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Performance of Solar Adsorption Cooling System with Different Solar Collectors Technologies

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Abstract- The use of different solar collector technologies to operate the adsorption chiller unit is the topic of this article. As the selection of the appropriate solar collector is still random, as had used different solar collectors have been used to operate the refrigeration unit. Therefore, a program was designed using TRNSYS to study the effect of using different collectors on the adsorption unit performance. The effect of parabolic trough concentrator, compound parabolic concentrator, and the evacuated tube collector on the thermal performance of the absorption refrigeration unit was investigated in terms of cooling capacity, coefficient of performance, and the operating period of the adsorption chiller during the summer climatic conditions of Cairo. The results proved that the parabolic trough concentrator (PTC) has the best effect on the performance of an adsorption unit of 7 kW cooling capacity, where the maximum outlet collector temperature was 102 °C compare to 95.8 and 87.3 °C for the Compound Parabolic Concentrator (CPC) and the Evacuated Tube Collector (ETC) respectively. For solar collectors of 20 m^2, the weekly operation periods were 47, 32.24, and 25.75 hours for the PTC, CPC, and ETC respectively. These values increase with increasing the collector area. Also, for different storage tank capacities, the PTC has the best effect on the operation period of the adsorption unit compare to the other solar collectors. Where the operation period increases from 96.25 to 124.25 h with increasing the storage tank capacity from 2 to 6 m^3.

Keywords Solar energy, adsorption cooling, solar collectors, simulation, TRNSYS.

1. Introduction

In recent times, the demand for the use of new energy instead of fossil fuels has increased due to the high prices of conventional energy, especially in the Middle East region. One of the most energy-consuming devices in this region is the cooling and air-conditioning equipment in buildings. As the cooling and air conditioning devices consume about 50% of the total energy demand for buildings [1]. As it becomes well known, renewable energy has no negative impact on the environment from fossil fuels. Also, scientists predict the depletion of fossil energy [2]. On the other hand, air conditioners that operate with liquids such as chlorofluorocarbons (CFCs) have a bad effect on the Ozone layer and it also causes global warming phenomena [3]. Many countries have tended to use promising methods of cooling that use solar thermal energy at low to medium temperatures, which are the absorption and adsorption cooling methods. Whereas, solar thermal energy is a new alternative energy source to reduce the harmful effects of fossil fuels as well as to reduce the use of harmful gases in traditional air conditioning systems [4]. Different solar heating technolgies are used to supply heat energy for different applications [5]. Many scientists have done studies on the use of solar energy as a heat source to operate absorption and adsorption units [6,7]. The widespread use of solar cooling by the absorption method is due to the many advantages that it has [8]. Saeed et al. [10] used the Ammonia based absorption cooling chiller for saving energy. However, many features attract researchers to the use and development of adsorption cooling methods [11]. The low ranger of operating temperature, no moving parts, long lifetime, very low maintenance …...etc. are the main advantages of the adsorption system over the absorption cooling system [12,13]. Different solar collector technologies to power the adsorption cooling system were investigated separately. Zhai and Wang [14] used evacuated tube collectors (ETC) with an adsorption cooling system using, the used ETC supplied the adsorption chiller with heat over 100 °C. the results proved that the coefficient of performance (COP) was affected by the collator area of the ETC, where the COP increase from 0.32 to 0.37 for a collector area of 80 to 240 m^2, respectively. Alam et al. [15] investigate the use of a compound parabolic concentrator (CPC) to drive solar adsorption cooling system. The results proved that the maximum COP of the cycle was 0.55 and the COP of the solar cycle was around 0.3. Gonzales and Rodrıguez [16] investigated experimentally a solar adsorption cooling system powered by CPC collectors where the receiver tube contains the adsorbent material, they used the activated carbon–methanol as working pair. Wang et al. [17] used CPC with activated carbon and methanol as a working pair to decrease the cycle time and improve the performance. The experimental results show that the COP increased by 27 %. and the rate of absorption has been clearly noticed. Januševičius et al. [18] simulated a small-scale adsorption cooling system with an ETC collector and a gas boiler as a backup heating system using TRaNsient SYstem Simulation (TRNSYS). The results were specific for the case under investigation only. Many researchers have used the parabola trough concentrator (PTC) to drive the adsorption chiller. Abu- Hamdeh et al. [19] used an adsorption chiller driven by PTC and the working fluid was olive waste-methanol pair. The results showed that the lowest temperature of 4 °C was attained for the cooled space with a COP of 0.75. In another research, the activated carbon -ammonia working pair were used with a PTC the COP of this unit recorded a value of 0.141 at an evaporation temperature of 0 °C [20]. El Fader et al. [21] present a theoretical study of a continuous adsorption refrigeration system powered by parabolic trough solar collector (PTC). the proposed system achieved an SCP of 104 W/kg, COP of 0.43, and it produced daily cooling energy of 2515 kJ per 0.8 m^2 of collector area.

