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PERFORMANCE OF A HEAT PIPE SOLAR COLLECTOR WITH EVACUATED POLYCARBONATE FRONT COVER

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In this research, the effect of vacuum on the thermal efficiency of a heat pipe solar collector is investigated. A comparative study of solar energy loss through different transparent covering materials, including different thicknesses of clear Polycarbonate (PC) and glass sheets, is performed to choose the best covering material. The results of solar energy loss tests show that for a 4mm, and 6mm thickness covering materials, transparent PC sheets have 11% and 22% less solar energy loss respectively than glass sheets. Three cases of flat heat pipe solar collector with different covering designs that are: no cover, non-vacuumed, and vacuumed double layer PC sheets are tested. Results show that the combination of a 4mm high transmittance PC cover with vacuumed spacing results in an overall collector thermal efficiency of about 70% in comparison with only 57% for non-vacuumed double layer PC cover.

Keywords: solar collector, heat pipe, thermal resistance, transparent PC sheets.

NOMENCLATURE:

Symbol	meaning and unit	Subscripts	
A	area (m^2)		
C_p	Heat capacity (J/kg.k)	In	incident solar irradiance
I	solar irradiance (W/m^2)	Out	solar irradiance passing through the sheet
m'	water flow rate (kg/s)	W	water
T	temperature (^oC)	w_o	water out
Q	heat (W)	w_i	water in
η	efficiency (%)		

1 INTRODUCTION

Energy demand has always been growing as the number of the population grows. Recent data show that in 2020, 47% of total heat consumed globally accounts for space and water heating sections [1]. In Europe during 2018, 64% of energy consumption in the residential sector was for heating purposes [2]. The increase of environmental awareness encourages implementing more sustainable energy resources like solar, wind, and ocean waves to reduce the consumption of fossil fuel. Solar water heating is one of the available solutions for space and water heating purposes. Different sustainable and green technologies are used for solar water heating, such as flat plate collectors, parabolic reflector tubes, and evacuated solar collectors. The last two methods have the advantage of having higher working temperatures, consequently higher efficiencies [3]. Flat plate solar collector is a widely used device in solar energy applications because of its simplicity and low cost in comparison with other types of solar collecting equipment. According to Kessentini et al [4], this type of collector can provide collector temperatures up to 100^{o}C with reasonable efficiency. Also some collectors can provide steam for some applications [5].

Many researchers have studied the usage and efficiency of flat collectors with different operational variables such as geographic setup location, inclination angle, the working fluid, and other factors. Other researchers have discussed different enhancement techniques like implementing Nanofluids, concentrating solar energy, using sun-tracking systems, and others. For instance, Papademetratos et al. [6] used a phase change material within an evacuated region of a solar tube. This method enables energy storage that can be used in peak demand time or incoming solar radiation shortage. This technique has shown an increase in the thermal efficiency of about 26% during regular operation time and a 66% increase in stagnation operation in comparison with regular design solar tube collectors. In addition, Abd-Elhady et. al. [7] studied the method of adding oil and foamed metal to improve the thermal efficiency of a heat pipe solar collector within a vacuumed tube. The results show that adding oil will enhance the heat storage, and heating efficiency as well since oil will provide a medium for convection heat transfer from the walls of vacuumed tube to the heat pipe. One other method that has been used to improve the performance of solar collectors is by implementing nanotechnology. As an example, Kiliç et al. [8] used Titanium dioxide nanoparticles that are added to water (2% by weight of TiO_2) as a circulation fluid to investigate the performance improvement of a flat collector. The results of this research show that an improvement of about 12% was achieved using Nanofluids additive in comparison to pure water only as a working fluid. In addition, Sarafraz et. al. [9] performed an experimental study to investigate the usage of carbon nanoparticles with acetone used inside of a collector using an evacuated tube design. Different parameters were studied including nanoparticle concentration, filling ratios, tilt angle and solar irradiance. The results show that addition on nanoparticles at wt. of 0.1% resulted to the highest thermal performance at a certain flow rate. Some researchers have focused on investigating the usage of heat pipe as heat transfer media. Azad [10] has made a theoretical and experimental study on the usage of a heat pipe as a part of a solar collection device. The researcher developed a theoretical approach using the effectiveness-NTU model to predict the thermal performance of the solar collector. The experimental results show a maximum efficiency of about 65% at around noontime but decreasing rapidly as solar radiation intensity decreases afternoon. Vacuumed chambers is another method that is used to improve the performance of solar collectors. Liang et al. 2011 [11] conducted a theoretical and experimental study of the thermal performance of a circular section double wall solar collector with a U shape fluid passage in the cases of filled core or hollow core. A vacuum is applied at the in-between layer to increase thermal insulation from the hot layer to the environment. The experimental data show that the thermal efficiency of the filled tube thermal collector is 12% higher than the hollow evacuated collector. Vacuumed flat plate collectors have also received noticeable attention as the vacuum will reduce heat transfer losses from the hotter core of the solar collector to the cooler environment. Some research has studied the performance of flat plate theoretically as in Shemelin and Matuska [12], who performed a theoretical analysis of the efficiency of flat plate solar collector with a vacuum applied at the covering glass. The results of the analysis show that using glass with low emissivity coating results in a higher thermal efficiency equal to or even better than vacuumed tube collectors.

