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Impact of Storage Tank Size and Backup Heating Unit on a Solar Absorption Cooling System

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Abstract

Solar energy has a great ability in cooling and air conditioning as the demand for cooling and air conditioning coincides with the availability of solar energy. In this study, a simulation program using TRNSYS platform was built to simulate and optimize the design and operating parameters. The hourly thermal performance of a single stage LiBr/H_2O solar absorption cooling system powered by linear Fresnel Concentrator was investigated under Cairo climate. The components size of the solar absorption cooling plant was optimized. The performance of the cooling system was studied in terms of the rate of useful energy from the concentrator, of the collector outlet temperature, and the coefficient of the performance COP of the absorption chiller. From the study, it was found that the optimum storage tank capacity depends on the area of the solar concentrator. Increasing the storage tank capacity from 3 to 9 m^3 leads to a decrease in the maximum outlet temperature from the collector from 182 to 120 ºC and consequently decreasing the Absorption chiller COP from 0.46 to 0.07 respectively. Supplying a gas backup heating unit ensures stability for powering the adsorption cooling system. Increasing the backup unit capacity increase the operating hours of the absorption chiller.

Keywords: *Solar Cooling, Absorption, Linear Fresnel Concentrator, Simulation, Storage Tank, TRNSYS*

1. Introduction

In recent years, the trend in the architecture of the larger glazed surfaces, coupled with greater comfort expectations meant a significant increase in the energy consumption of air conditioning. In some countries, this has already increased the load on the electrical grid and disrupted it. This risk and the need to reduce greenhouse gases to produce electricity make the introduction of refrigeration with renewable energy sources an attractive choice. Recently, the optimization of solar collectors and the enhancement of the adsorption cooling units have contributed in the spread of the solar absorption cooling systems. Now they are able to compete with electrified systems operating. The use the solar thermal energy directly in cooling and air conditioning is one of the most promising technologies in this area; several studies have been conducted in this area. Solar cooling is characterized by the availability of solar radiation abundantly at the same time when the needed for cooling is increasing. The solar absorption system provides both cooling and heating needed for rooms, improve the efficiency of the system compared to those who produce either hot or cold water alone [1]. Different solar assisted cooling systems using the absorption and adsorption techniques have been investigated and tested with successes by many researchers [2-5]. Balghouthi et al. [6] modeled an 11 kW solar adsorption system flat plate solar collectors with an area of 30 m^2 and a water storage tank capacity of 800 l. Le Lostec et al. [7] studied the performance of a solar cooling system where they performed several practical experiments on a 10 kW of an ammonia/water absorption chiller. They obtained many practical results and later used it to verify the validity of a simulation model of this module Hang et al. [8] predicted the environmental and economic impacts of a solar absorption cooling unit for one of the medium-sized administrative buildings in Los Angeles. The cooling system was simulated where the simulation model included a single-effect LiBr/H_2O absorption chiller, an evacuated tube solar collector, a hot water storage tank, and a gas-fired backup unit. The performance of the system has been optimized by varying the storage tank capacity and the area of the collector. They determined a trade-off between energetic/environmental performance (CO2 reduction and solar fraction) and cost

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(equivalent uniform annual cost). Assilzadeh et al. [9] investigated the performance of solar absorption cooling unit with $LiBr/H_2O$ as working fluids designed for Malaysia and other similar tropical areas and powered by evacuated tube solar collectors. The simulation of the system was performed with a well-known TRNSYS platform. Their cooling system produced 1 ton of refrigeration and predicted the optimum design parameters of the system (the area of the evacuated tube collectors was 35 m^2 and sloped 20.1º, a hot water flow rate of 0.25 kg/s and a 0.8 m^3 hot water storage tank). In order to enhance the recovery efficiency of low-temperature heat sources and reduce temperature fluctuations in the evaporator and the condenser, recently, an innovative dual-mode, four-bed adsorption chiller was suggested. The system can operate with a large range of temperatures increases the usage of the unit throughout the year [10]. The solar absorption system represents 82 % of the total solar cooling technologies in the market while the adsorption cooling system and the desiccant system represent 11 % and 7 % respectively [11]. The absorption chillers of single-effect type are normally operated with a low driving temperature ranging from 80 to 95°C as the Flat Plate (FPC) or the Evacuated Tubes (ETC) solar collectors [12]. The performance of a single effect LiBr + water absorption chiller of 35 kW nominal cooling capacity driven by hot water was presented by Syed et al. [13] presented the thermal performance of a single stage $LiBr/H_2O$ absorption cooling unit with 35 kW cooling capacity powered by hot water. A flat plate solar collector with an area of 49.9 m^2 and 2 m^3 stratified storage tank were used to supply hot water for the absorption unit. The maximum achieved cooling capacity was 7.5 kW which represents 21% of the nominal. The maximum measured values of the COP for the absorption unit at day and night were 0.42 and 0.34, respectively. A simulation of a single effect $LiBr/H_2O$ absorption cooling system with a capacity of 17.6 kW driven by parabolic trough solar collectors was presented by Mazloumi et al. [14]. The thermal efficiency of the solar system and the COP of the cycle were 0.69 and of 0.7 resulting in a global efficiency of 0.48. Qu et al. studied experimentally a cooling system with 52 m^2 Parabolic Trough Collector (PTC) and a double effect LiBr-water absorption chiller with a capacity of 18 kW [15]. The product of collector efficiency and the chiller COP was about 0.33–0.44.

The advantage of linear Fresnel reflector (LFR) solar collector compared to the parabolic trough solar collector is the decreasing in manufacturing, operation, and maintenance cost [16]. Bermejo et al. [17] studied double effect LiBr/H2O absorption system in Spain driven by LFR. The absorption unit was powered by pressurized hot water supplied by LFR with a backup gas burner. The average daily efficiency of the collector and the absorption chiller COP reached 0.35 and 1.25, respectively. The absorption cooling system using the ammonia-water solution can be driven also by the LFR [18]. Chemisana and Rosell [19] carried out a solar cooling system driven by LFR solar collector which provided thermal energy with a driving temperature of 150–170 ºC to a double effect $H_2O/LiBr$ absorption chiller, where a COP of 1.35 was observed.