As for the research efforts that focused on simulation, it was found that most simulation programs that were used in simulating the thermal performance of the solar adsorption cooling system are TRNSYS, MATLAB, and Engineering Equation solver (EES) or the combination of them. Assilzadeh et al. [22] investigated using TRNSYS the thermal performance of absorption chiller driven by evacuated tube collector under the climate of Malaysia. It was found from the results that an ETC with an inclination of 20 degrees and an area of 35 m^2 would be sufficient to meet the requirements of a 3.5 kW absorption chiller with a volume of a thermal storage tank of 0.8 m^3. A simulation program developed on TRNSYS-ESS to design a solar collector with a solar ejector cooling system. The dynamic hourly performance and the overall system performance were investigated and the ejector was modeled by EES [23]. Longo et al [24] analyzed the performance of an adsorption refrigeration system and compared it with a vapor compression cooling system, they used the TRNSYS program for the analysis and evaluation process. The comparison was during the lifetime of the system, where it was found that the vapor compression cooling system is better than systems based on renewable energy for a lifetime of about 10 years. while at a lifetime of 15 to 25 years, the devices that depend on renewable energy show better features under different weather conditions for all European regions. Palomba et al. [25] provided a tool for designing an adsorption solar cooling unit using the TRNSYS platform, and the model were validated through available data from the real refrigeration unit at Shanghai University. Vasta et al. [26] build a dynamic model on the TRNSYS platform to simulate the performance of a solar adsorption cooling system. The model was used to predict the effect of operation and design parameters on the overall system performance.

This work aims to investigate a small-scale solar adsorption system powered by three types of solar collectors. The solar collectors that are used in the study are the parabolic trough concentrator (PTC), the compound parabolic concentrator (CPC), and the evacuated tube collector (ETC). The study includes the effect of the collector used on the thermal performance of the adsorption cooling system unit in terms of the adsorption chiller capacity, the coefficient of performance of the chiller, and the operating period. The study includes also the effect of each collector surface area and the storage tank capacity on the adsorption chiller capacity and the operating period of the chiller.

2. System Description

The solar adsorption cooling system consists of different components as shown in Fig.1. the main components are the adsorption colling unit, solar collector, storage tank, cooling tower, pumps, valves, and fan coil for supplying conditioned air for two office rooms. The solar collector receives the solar irradiance and transfers it into heat, this heat is transferred by a heat transfer fluid (water) and stored in a sensible storage tank with a pump. Another pump pumps the hot water from the storage tank to the 7 kW adsorption unit, which then returns to the tank. The adsorption chiller needs cooling water for the condensation and adsorption processes, the cooling water circulates in a closed circuit and is cooled by a water-cooling tower. The chilled water which is cooled inside the evaporator in the adsorption cooling unit is pumped directly into a fan coil. The cooled air in the fan coil is distributed through a diverter into two rooms. The different solar technologies used in the comparison study are the parabolic trough concentrator, compound parabolic concentrator, and the evacuated tube collector.

