Water Extraction From A Solar Powered Lithium Bromide–Water Absorption System Under Riyadh City Climatic Conditions

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Water extraction, absorption chiller, lithium bromide–water.

ABSTRACT

An investigation of the air contained water extraction using a solar vapor absorption chiller working under the climatic condition of Riyadh city is carried out. Three typical days from different seasons were chosen for the study to evaluate the best operating conditions. Despite that the maximum cooling production is in July, the maximum water production is in January due to the high relative humidity, in fact the maximum of daily production 10.22 L/day. The performances of the absorption chiller and the solar collector are also evaluated and are found to be much influenced by the operating climatic conditions.

استخراج المياه عن طريق نظام امتصاص شمسي يعمل بخليط الليثيوم بروميد-ماء تحت الظروف المناخية لمدينة الرياض

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الكلمات الدالة

الحمل الحراري الجبري، السوائل الشبه بلاستيكية، أنبوب حلقي، التبعية الحرارية، طول المدخل الحراري.

المُستلخص

هذا البحث هوعبارة عن دراسة عددية لمشكلة التطور الحراري أثناء الحمل الحراري الجبري للسوائل الشبه بلاستيكية المتأثرة حراريا داخل أنبوب أفقي حلقي مركزي. و تتناول هذه الدراسة ثلاثة وضعيات حرارية: تعرض الاسطوانة الداخلية لتدفق حراري مسلط بينما الاسطوانة الخارجية معزولة ثم العكس وأخيرا كلتا الأسطوانتين يتم تسخينهما بنفس كثافة التدفق الحراري. تم تنفيذ جميع العمليات الحسابية على أساس مرحلة متطورة بشكل تام لتدفق تم تطويره ديناميكيا. الهدف من هذه الدراسة هو توضيح الآثار المترتبة لكل من مؤشر الانسيابية(n) ، نسبة الأبعاد (r1) ، التبعية الحرارية (Pn) ووضع التدفئة على ملامح السرعة و تطور عدد نوسلت بالإضافة إلى طول المدخل الحراري. أظهرت النتائج تحسنا في تبادل الحرارة مع الترقيق القصي للسائل. كما أن عدد نوسلت الخارجي ينخض كلما انخفضت نسبة الأبعاد في حين يرتفع عدد نوسلت الداخلي. وعموما، فإن التبعية الحرارية لها تأثير مشابه للترقيق القصي. كما أن هناك نتيجة مهمة جدا تظهر انخفاض في طول المدخل الحراري مع زيادة مؤشر الانسيابية و/ أوالتبعية الحرارية. و تم أخيرا وضع ارتباطات بسيطة ودقيقة وصحيحة إلى حد كبير لعدد نسلت وطول المدخل الحراري في وضعيات حرارية مختلفة.

Introduction

The next challenge to human life in the world is to seek solutions of the anticipated problems that are expected to appear in the near future. The three most critical problems that human beings face today are the energy crisis, the water crisis and the environment pollution (Attia, 2012). Fresh water supply and sustainable energy sources are considered to be the most important topics on the international environment and development plans. These are also crucial factors that govern the lives of humanity and promote civilization. The history of mankind proves that water and civilization are two inseparable entities. This is proven by the fact that all great civilizations developed and flourished near large sources of water. Rivers, seas, oases and oceans have attracted mankind to their coasts because water is the source of life (El-Ghonemy, 2012). Saudi Arabia is facing a water scarcity due to the prevailing weather conditions especially in remote areas caused by the over population, industrialization and agricultural expansion of the country. The extraction of water from atmospheric air can provide one possible solution to this water scarcity problem. This can be accomplished by different methods, the most common of these methods is cooling moist air to a temperature lower than the air dew point (Anbarasu, et al, 2012), and absorbing water vapor from moist air using a solid or a liquid desiccant (ASHRAE Handbook, 1994 and Tygarinov, 1947). The choice of methods is an engineering decision dependent on local climatic conditions and economic factors such as capital, operating, and energy costs. The problem of providing remote areas with fresh water is usually solved by using three techniques (Kandil, 2011); (i) transportation of water from other locations, (ii) desalination of saline water (ground, or underground), and (iii) extraction of water from atmospheric air). Water transportation from other locations is usually expensive and of high initial cost to those remote areas. The desalination of saline water (ground and underground) is also expensive, high initial cost and related to the availability of ground water in the area.

