Investigation The performance of a Linear Fresnel Solar Concentrator Integrated with an Adsorption Refrigeration Cycle

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Abstract. A large amount of the energy produced is used for heating and cooling application. Many studies at the present time are looking for ways to reduce this consumption or use a renewable energy source to reduce dependence on fossil fuel energy. In this research, the used of solar energy to power a hybrid adsorption ice-maker, a linear Fresnel solar concentrator type, with a total area of 5 m², is used for this purpose. The concentrator was designed, built, and conducting an experimental study in Baghdad (latitude 33.33 and longitude 44.14) for the solar system that which is consisting of the concentrator with a double absorber type evacuated tube has been used, tank, pump and accessories to investigate the performance of the system and the effect of the water flow on the unit performance. The performance of the adsorption system is studied theoretically. The adsorption system works with the activated carbon-methanol pair the mass of activated carbon is 0.5 and while the mass of methanol is 1.6 kg. The experimental work was achieved at July 2019 and the results showed that the maximum temperature of the water inside the tank obtained was 95 °C when the rate of water flow through the collector loop was 0.5 kg/min and that the maximum thermal efficiency was about 40% at the same flow amount. The theoretical results showed that the best coefficient of performance for the adsorption refrigeration system was 0.43 at the generator temperature of 95 °C and the condensing temperature of 30 °C.

1. Introduction
Energy is an essential and permanent topic of study in society today, it is necessary for powering of the technological civilization that have been built. Since the life daily trend shows an increase in technology. Because of increasing global energy demand, depletion of the fossil fuel, the rising in price rate of electricity and environmental issues due to emission of carbon dioxide it's necessary to use other alternative energy resources [1].

It is undeniable that a large quantity of energy is used for heating and cooling. International Institute of Refrigeration (IIR) has estimated that approximately 15% to 20% of power generation worldwide is used for refrigeration and air-conditioning [2]. It is memorable that the cooling requirements during the summer are more prominent in places have higher solar irradiation. Using a solar refrigeration system is a way to take advantage of the fact that the cooling necessity is one way or another proportional to solar radiation.

Adsorption refrigeration system uses the physical adsorption phenomenon to get the cooling effect. The principle operation of these systems depends on the adsorption dynamics of the adsorbent and adsorbate (working pair). Essentially, any change in the temperature changes the capacity of adsorbent at a given porous material (absorbent) on adsorption. This temperature change can be as low as 60–80
° depending on the type of working pair, which makes this type of systems simply powered with solar energy or waste heat. Solar adsorption refrigeration (SAR) system offer many advantages as compared with vapour compression refrigeration systems; it is comparatively easy to construction, the materials are affordable and, depending on the working pair operating them is environmentally friendly. Minimum maintenance required because such a system have a less moving nor electrical parts and no operative costs. This technology can help regions with plentiful solar energy resources, especially those where the use of conventional cooling systems is expensive and difficult through the non-existent electricity distribution networks [3]. In this work, a linear Fresnel solar concentrator type was adopted to power an adsorption refrigeration system with experimentally analyse the performance of the concentrator and conducted a theoretical study to analyse the performance of the refrigeration system based on the output of the concentrator.

2. Operating Principle
A hybrid system of solar-powered water heater and adsorption refrigeration is one of the alternatives for efficient heat-recovery which described by many works [4-8]. It consists of solar collector, storage tank, pumps, adsorption bed (generator), condenser, and an evaporator that is placed in a refrigerator box as showing in figure 1. The working fluid in this system is the water that is heated in linear Fresnel solar concentrator (LFSC) and circulated with storage tank as a heat exchanger. In the adsorption bed the adsorbent (activated carbon) can adsorb a large amount of refrigerant vapour (methanol) at ambient temperature. After the water reaches to satisfied temperature about 80-100 °C then the water was pumped from the tank to the generator that content the adsorbent and adsorbate at a high mass concentration. In desorption, the liquid refrigerant adsorbed in the adsorbent heats up and desorb. The refrigerant vapour condenses in condenser by released the heat to the environment and is stored in the evaporator. Water was used to decreases the temperature of the adsorption bed to the ambient temperature, and the adsorbent adsorbs the refrigerant from the evaporator. The liquid refrigerant in the evaporator vaporizes and absorbs the heat from the water contained in the container and take the refrigeration effect.