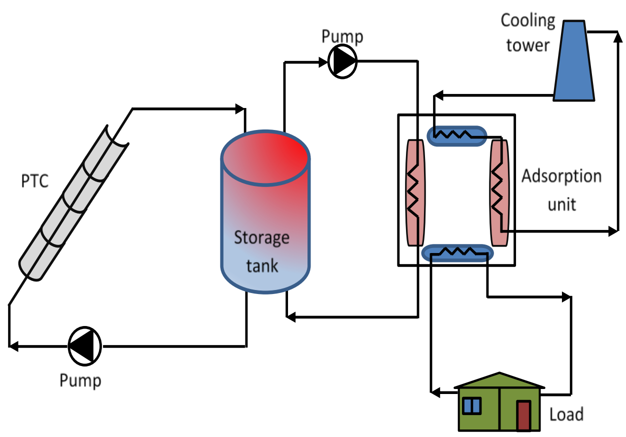

Fig. 1. Schematic diagram of the solar adsorption refrigeration system

3. Simulation Model

The transient simulation system program TRNSYS17 was used to model the solar adsorption cooling system. The model consists of several components called types; each component represents a simulation block for the solar cooling system. The components are connected where the output results of the components can be inputs for the other components. The types of the TRNSYS and the TESS libraries are used to build the solar adsorption colling model. The model view for the solar adsorption cooling components with the PTC in the TRNSYS platform is shown in Fig.2. The components used in the models are as follow:

3.1. Solar Collectors

Three solar collector technologies are used in this model. The first solar collector is the ETC and it is represented by type71, CPC that is presented by Type 74, and the PTC which is presented by type 1288. the thermal efficiency η of the ETC is given as following [24]:

$$\eta = a_0 - a_1 \frac{\Delta T}{I_T} + a_2 \frac{\Delta T^2}{I_T} \tag{1}$$

Where a_0, a_1, and a_2 are heat losses coefficients, It is the total solar radiation, ΔT is the temperature difference (T_m - T_{amb}).

The PTC component (type 1288) models the thermal performance of the parabolic trough concentrator. The model of this collector is based on the following equation [27]:

$$\dot{Q}_u = R_1 R_2 A_{ap} [F_R (\tau\alpha)_n \, IAM \cdot I_b - \frac{F_R U_L}{Cr} (T_{in} - T_{amb})] \tag{2}$$

Where $\dot{Q}$ is the useful energy gained from the PTC, Tin is the inlet fluid temperature, (τα)n is the product of the glass transmissivity and receiver tube absorptivity at the normal direction, FR is the heat removal factor, IAM is the incident angle modifier, R_1 and R_2 are modifier correlation.

The CPC component (type 74) provides for the theoretical analysis of compound parabolic concentrators (CPC). The Hottel-Whillier steady-state model is used for evaluating thermal performance. The useful outlet energy gain is calculated as follow:

$$\dot{Q}_u = F_R A_{ap} \left[I_{in} (\tau\alpha) - U_L (T_{in} - T_{amb}) \right] \tag{3}$$

Where Iin is total solar radiation entering the aperture area of the CPC and calculates as follow [27]:

$$I_{in} = F_b I_b + F_{sky} I_d + F_g \rho_g I \tag{4}$$

Where F_b, F_{sky}, and F_g are the view factor to the sun, sky, and the ground respectively. I_b is the beam radiation, I_d is the diffuse radiation and I is the total solar radiation on the horizontal surface.

3.2. Storage Tank

This component (type 4a) models the performance of a stratified storage tank. The storage tank is divided into 40 horizontal segments, each segment has a homogeneous fluid temperature. The heat and mass transfer governing equation was written for the ith segment. The type solves the equations for all segments and calculates the temperature of each segment. The outlet hot temperature to the load exit from the top segment and the outlet cold temperature to the heat source exit from the bottom segment.

3.3. Adsorption Chiller

This component (type 909) models the performance of the adsorption chiller. The chiller is powered by hot water from the storage tank (type 4a). this type is based on a data file containing normalized COP ratios and capacity as a function of the cooling water inlet temperature, the chilled water inlet temperature, and the hot water inlet temperature.

3.4. Cooling Tower

This component (type 51b) models a multi-cell counter flow cooling tower. The hot water is cooled by a sensible heat transfer as a result of contacting the hot water with the airflow and is cooled also by mass transfer due to the evaporation of the water to the air. The water losses in the tower in substituted by make-up water to the sump.