In this paper, a simulation of solar absorption cooling system powered by linear Fresnel Concentrator was carried out to study the effect of the collector area and the storage tank size on the daily performance under Cairo climate. The model described in this paper simulates the performance of double effect $LiBr/H_2O$ absorption powered by hot oil heated through LFR. An auxiliary backup heating unit was used. The effect of the tank size and collector area on the performance of the LRF solar collector and the absorption chiller was investigated. Also, the effect of the tank size on the energy consumed by the backup gas heater was investigated. The optimum storage tank size and collector area were estimated. These investigations and studies were carried out using the TRNSYS software.

2. System Description

The solar absorption cooling system in this investigation depends on coupling a double–effect $LiBr/H_2O$ absorption cooling machine with LFR solar collectors. The solar collectors are used as a heat source for heating the heat transfer fluid (HTF), which is synthetic oil. The LFR collector filed consists of 13 modules; each module has 18 flat mirrors with 0.41 m in width and 4 m in length. The total collector area is 384 m^2. A stratified storage tank was used between the solar concentrator and the absorption chiller for maintaining a constant energy input to the absorption machine. A variable speed pump was used to circulate the hot oil from the solar collector to the stratified storage tank. Another constant speed pump delivers the heated oil from the storage tank to the single effect absorption chiller. A backup gas heating unit was inserted between the collector and the storage tank and used to supply heat for the storage tank in the case of un-adequate solar radiation. The absorption chiller is connected with a cooling tower as shown in Fig. 1. The LFR solar collector was mounted with horizontally and rotates around a single north-south axis.

For maintaining the temperature rise of the LFR higher than 3 ºC an on/off differential controller was used. When the oil temperature rise of the LFC is smaller than 3 ºC the controller sends a signal to the pump to stop the oil circulation through the solar concentrator. The operation of the second pump which pumps hot oil from the storage tank into the absorption chiller is controlled by another differential controller. When the hot oil temperature in the storage tank is higher than 110 ºC the controller sends a signal to the second pump to push the hot fluid into the absorption chiller. The modeling and simulation in this study were carried out using the components library of TRNSYS17 and TESS, a widely used simulation program [20].

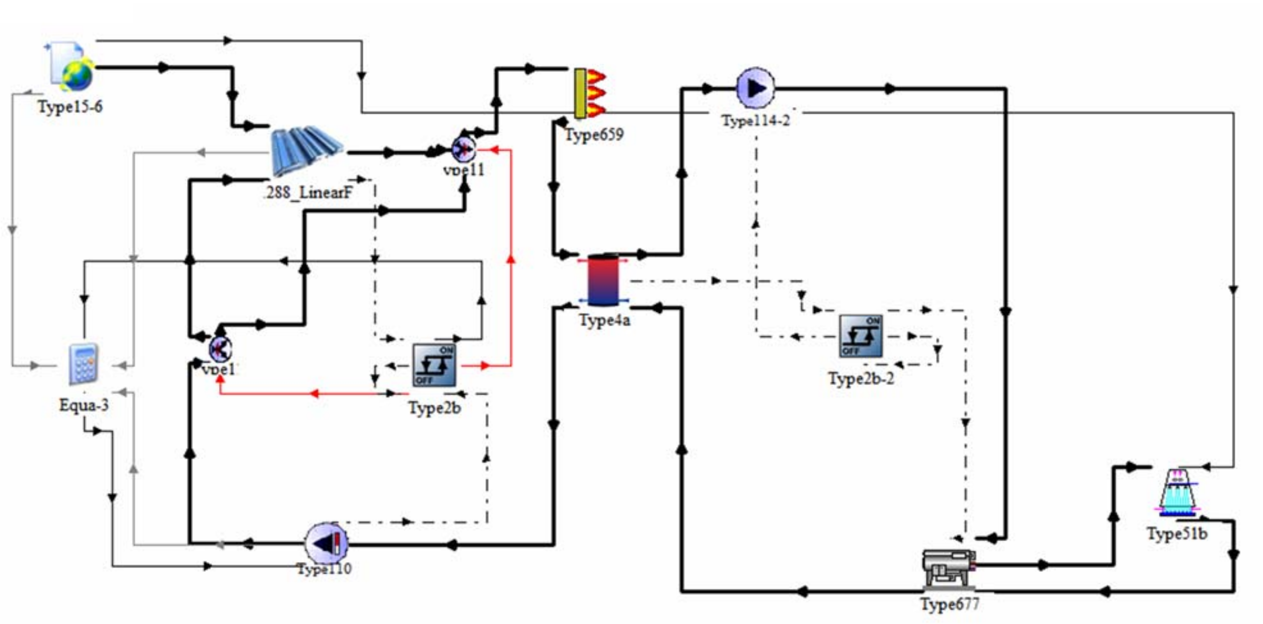

Fig. 1. The layout of the TRNSYS simulation model for solar absorption cooling system with LFC

3. Modeling of the Solar Cooling Plant

The previously described configuration of the solar absorption cooling system is modeled in TRNSYS 17 simulation program. TRNSYS is software used for academic purposes to simulate the thermal and electrical performance of the dynamic systems. It includes a large library of built-in components in addition to the TESS library. The components models are linked together to form the desired system.

The following assumptions have been taken into consideration while building the model of the system:

- The heat losses are only considered in the tank. i.e. heat losses in the pipelines and heat exchangers are negligible.
- The heat transfer to the oil through the pump was neglected.
- Thermal properties of the oil are assumed to be constant.
- The thermal storage tank is mounted in the vertical orientation to promote thermal stratification.

The solar absorption cooling model including the main components and subcomponents are schematically shown in Fig 2. The main components functions of the absorption cooling system are described as follow.