3. Performance of LFSC
The following formulae have been used for analysis the thermal performance [9]. Equation (1) is used to calculate the useful energy by taking energy balance in the volume of working fluid. This equation has been used in the experimental and numerical evaluation steps.

\[ Q_u = \dot{m} \cdot c_p \cdot (T_o - T_i) \]  

where:
\( \dot{m} \): mass flow rate of water (kg/s)
\( c_p \): specific heat of water (W/m².K)
\( T_o \): outlet temperature of water (°C)
\( T_i \): inlet temperature of water (°C)

The available solar energy \( Q_a \) for the collector is used to calculate the collector area as in equation (2). This quantity resulted from the product of the direct beam solar irradiation DNI and of the total aperture area of the collector \( A_p \). It is necessary to note that the reflectors have presupposed to employ the incident solar radiation in the horizontal plane and therefor the total aperture area of the collector is treat to be the projection of the all mirrors on the horizontal plane.

\[ Q_a = A_p \cdot DNI \]  

The ratio of the useful energy output to the available solar energy is the definition of thermal efficiency, according to equation (3).

\[ \eta_{th} = \frac{Q_u}{Q_a} \]
4. Experimental Work

A linear Fresnel solar concentrator was designed, manufactured, instrumented and tested at Baghdad (33.33°N latitude and 44.14°E longitude). A modular designed developed by Jaramillo [10] was used to determine the mirror inclination and the distance among its rows in which no shading and blocking occur between them during the operation period. The concentrator consists of nine mirrors with width 20 cm and 200 cm long. The aperture area of the collector was 3.26 m$^2$ and the total area of 5 m$^2$. A water system consists of 40 liter tank, Polyvinyl chloride (PVC) pipes and a centrifugal pump was used to feed the collector by water during day time. The collector is tracking the sun during day time using an automatic tracking system.

The mirrors were installed on a separated frame made from hollow galvanized rectangular of 200 mm width. Each mirror frame was supported by a hollow steel shaft of 25 mm in diameter. The shaft was installed on the main collector frame by two ball bearings. The ball bearings was used to provide a free rotational movement around the shaft. The nine mirrors were installed on the main collector frame, as shown in figure 2.

To obtain a high efficiency solar collector, it is necessary to focus the reflected solar radiation from the mirrors to a secondary reflector. The secondary reflector is in the form of Compound Parabolic Cavity (CPC). The length of the secondary reflector is 2000 mm in length and 282 mm aperture width it's installed at a height of 1750 mm above the middle of the main frame. The dimensions of the concentrator are calculated using a set of equations [10], only the mirror width and concentrate height are input to these equations to give the other dimensions.

The secondary reflector consists of two CPC sides made from mild steel of 6 mm thickness and stainless steel reflector. The CPC side is design and drawn using AutoCAD software and cut using a laser CNC machine. The reflector is made of 0.7 mm thickness, 2000 mm length and 1200 mm width, stainless steel is used. Then the CPC sides and the reflector are assembled to form the final shape of the secondary reflector as shown in figure 3.

Two conventional evacuated tubes of 48 mm inside diameter, 58 mm outside diameter with length of 1800 mm are modified and installed in the receiver to transport the water through the collector focal as shown in figure 4.

![Figure 1. The Schematic Diagram of the Adsorption Ice Maker.](image-url)
Figure 2. Linear Fresnel Solar Concentrator Designed Model.

Figure 3. Outer Shape of Receiver.