Atmospheric air is a huge and renewable reservoir of water. This endless source of water is available everywhere on the earth surface. The amount of water in atmospheric air is evaluated as 14000 km3, where the amount of fresh water in rivers and lakes on the earth surface is only about 1200 (Hamed, et al., 2011).

The first major project on an all solar absorption refrigeration system was undertaken by (Trombe and Foex, 1964). Ammonia-water solution is allowed to flow from a cold reservoir through a pipe placed at the focal line of a cylinder-parabolic reflector. Heated ammonia-water vaporized in the boiler is subsequently condensed ammonia in a cooling coil. The evaporator is a coil surrounding the container used as an ice box. In the prototype trials, the daily production of ice was about 6 to 4 kilograms of ice per square meter of collecting area for four-hour heating. The design of (Trombe and Foex, 1964). is very promising and should be studied further although modifications may be necessary on the solar collector, boiler, and condenser.

(Farber, 1970) built the most successful solar refrigeration system to date. It was a compact solar ice maker using a flat-plate solar collector as the energy source. It was reported that an average of about 42,200 kJ of solar energy was collected by the collector per day and ice produced was about 18.1 kilograms. This gave an overall coefficient of performance of about 0.1 m and of collector surface per day. 12.5 kilograms of ice per m². (Swartman and Swaminathan, 1971), built a simple, intermittent refrigeration system incorporating the generator-absorber with a 1.4 m2 flat-plate collector. Ammonia water solutions of concentrations varying from 58 to 70 % were tested. Tests were relatively successful; evaporator temperatures were as low as 12°C, but due to poor absorption, the evaporation rate of ammonia in the evaporator was low. (Staicovici, 1986), made an intermittent single-stage H2O-NH3 solar absorption system of 46 MJ/cycle. Solar collectors heat the generator. Installation details and experimental results were presented. The system coefficient of performance (COP) varied between 0.152 and 0.09 in the period of May–September. Solar radiation availability and the theoretical (COP), also applicable to the Trombe-Foex system, were assessed. Reference was made to evacuated solar collectors with selective surfaces. Actual (COP) system values of 0.25–0.30 can be achieved at generation and condensation temperatures of 80°C and 24.3°C respectively. In 1990, (Kouremenos, et al, 1990) made a laboratory mordent of absorption refrigeration. Using ammonia - water solution at 52% concentration by weight and the total weigh is 38 kg. This system was operated intermittently using this heat source. A heat source at temperature no higher than 80 °C was used to simulate the heat input to absorption refrigeration from solar pond. In this system the temperatures of generator was as high as 73°C and evaporator temperatures as low as -2 °C. Tap water was used to remove the heat generated from the condensation of the ammonia vapor and the absorption of the refrigerant in the water. The temperature of the tap water was near the ambient laboratory temperature of 28°C. The COP for this unit working under such condition was in the range 0.24 to 0.28. (Hammad and Habali, 2000), made a steel sheet cabinet of 0.6 m x 0.3 m face area and 0.5 m depth. The cabinet was intended to store vaccine in the remote desert area, away from the electrical national grid. A solar energy powered absorption refrigeration cycle using Aqua Ammonia solution was designed to keep this cabinet in the range of required temperatures. The ambient temperatures reached about 45°C in August. A computer simulation procedure was developed to study the performance and characteristics of the cooling cycle. The simulation included MATLAB computer programs for calculation the absorption cycle. In this system using a cylindrical solar concentrator extended the daily operating time to about 7 h and increased the output temperature up to 200 °C and the range of the COP was between 0.5 to 0.65 .While the temperature which gives optimum condition (of COP = 0.65) was 120 °C. For this study a solar absorption refrigeration unit was constructed. The working fluids employed was aqueous ammonia (25 wt% NH_3 – H_2O). The system was operated during the months of June and July (2009) for a period of 8 hours per day (8 am to 4 pm).