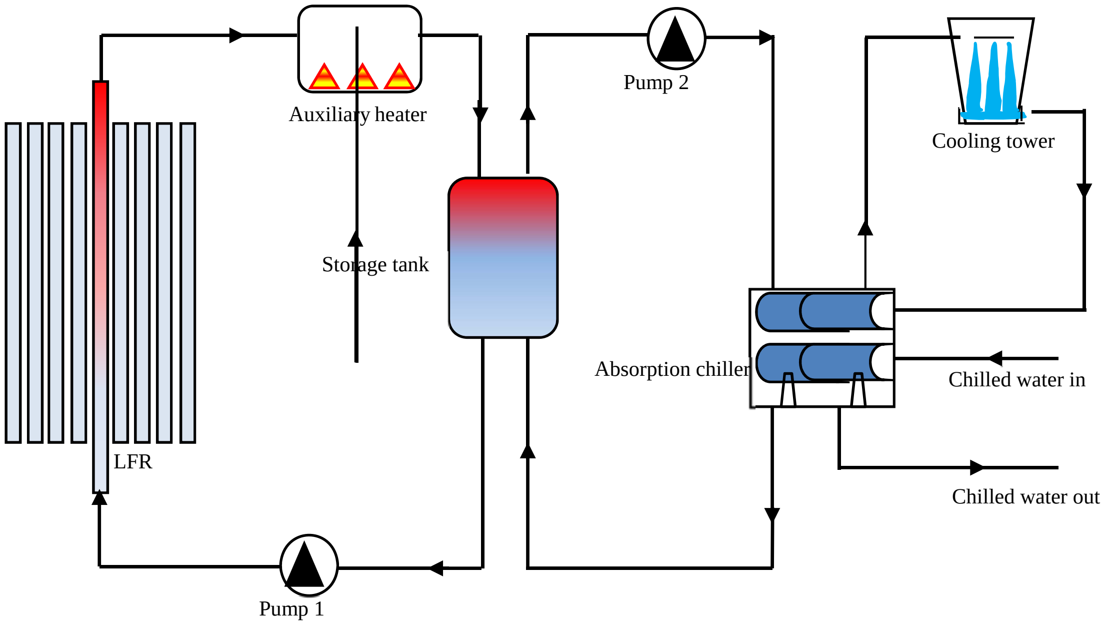

Fig. 2. A Schematic diagram for the solar cooling plant.

1. Linear Fresnel concentrator (Type 1288): this subroutine model the thermal performance of linear Fresnel solar concentrator. This type of solar collector is used in high-temperature applications. Where the solar radiation is concentrated in line focus. A heat transfer fluid (HTF) flow in an evacuated receiver tube that located in the line focus. The HTF is heated due to the conversion the concentrated solar ration into heat, the heated HTF flow to the storage tank. In this version, the incidence angle modifiers are to be provided in a look-up table as a function of the longitudinal and transverse angles. The efficiency equation for this concentrator is based on the EN12975-2-2006 standard using the dynamic efficiency equation approach.
2. Stratified Storage Tank (Type4a): The stratified storage tank with uniform losses models the thermal performance of a storage tank. The storage tank is subject to thermal stratification. The model is designed on the assumption that the storage tank consists of 25 equal segments of equal size.
3. Absorption Chillier (Type 677): model the thermal performance of a double-effect LiBr/H_2O absorption chiller. The energy supplied to the machine’s generator comes from a hot fluid stream.
4. Auxiliary heater (Type 659): model an auxiliary heater to supply a fluid at a desired temperature. This subroutine works as a heat exchanger and calculates the energy delivered to hot fluid stream and the outlet fluid temperature.
5. Cooling Tower (Type 51b): In this component, a hot water stream is in direct contact with an air stream and cooled as a result of sensible heat transfer due to temperature differences with the air and as a result of mass transfer resulting from evaporation to the air. The air and water flow paths are configured in counter-flow arrangements. Ambient air is drawn upward through the falling water. The cooling tower is composed of four tower cells that are in parallel and share a common sump. The loss of water from the tower's cells is replaced by compensatory water to the sump.

4. Results and Discussion

In this section, several runs were carried out using the simulation TRNSYS program on the proposed solar cooling plant under Cairo climate. The thermal performance for the cooling plant was investigated for three days three days in summer and winter. The effects of the collector area and the tank size on the collector outlet temperature and energy gained were investigated. The days selected for the study represent the actual climate condition for Cairo in each season. The days selected are from 27 to 29 of January and July for winter and summer seasons, respectively. The ambient and solar beam radiation for three days in summer and winter was presented in Fig. 3. The ambient temperature varies between 8.6 and 20 ºC in the winter days and varies between 21.2 and 35.1 ºC in the summer days. While the maximum solar beam radiation is 541 and 712 W/m^2 in the winter and summers days, respectively.

The rate of energy collected by solar LFC with an area of 350 m^2 was presented in Fig. 4 for different sizes of the storage tank. The size of the storage tank varied from 3 to 18 m^3 with 3 m^3 step. It can be observed that increasing the storage tank size from 3 to 9 m^3 leads to increasing the rate of energy collected from the solar concentrator. Insignificant effects were observed with increasing the storage tank size over than 9 m^3. This means that for solar LFC area of 350 m^2, the optimum tank size is 9 m^3. The rate of the energy gained of the LFC collector varied through the day as shown in Fig. 4. The maximum rate of energy collected was recorded around the solar noon time. Varying the storage tank from 3 to 9 m^3 lead to increase the maximum rate of energy collected from 123 to 145 kW and raising the storage tank to 18 m^3 leads to increase in the rate of the energy collected to 148 kW. Certainly, any change of the solar LFC area will result in a change in the previous values of the optimum storage tank size and the rate of energy collected.

