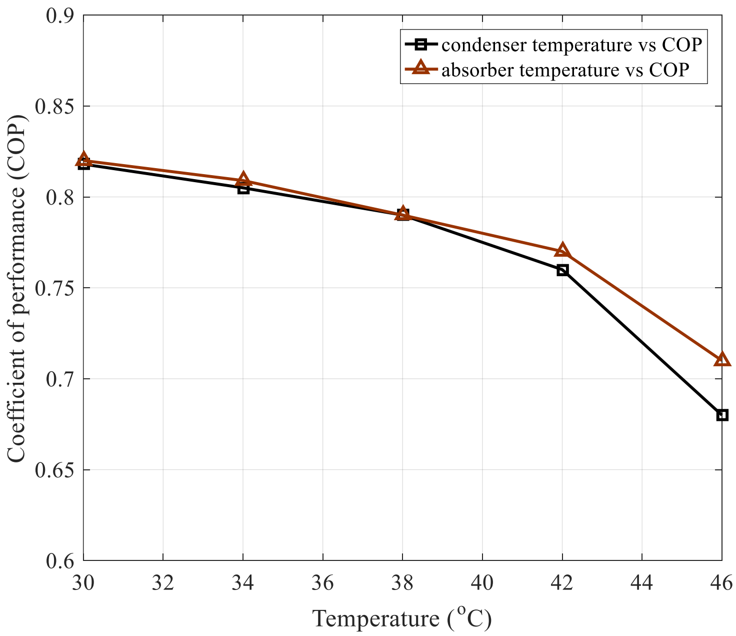

Fig. 5. Variation of COP with Condenser temperature and Absorber temperature (T_G=80°C, T_E=10°C, ε_{HEX}=0.7)

The effect of condenser and absorber temperature on COP of the system is shown in Figure 5. When the condenser temperature increases, the pressure increases and the concentration of the strong solution leaving the generator decreases. The circulation ratio is increased. Hence the COP reduces.

When the absorber temperature increases, the weak solution concentration increases and circulation ratio increases. So, the COP decreases. The GA optimization parameters are given in Table 2.

Table 2
Parameters for GA optimization

Parameter	Value/type
Population size	50
Population type	Double vector
Creation function	Constraint dependent
Selection function	Stochastic uniform
Crossover fraction	0.8
Mutation function	Constraint dependent
Function tolerance	1e-6

6. Solar Collector Modelling

A liquid flat plate collector is modelled in Matlab considering the location parameters and using the thermodynamic relations (Eq. (14) to Eq. (19)). A flat-plate collector can utilize both the beam and diffuse components of the solar radiation and the maintenance of the collector is also low [19]. The specifications of flat plate collector are shown in Table 3 [20].

Table 3
Specifications of the flat plate collector

Surface azimuth angle	0^o
Collector tilt	9^o
Ground reflectivity	0.2
Refractive index of glass relative to air	1.526
Number of covers	2
Diffuse reflectivity of cover system	0.22
Plate emissivity	0.12
Plate absorptivity	0.95
Glass cover emissivity	0.88
Spacing between the covers and with plate	0.05 m
Thermal conductivity of the insulation	0.05 $Wm^{-1}K^{-1}$
Back insulation thickness	0.05 m

The location selected is Thiruvananthapuram, Kerala (8.52°N, 76.9°E). The meteorological data (solar radiation, ambient temperature, wind speed) for the location for the year 2019 is obtained from the Indian Meteorological Department, Pune [21]. The monthly total value of the daily global solar radiation during the year is computed and is shown in Figure 6.

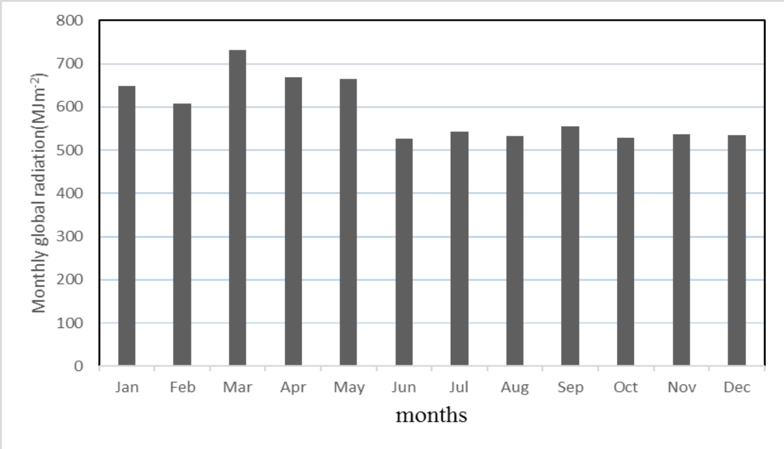

Fig. 6. Monthly total global solar radiation

The lowest monthly total solar radiation value (527 MJ/m^2) recorded is in the month of June. The monthly average daily global solar radiation for June is 17.5 MJ/m^2-day. For the year round operation of the system the solar radiation for the month of June is considered in this study. The meteorological data for June 02, 2019 which has nearly the same monthly average daily global solar radiation value (17.5 MJ/m^2-day), is chosen as the reference day for modelling. The global solar radiation and ambient temperature variation on the reference day is shown in Figure 7.