The absorption cycle is a process by which refrigeration effect is produced through the use of two fluids and some quantity of heat input, rather than electrical input as in the more familiar vapor compression cycle (Sun, 1998). Both vapor compression and absorption refrigeration cycle accomplish the removal of heat through the evaporation of refrigerant at a low pressure and the rejection of heat through the condensation of the refrigerant at a higher pressure. The method of creating the pressure difference and circulating the refrigerant is the primary difference between the two cycles. The vapor compression cycle employs a mechanical compressor to create the pressure differences necessary to circulate the refrigerant. In the absorption system, a secondary fluid or absorbent is used to circulate the refrigerant. Because the temperature requirements for the cycle fall into the low – to – moderate temperature range, and there is significant potential for electrical energy savings, absorption would seem to be a good prospect for cooling applications (Sultan, 2004).

Cycle description and Numerical procedure

The absorption refrigeration cycle shown in figure 1 is a closed cycle where the working fluid (lithium bromide and water) remains within the closed system and the interface with the surroundings is at boundaries through which heat and work are transferred. The working fluid for the absorption system is a solution of refrigerant (water) and absorbent (Lithium bromide) which have a strong chemical affinity for each other.

Heat from a high-temperature source (solar energy) is added to the solution in the generator; as a result, a part of the refrigerant evaporates from the boiling solution which becomes stronger in absorbent concentration. Heat is removed from the refrigerant vapor as it is condensed in the condenser. The liquid refrigerant goes then to the evaporator via an expansion valve or a pressure restrictor in the feeding pipes. Evaporation of the refrigerant liquid takes place in the evaporator because the vapor pressure of the solution in the absorber, at the absorber temperature, is lower than that of the refrigerant at the evaporator temperature. The solution draws vapor away from the refrigerant surface and causes the refrigerant temperature to fall until it can perform some useful refrigeration. The vapor (water) leaving the evaporator is mixed with a strong solution (Lithium bromide) in the absorber. Since this reaction is exothermic, heat must be removed from the absorber to maintain its temperature at a sufficiently low value to assure a high chemical affinity between the refrigerant and the solution. The liquid solution, weak in its affinity for refrigerant, is now pumped to the generator so that the cycle can be continuous. The solution returns to the absorber through an expansion valve. A heat exchanger is placed in the solution circuit between the generator and absorber to minimize the sensible heat losses.