3.5. Fan Coil

This component (type 995) simulates the performance of a fan coil where the performance of the coil is read from an external data file containing the normalized total and sensible cooling data as a function of the entering air dry bulb and wet bulb temperatures, the airflow rate, the liquid flow rate, and the entering cooled liquid temperature.

3.6. Weather Data

This component (type 15) is a reader of the data file in a different format, in this study the weather date data file in TMY2 format was used for Cairo.

The TRNSYS program connects all previous components to form a complete model for the solar adsorption cooling system as shown in Fig. 2. The simulation was carried out for one week in June and the calculation was done every 15 minutes.

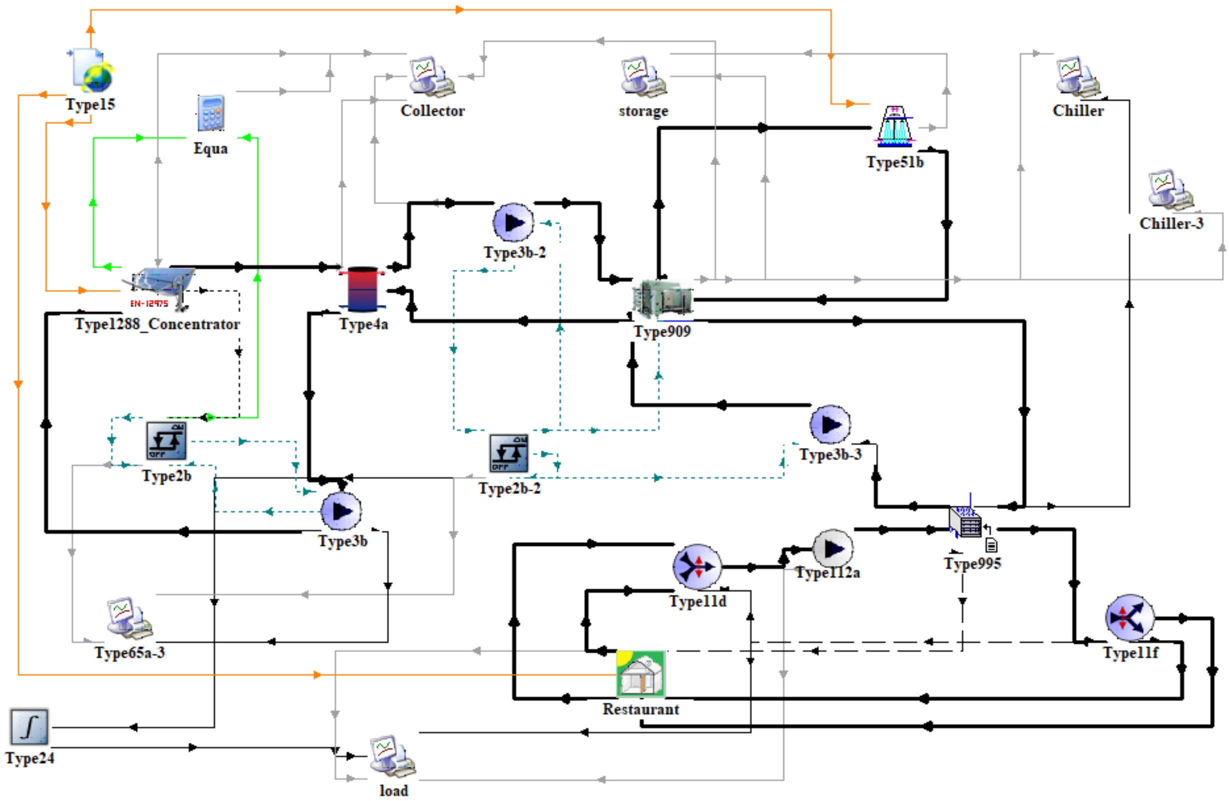

Fig. 2. View of the TRNSYS project for the solar adsorption cooling system.