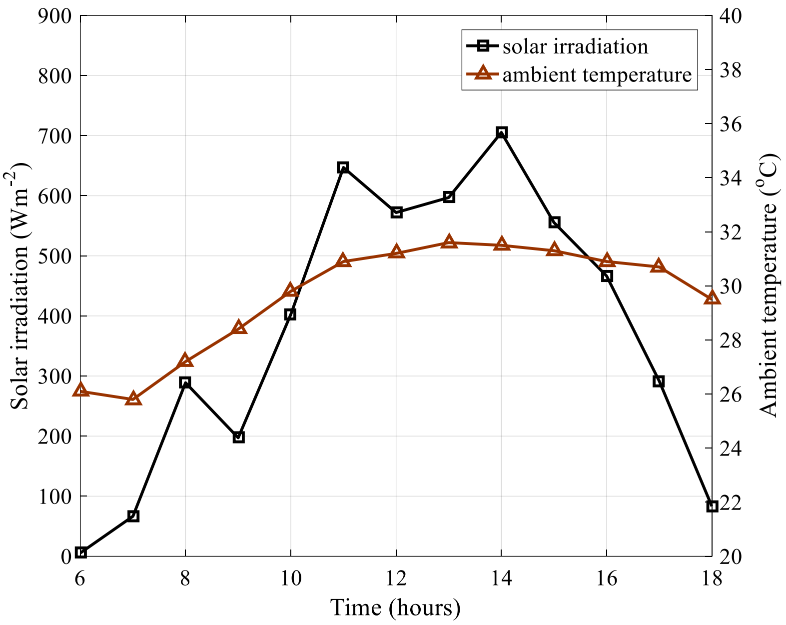

Fig. 7. Solar radiation and ambient temperature variation with time on June 02, 2019

The solar integrated absorption refrigeration system is considered for the air conditioning of a building with cooling load profile as reported in Ding *et al.,* [22]. The dynamic interior cooling load variation as reported in the evaluation for an office building is shown in Figure 8. The cooling load varies from 0.8 kW to 2.4 kW and the floor area of the building is 100 m^2.

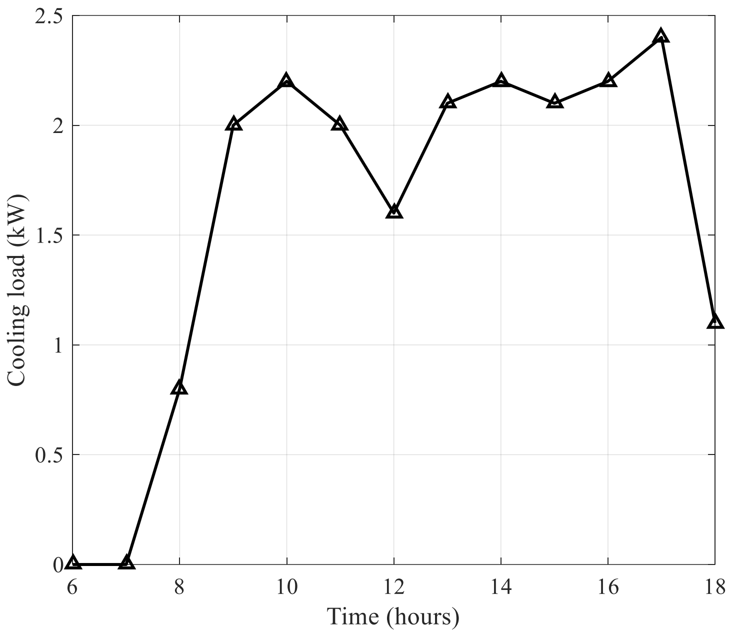

Fig. 8. Cooling load profile of the building

7. Dynamic Modelling of The Solar Integrated Absorption Refrigeration System

The system is modelled using the solar radiation input profile for the location corresponding to June 2, as the energy source to the generator. The optimized input parameters of the solar absorption system are used in the analysis. The system is modelled to meet the cooling load profile along with the solar incident profile and ambient temperature profile. The absorption refrigeration system performance is linked to the ambient temperature profile. To control the hot water temperature circulated through the solar collector a variable flow rate pump is envisaged. This is required to limit the water temperature during high heat flux condition. The integrated system is modelled and the solar collector area required to meet the dynamic heat load profile is calculated. Also, to meet the deficit in solar heat condition against high cooling demand a hot water storage is coupled in the system.