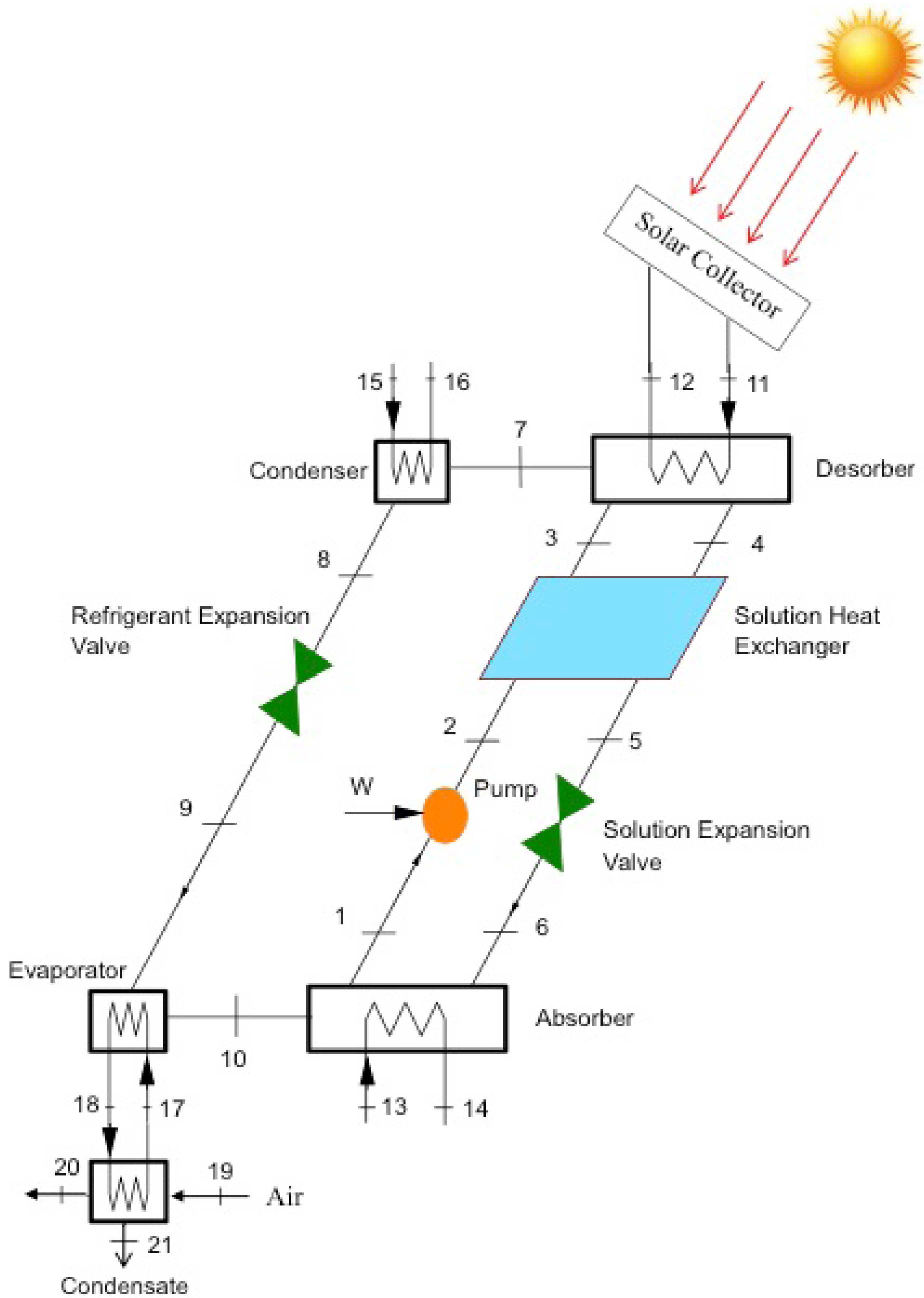

Fig.1. Schematic of the chiller system

Mass and energy balances

Simulation is carried out using Engineering Equation Solver (EES) software, which contains the thermo-physical properties of the working fluids. A model for the absorption chiller is developed based on energy and mass conservation applied to every component.

A model for the absorption chiller is developed based on energy and mass conservation applied to every component considering the following assumptions:

- Steady state operation.
- The refrigerant at the outlet of the condenser is saturated liquid.
- The refrigerant leaving the evaporator is saturated vapor.
- Pressure drop is neglected.
- No heat losses to the surrounding.
- Kinetic and potential energy variations are neglected.