Figure 4. The receiver
4.1 Tracking system
The tracking system is needed to pick up the benefit of the maximum direct beam radiation from the sun. The design of the tracking system of this collector depends on multiple actuators as shown in figure 5, and this means that each mirror have own operator which rotating around its axis at a very slow angular velocity to keep the reflected beam focused on the secondary reflector. Single-axis north-south orientated tracking system is designed and fabricated for this module, A 9 DC stepper motors of 2 N-m torque are used so it’s connected with mirror rod using a simple mechanical coupling and controlling by Arduino Microcontroller.

Figure 5. Tracking System used in the LFSC.

4.2 The Experimental Instrumentation Setup
A high operating temperature 75 W pump of type DAB VA 65 is used for circulated the hot water from the LFC to the heat exchanger tank. The capacity of the pump ranging from 0.5 to 6 m³/h, with a head of 6 m, the operating pump temperature is from -10 to 110 °C.
The temperature of the water, air, and volume flow rate of the water, solar irradiance were measured using different instrumentations as follows.
The temperatures were measured in three-point the first two at the inlet and outlet of the collector absorber tubes for measuring water temperature and the third for measuring ambient temperature. Type DS18B20 sensors were used for measuring the air and water temperatures. The sensor temperature range are from -55 to 125 °C. The accuracy of those sensors over the temperature range from -10 to 85°C is ±0.5 °C according to the sensor manufacturer. The measured data are saved in a micro card adapter reader of types SDHC.
A Digital solar power meter of type TES-1333 used to measure the solar irradiance during the day time in a wide spectral range up to 2000 W/m², resolution 0.1 W/m² and accuracy typically within ± 10 W/m² or ± 5.
The water flow circulated from the heat exchanger tank to the collector was measured using water flow meter LZM-15J series zyia OEM acrylic panel with operation range 0.5-4 LPM and ± 4% accuracy. It consists of a variable area section, on which gradients are placed to show the reading, and inside it contains floated part moves with the force of water flow.
The geometric design parameters of the collector are illustrated in the table 1
Table 1. Design parameters of LFSC.

| Design parameters of LFSC | Value | Unit |
|---------------------------|-------|------|
| NO of mirror row          | 9     |      |
| Mirror width              | 200   | mm   |
| Module length             | 2000  | mm   |
| Center focal length       | 1750  | mm   |
| Aperture area             | 3.26  | m²   |
| Concentration ratio       | 6     |      |
| No of absorber tube       | 2     |      |
| Absorber tube diameter    | 48    | mm   |
| Glass cover diameter      | 58    | mm   |
| Receiver coating absorbance| 0.93 |      |
| Reflectivity of mirror    | 0.94  |      |
| Reflectivity of secondary reflector | 0.7  |      |
| Transmissivity of glass cover | 0.89 |      |

5. Results and Discussion
The effect of mass flow rate of the water through the LFSC on the inlet and outlet water temperature, the theoretical performance of the adsorption refrigeration cycle were studied using EES Software. The experimental work was achieved in Baghdad at 5th of July when the mass flow rate of water is 0.5 kg/min and the collector was operated during the time from 9:00 to 16:00 and the presented results are taken every hour.

The weather data measured at the examined day are presented in figure 6 more especially the direct normal irradiance DNI and the ambient temperature are taken for the examined hours, it can be seen from the figure that the maximum solar radiation was at 12:00 and the maximum ambient temperature at 16:00. In this day the maximum ambient temperature reached up to 46 °C while the maximum solar intensity is about 840 w/m².

![Figure 6. The DNI and Ambient Temperature for Examined Day.](image)

The effect of the water mass flow rate on the outlet temperature of water from LFSC was shown in Figure 7, it can be seen from the figure that the maximum outlet temperature when the mass flow rate of water was at 0.5 kg/min. The increases in the mass flow rate to 1 kg/min shows a sharp reduction in the water outlet temperature.