4. The Results

This section presents the results of the simulation program for the solar adsorption cooling system at different solar collector technologies. The program performed the simulation under the climatic condition of Egypt, Cairo (30.02° N, 31.13° E) for the first week in June. Figure 3 present the instantaneous solar beam, diffuse and total radiation for four days in June, as well as the ambient temperature. From the figure, it can be seen that the total radiation varies from 295 W/m² at sunrise to 955 W/m² at solar noon, while the beam radiation various from 184 W/m² to 929 W/m².

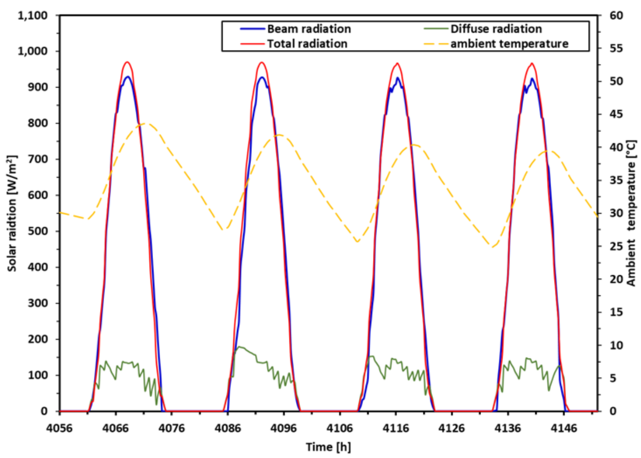

Fig. 3. The beam, diffuse, and total solar radiation on a horizontal surface through 4 days of June.

Comparison between the measured and TRNSYS meteorological data for Cairo during four days in June is presented in Fig 4. The difference between the measured and TRNSYS Data doesn't exceed 6 % for total solar radiation and 9 % for ambient temperature.

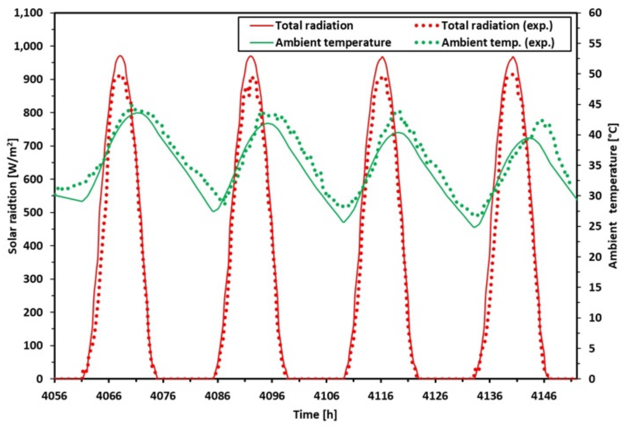

Fig. 4. Comparison between the measured and TRNSYS meteorological data for Cairo during four days in June.

The outlet fluid temperature from the solar collector is an important parameter to drive the adsorption chiller. The outlet temperatures of the PTC, CPC, and the ETC are presented in Fig. 5 through four days in June for a collector area of 40 m². From the results, it can be observed that the outlet water temperature of the PTC has the highest value compared to the CPC and the ETC. Where the maximum outlet temperatures through the four days, were 99.75, 93.8, and 86.7 °C for the PTC, CPC, and ETC respectively.

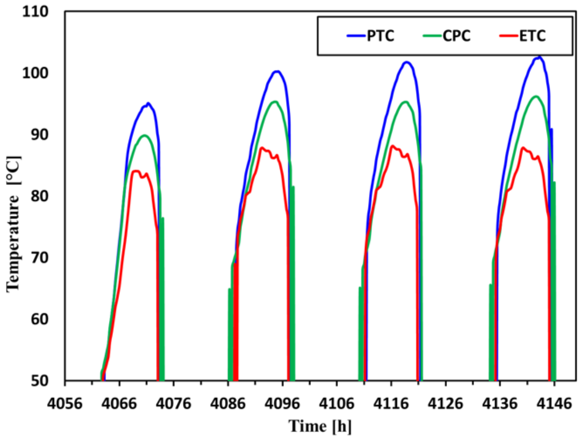

Fig. 5. Comparison between the outlet temperature for the PTC, CPC, and ETC solar collectors.