- Desorber:

$$\dot{m}_3 = \dot{m}_4 + \dot{m}_7;\ \dot{m}_3 x_3 = \dot{m}_4 x_4;\dot{Q}_d = \dot{m}_4 h_4 + \dot{m}_7 h_7 - \dot{m}_3 h_3;\ \dot{Q}_d = LMTD_d.(UA)_d;$$

$$LMTD_d = \frac{T_{11} - T_4 - (T_{12} - T_7)}{\ln\left[\frac{T_{11} - T_4}{T_{12} - T_7}\right]};\ (U.A)_d = 1.8\,\text{kW.K}^{-1}$$

- Absorder:

$$\dot{m}_1 = \dot{m}_6 + \dot{m}_{10};\ \dot{m}_1 x_1 = \dot{m}_6 x_6;\ \dot{Q}_{ab} = \dot{m}_6 h_6 + \dot{m}_{10} h_{10} - \dot{m}_1 h_1;$$

$$\dot{Q}_{ab} = LMTD_{ab}.(UA)_{ab};\ LMTD_{ab} = \frac{T_6 - T_{14} - (T_1 - T_{13})}{\ln\left[\frac{T_6 - T_{14}}{T_1 - T_{13}}\right]};\ (U.A)_{ab} = 1.8\,\text{kW.K}^{-1}$$

-Evaporator

$$\dot{m}_9 = \dot{m}_{10};\dot{Q}_{ev} = \dot{m}_9(h_{10} - h_9);\ \dot{Q}_{ev} = LMTD_{ev}.(UA)_{ev};$$

$$LMTD_{ev} = \frac{T_{17} - T_{10} - (T_{18} - T_{10})}{\ln\left[\frac{T_{17} - T_{10}}{T_{18} - T_{10}}\right]};\ (U.A)_{ev} = 2.25\,\text{kW.K}^{-1}$$

-Condenser

$$\dot{m}_7 = \dot{m}_8;\ \dot{Q}_{cd} = \dot{m}_7(h_7 - h_8);\ \dot{Q}_{cd} = LMTD_{cd}.(UA)_{cd};$$

$$LMTD_{cd} = \frac{T_8 - T_{15} - (T_8 - T_{16})}{\ln\left[\frac{T_8 - T_{15}}{T_8 - T_{16}}\right]};\ (U.A)_{cd} = 1.2\,\text{kW.K}^{-1}$$

- Pump

$$\dot{m}_1 = \dot{m}_2;x_1 = x_2;\dot{W}_p = \dot{m}_1(h_2 - h_1)$$

- Solution Heat Exchanger

$$\dot{m}_3 = \dot{m}_2;\ x_3 = x_2;\ \dot{Q}_{SHX} = \dot{m}_2(h_3 - h_2) = \dot{m}_4(h_4 - h_5);\ \varepsilon_{SHX} = \frac{T_4 - T_5}{T_4 - T_2} = 0.64;$$

$$\dot{Q}_{SHX} = LMTD_{SHX}.(UA)_{SHX};\ (UA)_{SHX} = \frac{\dot{Q}_{SHX}}{LMTD_{SHX}};$$

$$LMTD_{SHX} = \frac{T_3 - T_4 - (T_2 - T_5)}{\ln\left[\frac{T_3 - T_4}{T_2 - T_5}\right]}$$

- Refrigerant expansion valve

$$\dot{m}_8 = \dot{m}_9;\ h_8 = h_9$$

- Solution expansion valve

$$\dot{m}_5 = \dot{m}_6;\ x_5 = x_6;\ h_5 = h_6$$

- Mass and energy balance for external fluids

Desorber: $\dot{Q}_d = \dot{m}_{11} C_p (T_{11} - T_{12})$

Absorber: $\dot{Q}_{ab} = \dot{m}_{13} C_p (T_{14} - T_{13})$

Evaporator: $\dot{Q}_{ev} = \dot{m}_{17} C_p (T_{17} - T_{18})$

Condenser: $\dot{Q}_{cd} = \dot{m}_{15} C_p (T_{16} - T_{15})$

Solution Heat Exchanger:

Coefficient of performance: $COP = \frac{\dot{Q}_{ev}}{\dot{Q}_{gen}}$

Air stream: $\dot{Q}_e = \dot{m}_{air} (h_{19} - h_{20})$

Water condensate: $\dot{m}_w = \dot{m}_{air} (\omega_{19} - \omega_{20})$

The energy supplied by the collector to drive the absorption chiller is given by:

$$\dot{Q}_u = A_c . I . \eta_c$$

Where η_c is the coversion efficiency of the solar collector given as:

$$\eta_c = \eta_0 - a_1 \frac{\frac{T_{11} + T_{12}}{2} - T_{amb}}{I} - a_2 \frac{\left(\frac{T_{11} + T_{12}}{2} - T_{amb}\right)^2}{I}; \text{ with } \eta_0 = 0.73,$$

$a_1 = 0.15\, W.m^{-2}.K^{-1}$ and $a_2 = 0.0054\, W.m^{-2}.K^{-2}$

$$A_c = 50\, m^2$$

$$T_{13} = T_{15} = 25°C$$

$$\dot{m}_{13} = \dot{m}_{15} = 0.28\ \text{kg.s}^{-1}$$

$$\dot{m}_{19} = 0.3\ \text{kg.s}^{-1}$$

$$\dot{m}_{11} = 0.3\ \text{kg.s}^{-1}$$

$$T_{17} = 10°C$$

$$\dot{m}_{17} = 0.4\ \text{kg.s}^{-1}$$

$$\dot{m}_1 = 0.05\ \text{kg.s}^{-1}$$

Results and discussion

This paper details the effects of the climatic conditions on the thermodynamic performance and water extraction from atmospheric air of a solar absorption system working with lithium bromide–water in Riyadh City (24° 42’ N, 46° 43’ E), Saudi Arabia. The climatic conditions of Riyadh city were taken from the Energy Plus TMY3 weather files, associated with the ASHRAE Standard 90.1 Prototype Building Models. Calculations were done based on solar beam radiation, ambient temperature, and relative humidity.

The hourly climatic data (Irradiation, Ambient temperature and relative humidity) for three typical days for Riyadh city are respectively presented in Figures 2, 3 and 4. These days were chosen to evaluate the performances under different conditions.

The cooling power exhibit an obviously similar variation trend with the incident solar flux, and reach a peak value at around noon as shown in figure 4. The cooling power is higher in summer season (July 15) due to the higher solar flux and ambient temperature. It is noted that the cooling power is not evaluated on all hours of the days; this is due to temperature activation which is not reached for low solar flux and low ambient temperature. For example on January 1, the absorption chiller can be operational only between 9 AM and 4 PM.