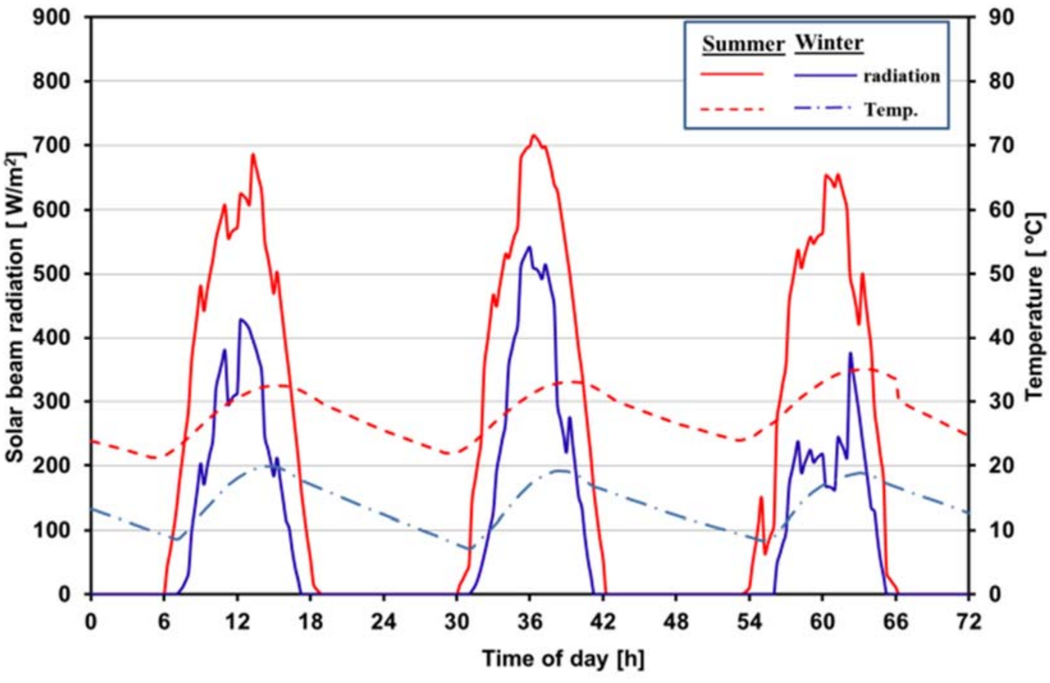

Fig. 3. The ambient and beam radiation for three days in summer and winter.

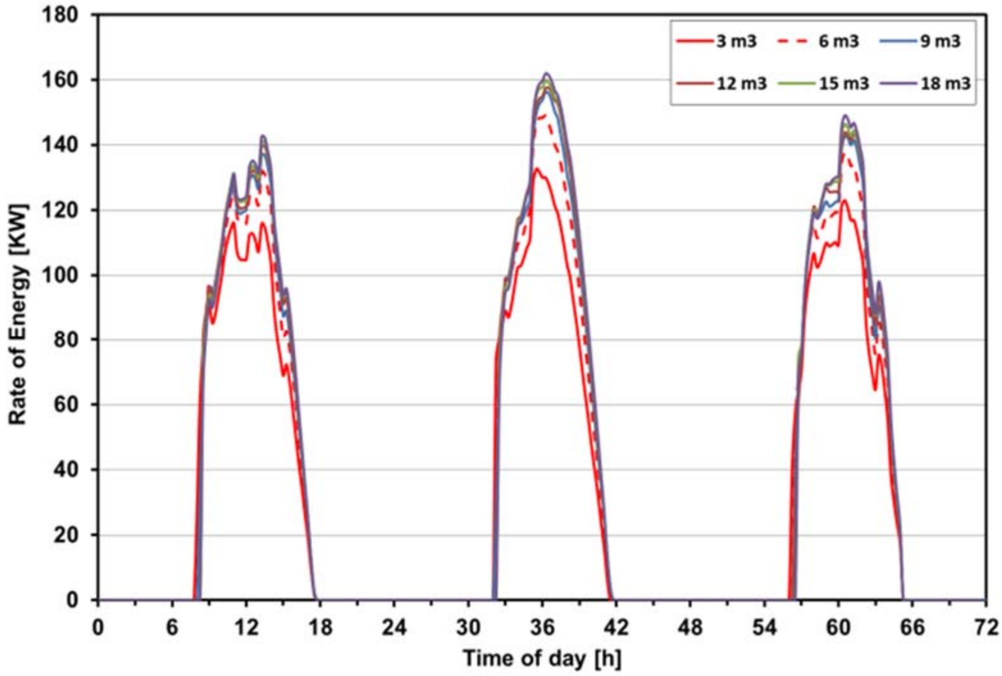

Fig. 4. The rate of the energy collected by the solar LFC at different storage tank sizes.

Figure 5 presents the effect of increasing the storage tank size on the rate of energy collected from the concentrator at different solar LFC area. It can be seen that the energy gained from the LRF solar collector increase with increasing the collector area. The storage tank has a significant effect on the energy gained for a tank size range from 3 to 9 m^3 for LFR solar collector area range from 290 to 350 m3. Any increase in the tank size more than 9 m^3 leads to an insignificant increase in the energy gained.

Figure 6 presents the profile of the LFC outlet temperature at different concentrator areas from the figure it can be observed that there is a continuous increase in the outlet oil temperature with increasing the area of the solar LFC. The maximum outlet oil temperature increases from 154 to 198 ºC at solar noon for the first day. The slightly decreasing in the temperature profile through the next two days can be attributed to the lower temperature of the bottom layers of the tank than their initial values consequently lowering of the inlet temperature to the solar LFC collector. The variation of the outlet oil temperature with the collector area is illustrated in Fig. 7 for different mass flow rate. From the figure, it can be observed that for each mass flow rate there is a maximum collector area where an increase in the collector area after this value has no effect on the outlet temperature. Where it can be found that for oil flow rate of 500 kg/h, there is no increase in the outlet temperature for increasing of the concentrator area over than 400 m^2. With increasing the oil flow rate to 3000 kg/h, the maximum collector area will increase to 2200 m^2 as shown in Fig. 7.

The variation of outlet oil temperature from the solar LFC collector is presented through one day for different storage tank sizes in Fig. 8. The outlet hot oil temperature decreases with increasing the storage tank size in the middle of the day. But decreasing the tank size leads to a sharp decrease in the outlet temperature after the daytime period and that can be attributed to the low energy stored in a smaller size. Increasing the storage tank size from 3 to 18 m^3 for the same collector area, 380 m^2, results in a decrease in the outlet collector temperature from 182 to 120 ºC, respectively. The positive effect of increasing the storage tank size is keeping the outlet collector temperature higher through the after sunset period.