Figure 6 presents the rate of energy gained for the PTC, CPC, and ETC through four days at a collector area of 40 m^2. The rate of energy gained from the PTC is slightly higher than the CPC as shown in the figure. The maximum value of the rate of energy gained from the PTC, CPC, and the ETC are 26.5, 25.8, and 21.7 kW, respectively.

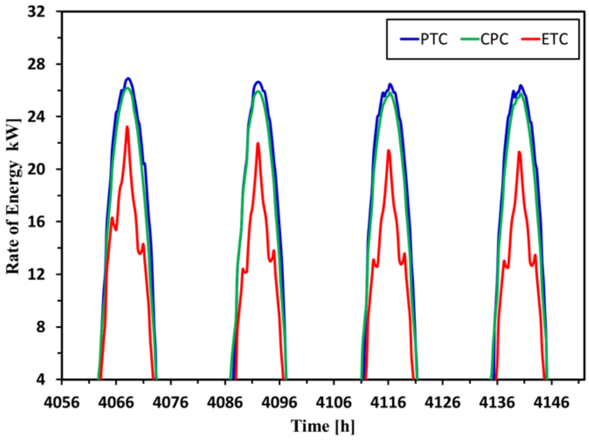

Fig. 6. Comparison between the rate of collector energy gained for the PTC, CPC, and ETC.

The effect of the solar collector area of the PTC, CPC, and ETC on the adsorption chiller COP are illustrated in Fig. 7 to Fig. 9. In these figures, the surface area of the solar collector changes from 20 to 60 m^2. Figure 7 present the adsorption chiller COP for different PTC collector's areas. Increasing the PTC collector area increases the Chiller COP, where increasing the collector's area from 20 to 40 m^2 results in an increase in the COP from 0.51 to 0.6 respectively. it can be also observed that increasing the area from 40 to 60 m^2 leads to an increase in the operating period of the chiller to its rated COP which is 0.6. The effect of the CPC collector's area on the COP of the adsorption chiller is presented in Fig. 8. From the figure, it can be seen that increasing the collector's area from 20 to 40 m^2 results in an increase in the COP from 0.52 to 0.6 respectively. it can be also observed that increasing the area from 40 to 60 m^2 leads to an increase in the operating period of the chiller to its rated COP. Figure 9 illustrates the effect of increasing the collector area of the ETC on the COP of the adsorption chiller. From Fig. 9, it can be observed the same observations as in the previous two solar collector types, but we find that in this type we need to increase the area of the collector from 20 to 60 m^2 to reach the rated COP of the adsorption chiller. For the ETC collector's area of 60 m^2, it can be observed that the COP of the adsorption unit reaches its rated COP for a short time, 2 hours, around solar noon.

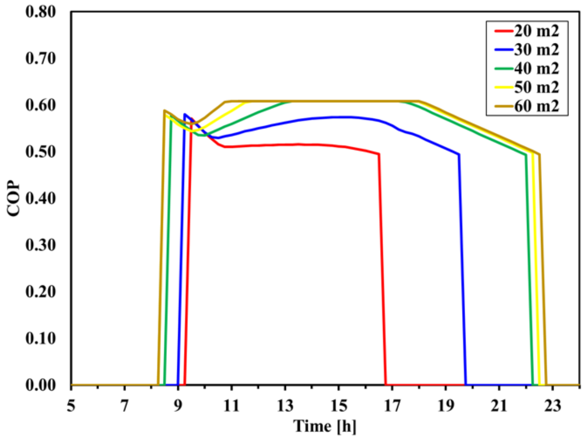

Fig. 7. Variation of the adsorption chiller COP for the PTC collector at different collector areas.