8. Results and Discussions

The result of the simulation is presented in the following sections. The system is configured to meet the cooling load profile using the solar heat available on the reference day. The performance of the system is also coupled to the ambient temperature profile. The change in cooling load is met by varying the solution pump rate. The variation of solution pump flow rate in the absorption system is shown in Figure 9. The solution flow rate increases with the evaporator load. The generator heat load required for meeting the varying cooling load during the office hours is shown in Figure 10. The generator temperature (80°C) and evaporator temperature (10°C) are kept constant (optimized conditions) throughout the operating period.

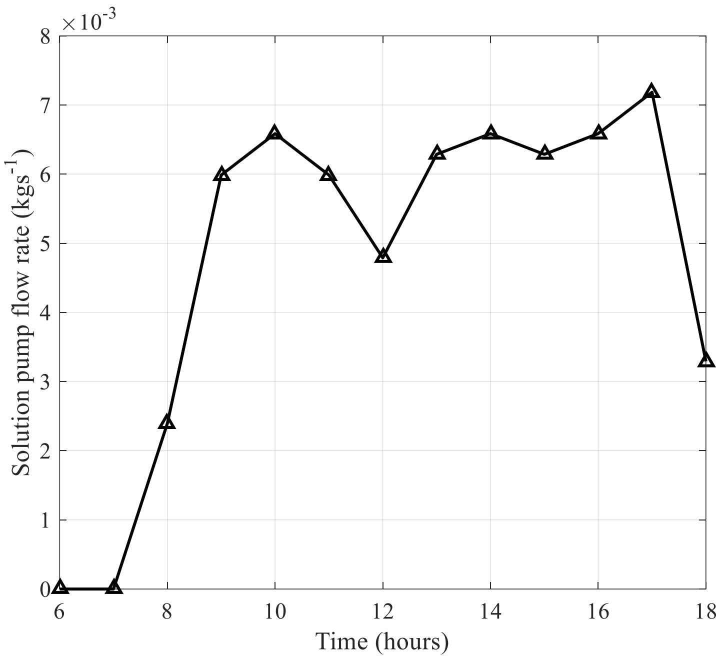

Fig. 9. Variation of solution pump flow rate with time

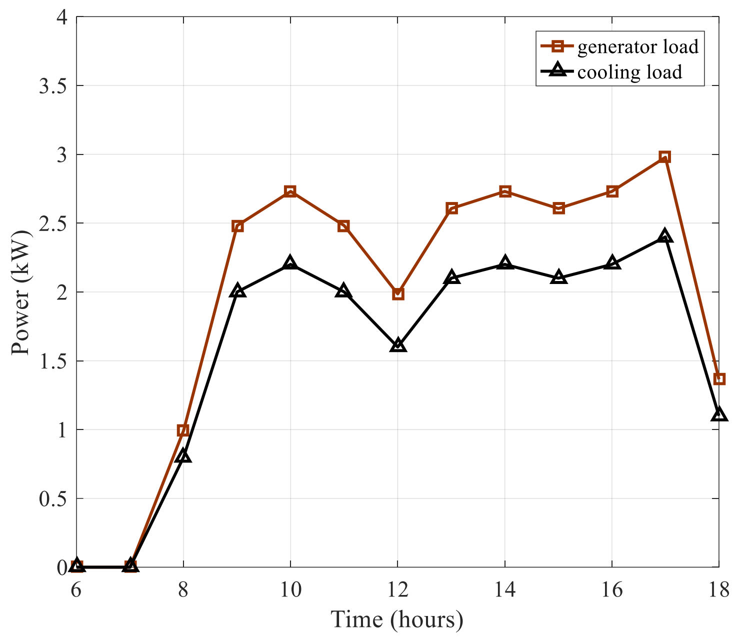

Fig. 10. Variation of generator load and cooling load with time

The hot water produced using the flat plate collector is used as the heat source for generator. The hot water is stored in a storage tank. The generator temperature is fixed as 80°C. Considering a 5°C temperature difference between the hot water input to the generator and the generator, the hot water storage temperature is fixed as 85°C. The total generator load required to meet the cooling load profile of the building is found from the vapor absorption system model in Matlab. For a given inlet temperature and flow rate of water circulating through the solar collector, the total area of the collector required for meeting the total generator load is found. The area of the flat plate collector is determined in such a way that total useful heat energy produced in the flat plate collector for the day matches the total generator load in the absorption system. The total area required for the flat plate collector to run the air conditioning system of the building during office hours without any external source of energy is found to be 14.6 m^2. The storage volume required is 0.48 m^3. The solar useful power, generator load and cooling load profiles are shown in Figure 11. The excess energy produced in the collector during peak hours is stored for running the system when the available solar power is less.