The effect of the storage tank size on the energy consumed by the backup gas heater is presented in Fig. 9 for three days in summer. From the figure, it can be concluded that the maximum energy consumed by the backup heating unit was for a tank size of 3 m^3 during the night period and the energy consumed by the backup heating unit decrease with increasing the tank size. However, during the daytime, the effect is inverse where increasing the volume of the tank increases the energy consumed by the reserve heater. The increase in energy consumption during the daytime is low compared to the decrease in energy consumed at night period.

The variation of the absorption chiller COP through one day is presented in Fig. 10 for different storage tank size. The figure illustrates that the COP varying through the day as a result of varying the inlet hot oil temperature to the absorption chiller. However, increasing the storage tank size has a bad effect on the COP of the absorption chiller as shown in the figure. Where increasing the tank size from 3 to 15 m^3 leads to decrease the maximum COP from 0.46 to 0.07, respectively. It can be also observed that in the low tank size, 3 m^3, the COP has values for large period, from 10:30 to 19:30, while in the case of increasing the tank size to 15 m^3, the COP has values for small periods, 13:00 to 15:00. The previous observation means that for low tank size of about 3 m^3 the absorption chiller work for 9 hours with high COP while for big tank size of about 15 m^3 the absorption chiller work for only two hours with low COP. That can be attributed to temperature values of the inlet hot oil to the chiller.

The chilled water energy was predicted without a backup heater and with backup heaters of 15, 30, 45 and 60 kW as shown in Fig. 11. In absence of the backup heating unit, the cooling energy supplied to the chilled water depends only on the solar radiation as a heat source so it is possible to observe a change in the rate of cooling energy during the day and decay during the night. The addition of different heating units of different capacities has different effects on the rate of cooling capacity according to the heating unit power as seen in Fig. 11. A backup heating unit of 15 and 30 kW increase the period of operating the absorption chiller to 15:30 and 20:15 h per day, respectively. While a heating unit of 45 kW gives a continuous operation of the absorption chiller with low cooling energy rate at night. Install a backup heating unit of 60 kW provides a continuous cooling with more stability at night a slight increase at the noon period.

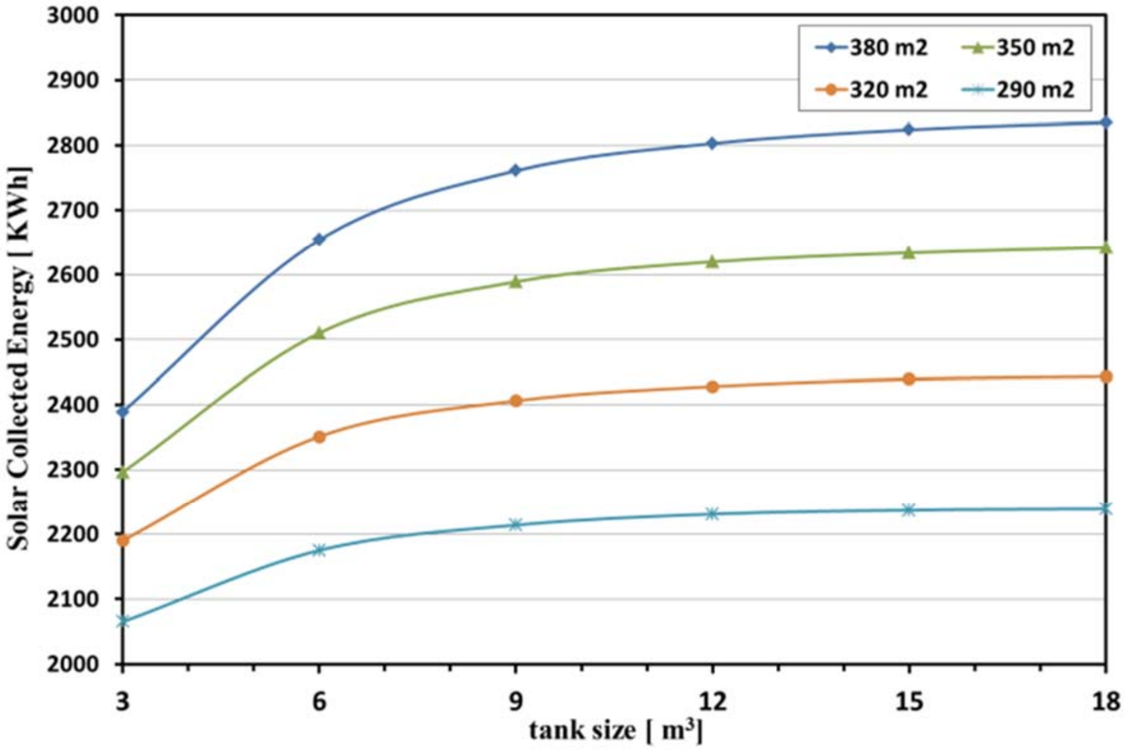

Fig. 5. **Effect of the storage tank size on the rate of energy gained from the concentrator at different collector area.**