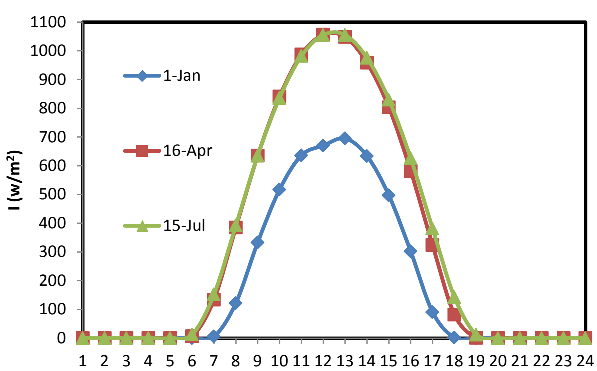

Fig. 2. Hourly Irradiation

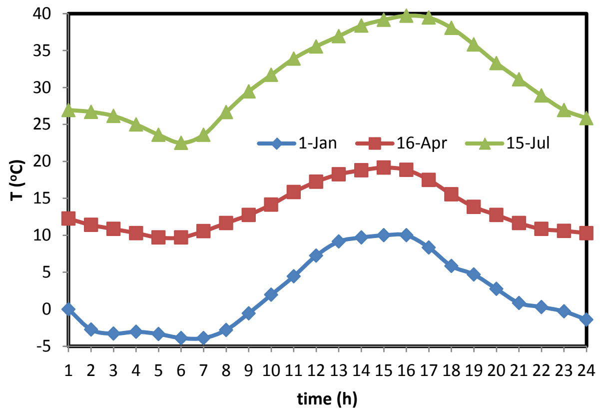

Fig. 3. Hourly ambient temperature

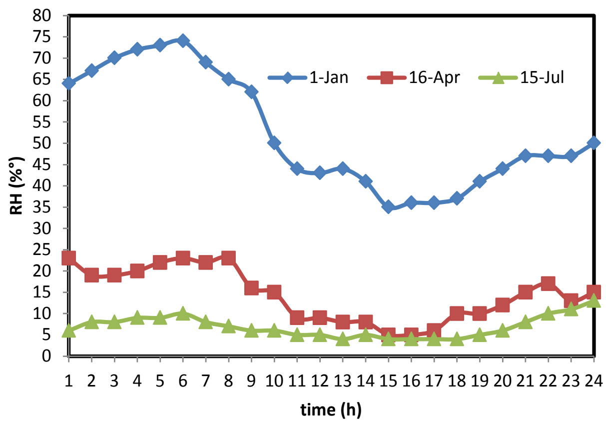

Fig. 3. Hourly relative humidity

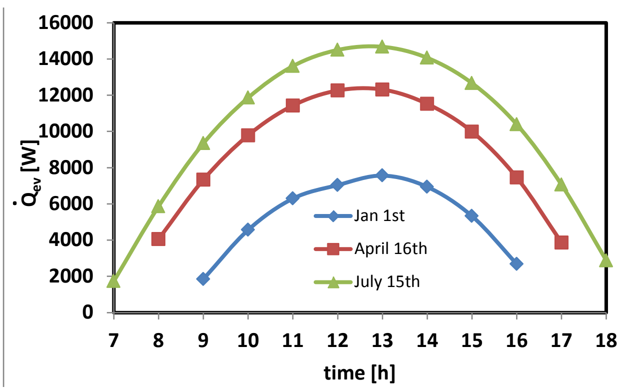

Fig 4. Hourly cooling power

The COP of the cooling unit is a relationship between the heat added in the generator and the cooling effect in the evaporator. It is generally desirable to obtain a higher cooling capacity in the evaporator with a smaller amount of energy in the generator. The heat added in the generator depends on the solar collector temperature and the mass flow rate. Generally, the generator is affected by the solar radiation while the evaporator is influenced by the cooling loads, which depend on ambient temperature. A comparison of the effect on the hourly COP of the cooling unit for different days (the 1st of January, 16th of April and 15th of July) is presented in Fig. 5. It is seen that except for early and late hours of operation the COP is almost constant, with a small decrease at around noon. The COP decreases because the cooling temperature of the absorber is increased. This reduces the capacity of working fluid to absorb the refrigerant. Furthermore, the temperature in the condenser also increases because the cooling system is cooled under ambient conditions.