The increases in mass flow rate of water more than 1.5 kg/min show an insignificant increase in the outlet temperature. This effect can be seen clearly from Figure 8, so, the maximum difference between inlet and outlet water temperature was for the minimum water mass flow rate of 0.5 kg/min because of the long exposure period of water to solar radiation. The temperature difference at the early time of the day shows maximum value since the inlet water temperature is at the minimum value, this leads to reduce the heat lost from the collector.
Figure 9 shows the inlet and outlet water temperatures at July 5, 2019, at water mass flow rate of 0.5 kg/min. It can be seen from the figure that the maximum difference between the inlets at outlet water temperatures is at the early time of the day. The temperature difference tends to decrease along the day time; this is because of the increases in thermal loss due to the high inlet water temperature. The figure shows the minimum temperature difference at about 16 hr. the water temperature reaches the operating temperature of the adsorption unit at 14 hr. As it is expected that the maximum useful energy is early day and reduces to the minimum at the end of the day, as shown in figure 10. While the hourly collector thermal efficiency is shown in figure 11. The figure shows that the maximum hourly thermal efficiency is at the beginning of the day and reaches the minimum at the end of the day.

Figure 7. The Effect of Mass Flow Rate of Water on the outlet Water Temperature.

Figure 8. The Effect of Mass Flow Rate of Water on the Water Temperature Difference.
Figure 9. Water Temperature Difference.

Figure 10. Hourly Useful Energy Produced.

Figure 11. Hourly Thermal Efficiency.

Figure 12 shows the effect of the mass flow rate of water on daily thermal efficiency. The figure gives impression that the mass flow rate of water have slight effects on the performance of the collector. The maximum daily thermal efficacy is about 40% at 0.5 kg/min mass flow rate of water and the average efficiency during the day is about 25.4%. A plentiful quantity of energy is delivered on 19th July it’s in about 5.43 kW. While the least energy obtained on 23th is 4.7 kW as shown in figure 13.

Figure 14 shows the effect of condensing temperature on the methanol concentration in the adsorption pair when the evaporator temperature is kept constant at 0 °C, and the mass ratio of adsorption pair is 0.5 kg methanol and 1.6 kg activated carbon. It can be seen from the figure that, as the adsorbent temperature increase the methanol concentration decrease and when it reaches a temperature of 120 °C then the effect becomes insignificant. Reducing the condensing temperature from 40 to 20 °C reduces
the concentration in about 58% at low adsorbent temperature and less than 33% for high adsorbent temperature above 120 °C.

As it is well known that the evaluation of any refrigeration system is through the calculation of the coefficient of performance cycle (COP). The COP is the ratio of the refrigeration effect to the heat power input to the cycle. Figure 15 shows the effect of generator temperature on the cycle COP, it can be seen from the figure that the best COP can be reached for the condensing temperature in the range 30 to 35 °C when the generator temperature range from 95 to 110 °C above the temperature range mentioned above the COP tends to reduce, as well as at the high generator temperature the cycle COP are almost equal especially when temperatures above 110 °C.

Figure 16 shows the relation between ice production and cycle COP at different condensing temperature when the generator temperature is 90 °C, it can be seen from the figure that as the condensing temperature increases the amount of ice production, as well as the cycle COP reduces, this is because as the condensing temperature increase the amount of adsorbed methanol reduces, which reflects negatively on the ice production, and then of the cycle COP.
Figure 14. Mass Concentration of Methanol within Active Carbon.

Figure 15. Coefficient of Performance at a Various Absorbent Temperatures.

Figure 16. The Relation between Ice Production and Cycle COP at Different Condensing Temperature when the Generator Temperature is 90 °C.

5. Conclusions

1. Increasing the mass flow rate of water more than 1.5 kg/min show an insignificant increase in the outlet temperature.
2. The maximum water temperature in the storage tank was 95 °C at the mass flow rate 0.5 kg/min of the collector loop.
3. In the adsorption system for adsorbent temperature above 120 °C the change in the methanol concentration become little.
4. Reducing the condensing temperature from 40 to 20 °C can reduce the methanol concentration in about 58% at low adsorbent temperature and less than 33% for high adsorbent temperature above 120 °C.
5. When the condensing and generator temperatures at 30 and 95 °C respectively the peak COP of the adsorption refrigeration cycle is about 0.43.

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