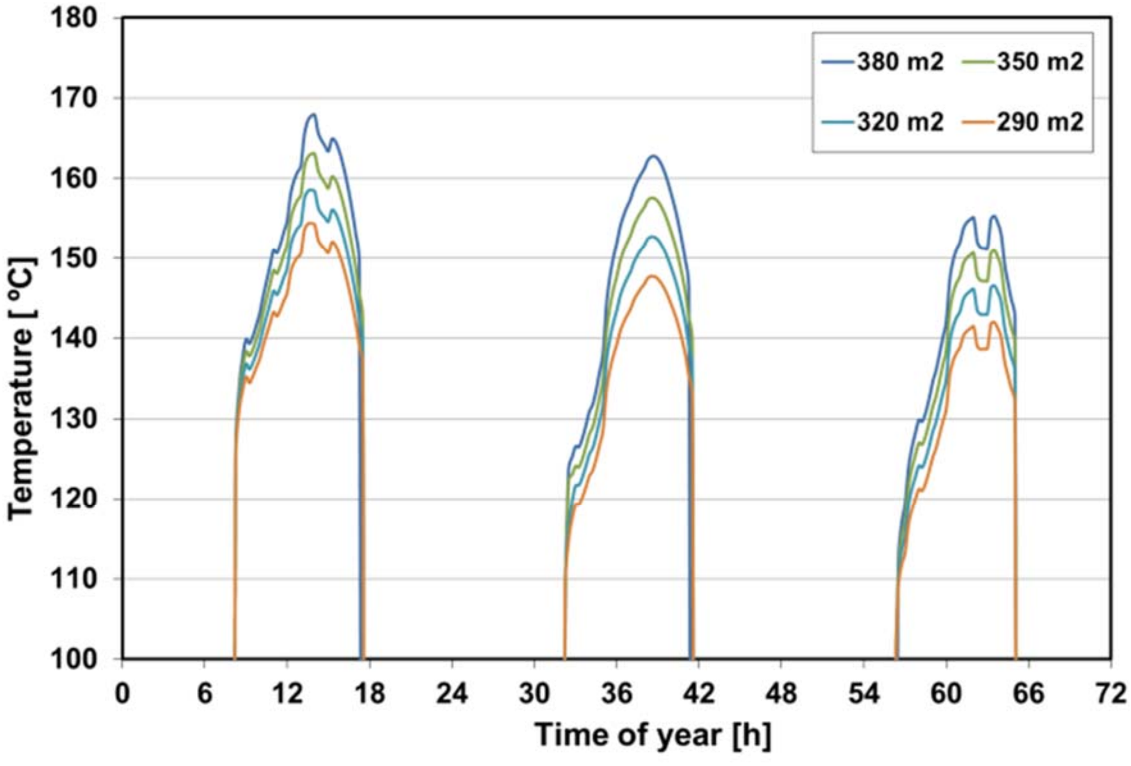

Fig. 6. **Effect of the storage tank size on the rate of energy gained from the concentrator at different collector area.**

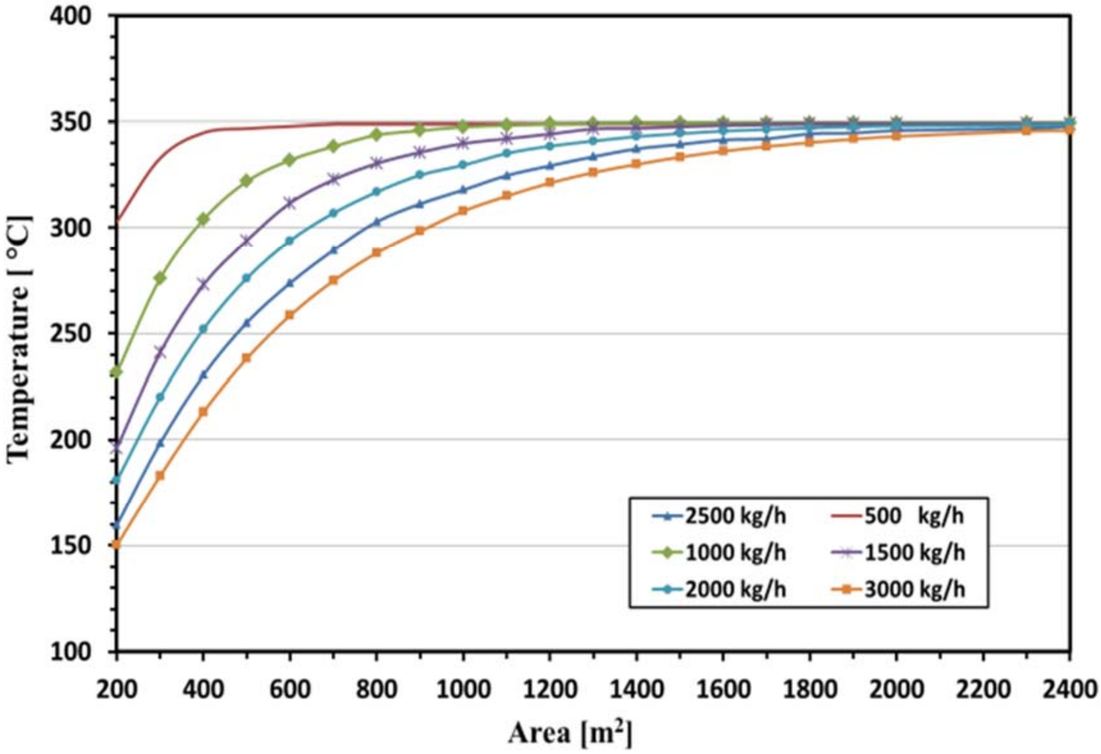

Fig. 7. Variation of the collector outlet temperature versus the collector area at different mass flow rates.