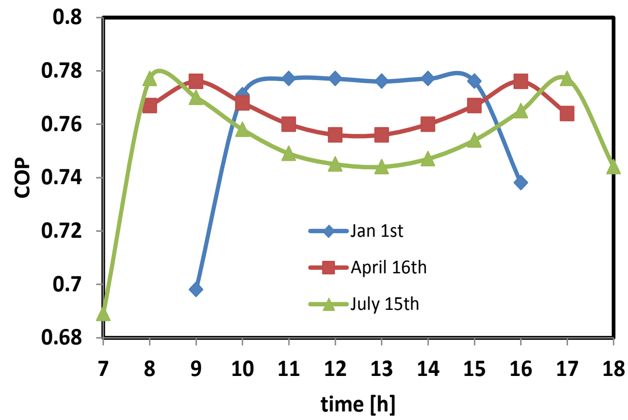

Fig 5. Hourly COP

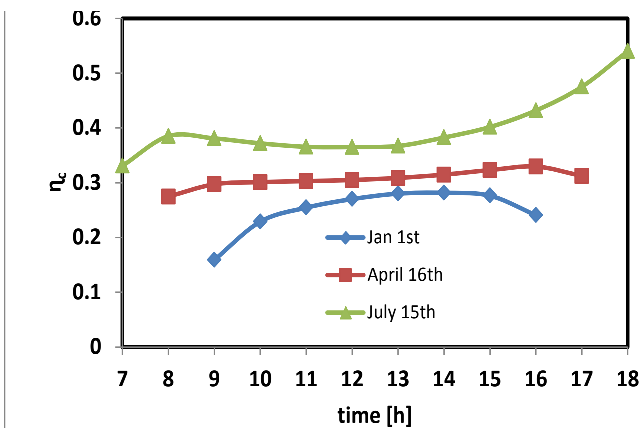

Fig 6. Hourly solar collector efficiency

The solar collector efficiency depends on the gradient between the solar collector and the ambient temperatures. The increase in ambient temperature improves the operation of the solar collector. If the difference of solar collector absorber temperature and the ambient temperature is reduced, the heat losses to the environment are reduced and the heat transferred into the fluid is increased. Thus the solar collector efficiency is maximized during the summer season. Variation of rate of water production with time is shown in Fig. 7. The water production rate is higher on January 1, despite that in this day the solar flux is lower. The result becomes obvious when comparing the hourly variation of relative humidity (shown in fig. 3). In fact on July 15, the relative humidity does not exceed 12%, while on April 16, it does not exceed 24%, but on January 1 it varies between 35% and 75%. It is noted that despite that though the absorption chiller is producing cooling effect, yet at times there is no water production, this means that the cooling produced by the chiller is not enough to condense water. In order to have an idea on the daily production cumulative yield is presented in fig. 8. The maximum production is 10.22 L/day for January 1.

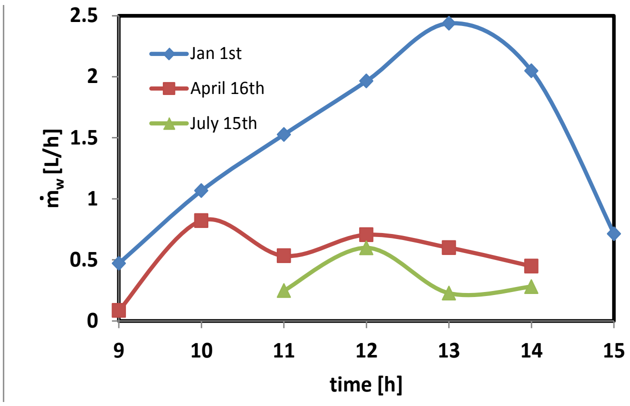

Figure 7. Rate of water production

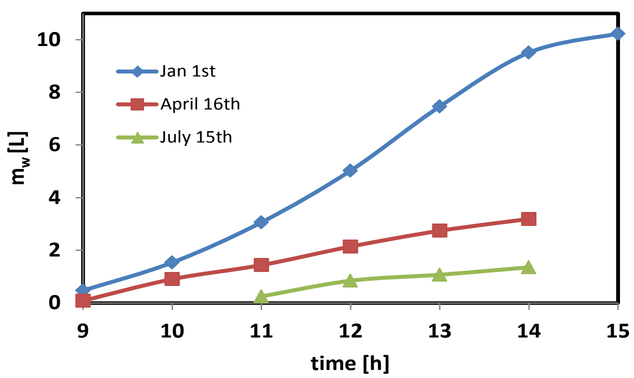

Figure 8. Cumulative yield

Conclusion

A thermodynamic analysis on the performance of solar powered lithium bromide–water absorption system used to extract water from air is presented in this paper. The input data were the climatic conditions of Riyadh city. The results are calculated using computer program based on thermodynamic properties of the working fluids. It was found that the maximum cooling production is in July due to the high solar radiation but the maximum of water yield is in January due to the relatively high relative humidity. The results revealed that the operating climatic conditions had a huge influence on the performance of the system.

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