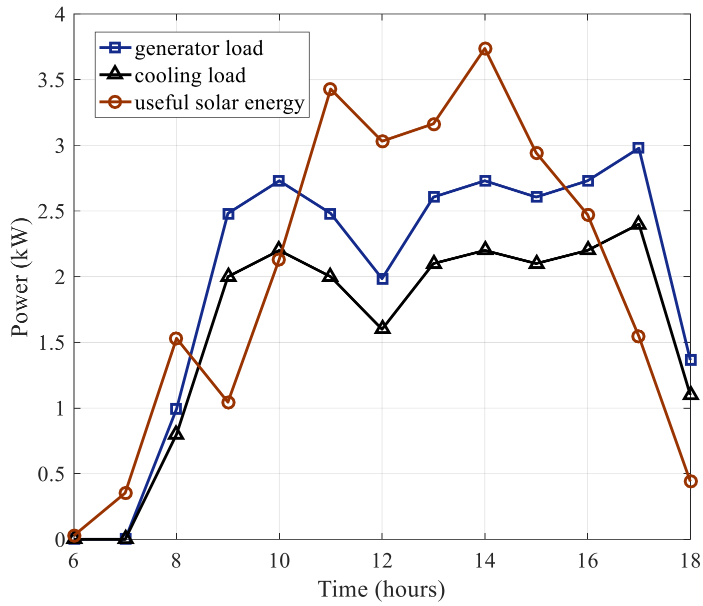

Fig. 11. Variation of useful solar power, generator power and cooling capacity with time

A constant temperature is maintained in storage tank for the supply of hot water to the generator. The pump flow rate to the solar collector is controlled so that the outlet temperature of hot water during peak solar insolation does not affect the performance. The pump flow rate profile to get a constant outlet temperature of 85°C in storage tank is shown in Figure 12.

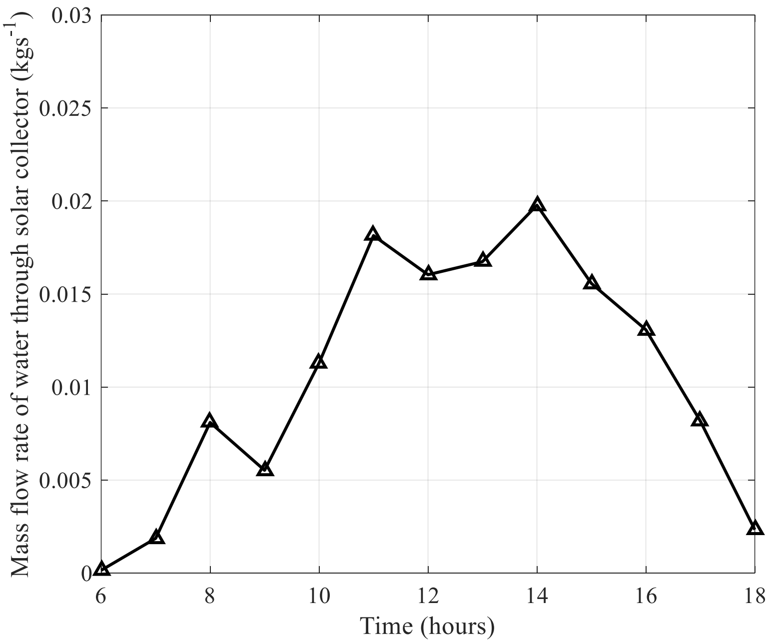

Fig. 12. Variation of mass flow rate of water through solar collector with time

9. Conclusion

A solar integrated vapor absorption system is presented to meet the cooling load demand of an office building. The system is modelled and simulated in Matlab. From the parametric study of the effect of operating conditions on COP, it is understood that the COP of the system increases as generator temperature and evaporator temperature increases. Higher condenser and absorber temperatures reduces the COP of the system. The absorption refrigeration system is optimized to get an optimum generator-evaporator temperature combination required for running the system efficiently. The solar insolation at a location is used as the heat source for the absorption refrigeration generator heat input. The monthly total global radiation at the location for a particular year is found. The insolation profile of a representative day of the year is the input source for the sizing of the solar flat plate collector. A variable water flow rate for the solar collector is used to maintain the generator temperature. The flat plate collector area required for meeting the generator load is 14.6 m^2 for the year round operation. It is found that to maintain the storage tank temperature of 85°C the storage volume needed is 0.48 m^3. Thus, the system designed offers a solution to meet the cooling load requirement throughout the year and the methodology developed can be implemented for other locations and different load conditions.

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