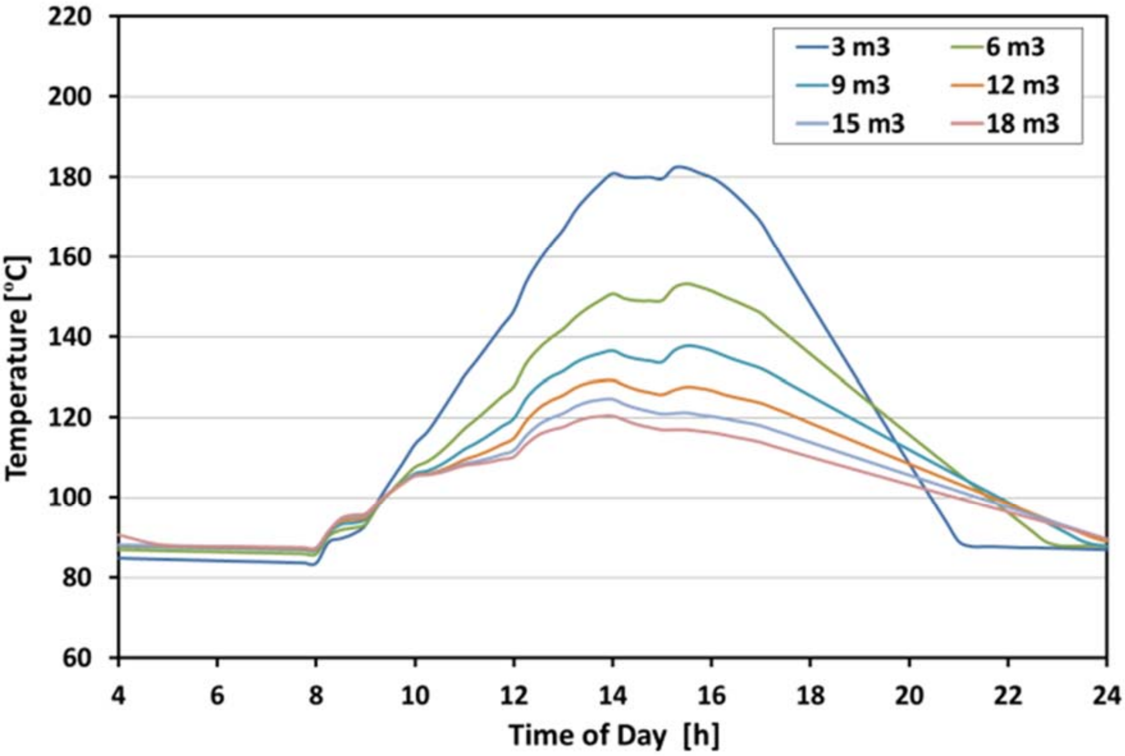

Fig. 8. The outlet temperature of the solar LFC at a different storage tank sizes.

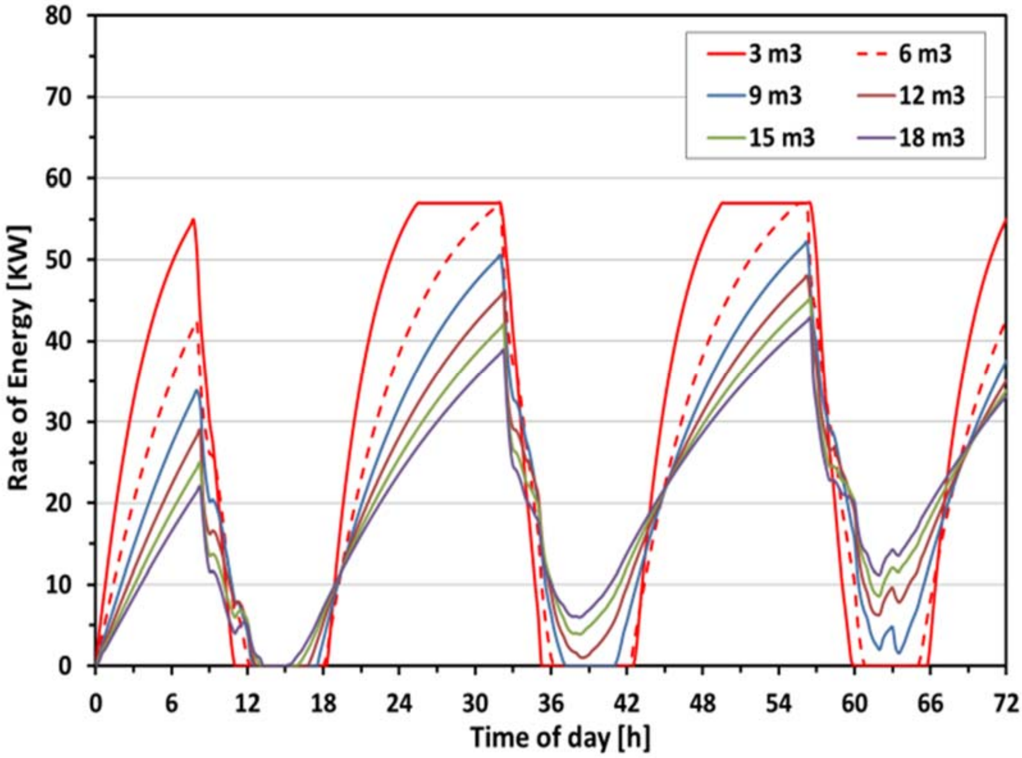

Fig. 9. The rate of energy consumed by the backup heater unit at different stage tank sizes.