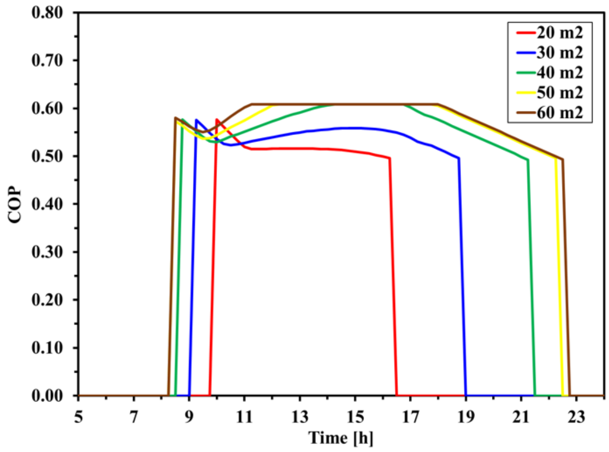

Fig. 8. Variation of the adsorption chiller COP for the CPC at different collector's areas.

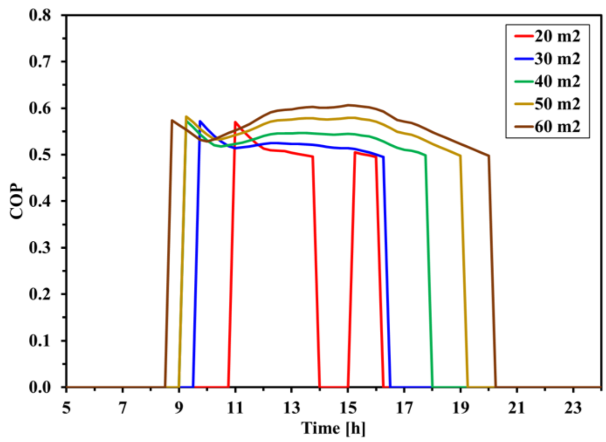

Fig. 9. Variation of the adsorption chiller COP for the ETC collector at different collector areas

The accumulation of the adsorption chiller energy through one week is presented in Fig. 10 for the PTC, CPC, and the ETC for different collector's areas. It can be observed an increase in the weekly chiller energy with an increase in the collector surface area from 20 to 60 m^2. Where increasing the PTC's surface area from 20 to 40 m^2 increases the weekly chiller energy from 1.11 to 2.65 GJ, respectively. Also increasing the CPC's surface by the same value increase the weekly chiller energy from 1.01 to 2.65 GJ. While for the ETC, the weekly chiller energy increase from 0.6 to 2 GJ. It can be easily observed a good performance for the PTC in terms of weekly chiller energy compared to the CPC and the ETC.

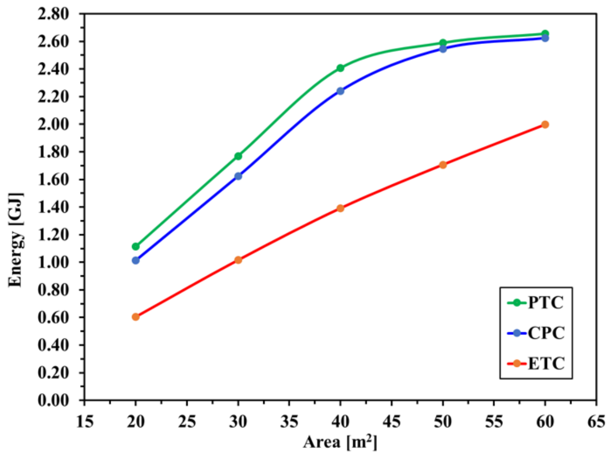

Fig. 10. Variation of the weekly chiller cooling energy of the PTC, CPC, and ETC at a storage capacity of 2.5 m^3.

The collector surface area of the different solar collector technologies has an important effect on the operation period of the adsorption chiller as shown in Fig. 11. It can be seen that the operation period of the adsorption chillier with the PTC collector increase from 47 to 102.75 h with increasing the collector surface area from 20 to 90 m^2, and for the CPC the operation period increases from 32.25 to 101.5 h, while for the ETC the weekly operation period increases from 25.75 to 91.5 h. It can be also observed a big difference in the operation period of the adsorption chiller for both PTC and CPC compared to ETC. It can be attributed to the higher concentration ratio of the PTC and CPC.