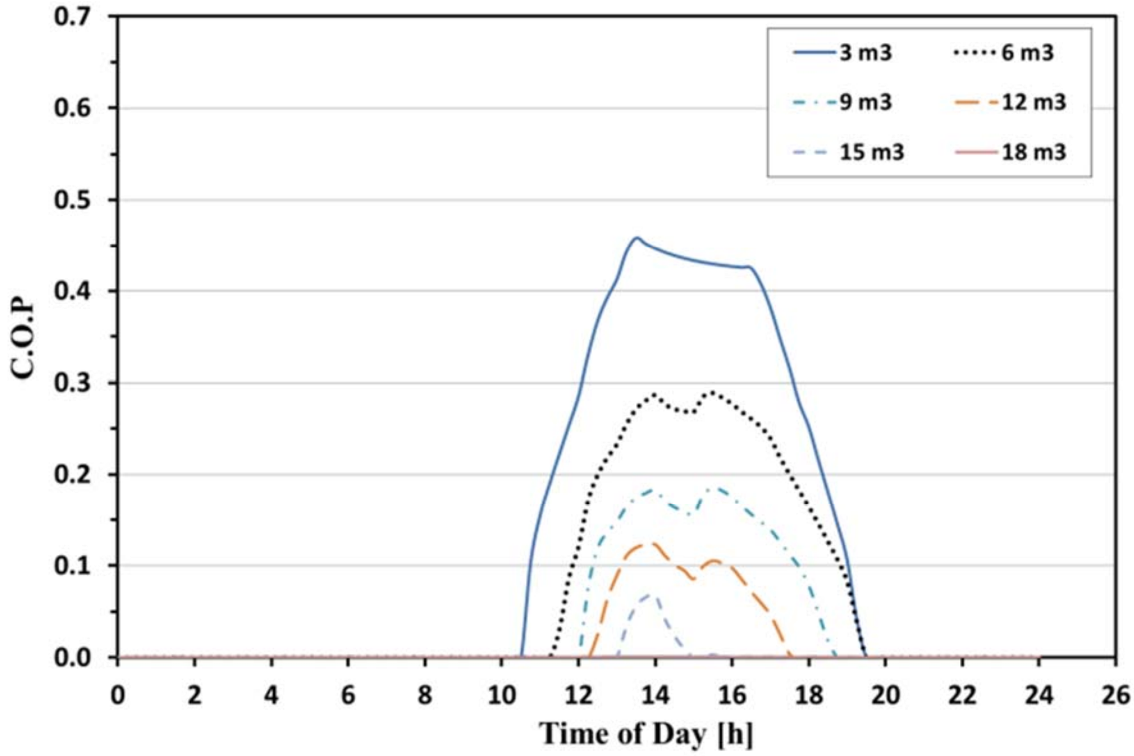

Fig. 10. The COP of the absorption chiller at different storage tank sizes through one day in summer.

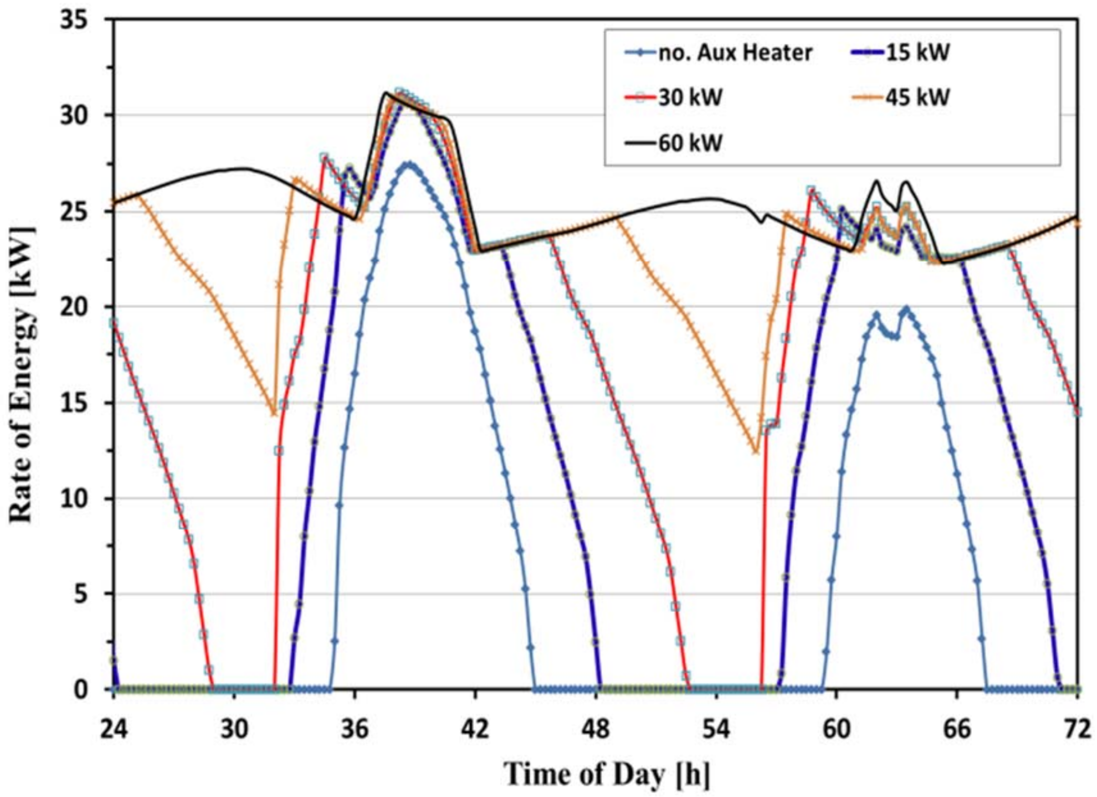

Fig. 11. The absorption chiller cooling capacity without and with 15, 13, 45 and 60 kW backup heating unit.

5. Conclusion

Dynamic simulation of solar absorption cooling system was carried out using TRNSYS 17 software. The effect of the storage tank size on the outlet temperature and the collector energy gained from the LFC collector were investigated. The effect of the storage tank size and the capacity of the backup heating unit on the COP and the cooling energy supplied by the absorption chiller were also investigated. The following conclusions were summarized from the previous results and discussions:

- For LRF solar collector area range from 290 to 350 m^2, increasing the tank size from 3 to 9 m^3 lead to an increase in the collector energy gained while increasing the tank size more than 9 m^3 has an insignificant effect.
- For each oil mass flow rate, there is a maximum value of the collector area give the highest outlet temperature, increasing the collector area more than this value has no effect on the outlet temperature. Where varying the oil mass flow rate from 500 to 3000 kg/h results in an increase in the maximum collector area from 400 to 2200 m^2.
- The outlet temperature of the collector decreases with increasing the storage tank size during the daytime, but the higher tank size leads to supply hot oil to the chiller for a long time through the night period.
- Increasing the storage tank size has a bad effect on the COP of the absorption chiller, where increasing the tank size from 3 to 15 m^3 leads to decrease the maximum COP from 0.46 to 0.07 and decrease the operating period from 9 to 2 hours, respectively. As a result of decreasing the hot oil temperature less than the minimum value required to operate the chiller.
- The maximum energy consumed by the backup heating unit during the night period was when a 3 m^3 tank size was used, where the energy consumed by the backup unit decrease with increasing the tank size.
- Increasing the backup heating unit capacity from 15 to 30 kW leads to an increase in the operating period of 35 kW absorption chiller from 15:30 to 20:15 h/day, respectively. While a heating unit of 45 kW and more gives a continuous operation of the absorption chiller.

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