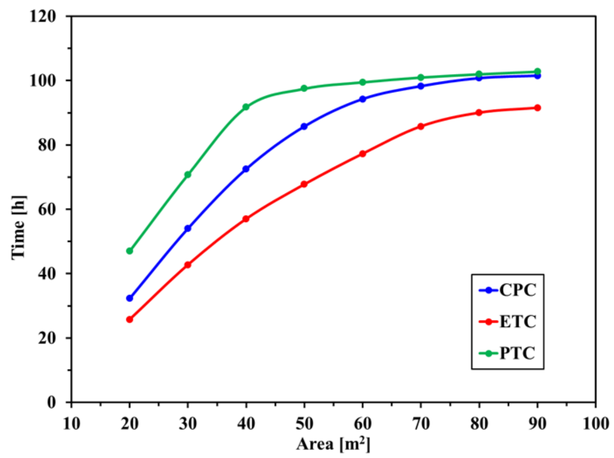

Fig. 11. Variation of the weekly chiller operation period of the PTC, CPC, and ETC at a storage capacity of 2.55 m^3.

Figure 12 present the effect of the storage tank capacity on the operation period of the adsorption chiller for the PTC, CPC, and the ETC for different solar collector's areas. For the solar collector area of 30 m^2, increasing the storage tank capacity from 2 to 6 m^3 leads to a decrease in the operating period for the adsorption chiller for all collector types. This decrease in the operation period is attributed to the time consumed to raise the fluid temperature inside the storage tank to the desired level to operate the adsorption chiller. For solar collectors' area of 60 m^2, increasing the storage tank capacity from 2 to 6 m^3 leads to an increase in the operating period of the adsorption chiller with the PTC from 93.25 to 124.25 h, respectively. While with the CPC, ETC solar collector the operation period increases slightly up to a tank capacity of 3 m^3 then decreases again with increasing the tank capacity to 6 m^3.

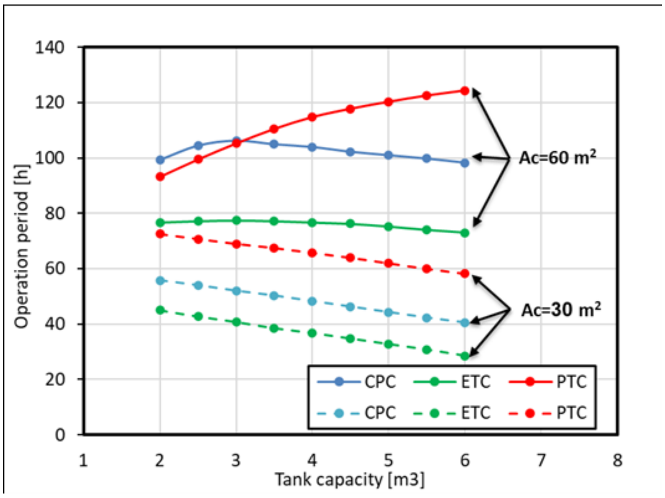

Fig. 12. Effect of the storage tank capacity on the weekly operation period of the adsorption chiller for PTC, CPC, and ETC for two collector's surface areas.

5. Conclusion

The solar adsorption cooling system is an important issue to replace the air conditioning units powered by fossil fuel with the system powered by renewable and clean energy especially solar energy. This work uses the TRNSYS program to model the effect of different solar collector technologies which are PTC, CPC, and ETC on the performance of the adsorption chiller. From the previous results, it can be concluded that the PTC collector is the best choice compared to the other types. Where it gives the best performance for the adsorption chiller in terms of adsorption chiller capacity, operation period, and COP. Where a PTC surface area of 40 m^2 is enough to reach a COP of 0.6 which is the rated COP of the adsorption chiller. The PTC collector operates the chiller for 47 and 102.75 h for a collector surface area of 20 and 90 m^2, respectively. The weekly chiller cooling energy increases from 1.11 to 2.65 GJ with increasing the PTC collector area from 20 to 60 m^2. From the previous conclusion and results, the simulation model can be considered as a valuable tool to investigate the performance of the adsorption chiller under different solar collectors' types and surface areas.

Acknowledgements

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