Regarding collector covering material type, glass has been the most popular covering material specifically for flat collectors because of its availability, reasonable cost, and good optical properties [13], [14]. Most researchers use glass as a covering material for different solar applications. The researches that deal with the effect of cover type material on the performance of solar devices are limited and seldom. For instance, Bozkurt et al. [15] studied the effect of cover material type on the operation of a cylindrical solar pond that is used as a thermal energy storage technique. Three covering materials are used in this study, including glass, Polycarbonate, and transparent mica covers. In this research, monthly energy content is calculated for the solar pond. The results show that glass cover gave a slightly better overall efficiency than Polycarbonate cover with values of 17.86 and 16.95%, respectively.

Compared to glass, which is the most common covering material for solar collectors (and other solar devices), polycarbonate sheets are more expensive as an initial cost, prone to scratch. However, with new development in the polymer industry, newer versions of Polycarbonate sheets are available in the market that have higher optical characteristics and better ultraviolet light resistance. With the existence of this new polycarbonate types, there is scarce data about using newer Polycarbonate sheets as transparent cover instead of glass sheets. The current study aims to provide new data on evaluating the performance of flat solar collector following two pathways. The first is by studying solar energy transmission through different collector covering materials, including Polycarbonate and glass sheets with different thicknesses to determine the best material with the least solar energy loss. The second path is to design, fabricate, and test a flat heat pipe solar collector using different Polycarbonate covering cases, including no cover, double layer cover, and a vacuumed double layer covering. This procedure will provide a better understanding of the role of vacuum on the thermal performance of a flat solar collector using higher solar transmittance Polycarbonate covering.

2 SOLAR COLLECTOR DESIGN

This study aims to measure the performance of a heat pipe solar collector with a transparent double layer covering. The effect of a vacuum of the gap between the double-layer covering on the overall collector efficiency is also investigated. For this purpose, an experimental test rig is designed, fabricated, and tested to meet the goals of the research. Thesystem consists of a wooden frame with dimensions of 1000 x 570 x 70 mm, as shown in Figure 1. Eight heat pipes are built and installed inside the frame. Each heat pipe is made of a copper tube with 1100 mm length, 20 mm outside diameter, and 1.2 mm wall thickness. The tubes are brazed at both ends, and an HVAC service valve is attached to the upper end for air evacuation and working fluid injection. The tubes are evacuated using an HVAC vacuum pump to 0.1 Pa, then 61 mL of Acetone as working fluid is injected into each tube, filling 20% of its volume. The heat pipes are coated with matt black paint to increase the absorptivity of solar radiation. Heat energy is absorbed by working fluid through 1000 mm of the heat pipe length that works as an evaporator.The working fluid evaporates and transmits heat to the upper 100 mm of the pipe that works as a condenser, where working fluid vapor condenses and releases heat to water flowing inside a water channel with dimensions of 570 x 50 x 120 mm. To minimize the heat loss from the system to the surrounding, 30 mm of glass wool is installed at the inner surface and inner sides of the frame box beneath the heat pipes, as well as the outer surface of the water channel.

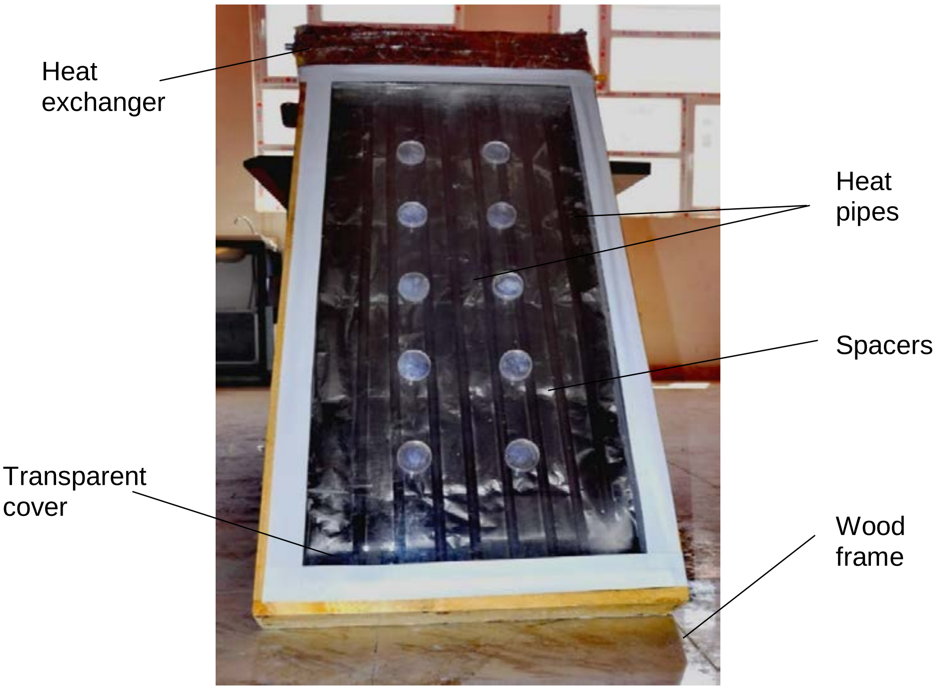

Figure 1. The final layout of the solar collector.

To ensure maximum solar energy transfer through the top transparent cover, a set of experiments were conducted on five sheets of glass and clear Polycarbonate (PC) sheets (Palram, model: SUNLITE®) with different thicknesses to evaluate solar energy loss through these materials. Solar loss, or optical efficiency as presented by Kalidasan and Srinivas [16], which is defined as the ratio of solar energy absorbed or reflected by the transparent cover over the total incident solar intensity. Two solar intensity sensors are used to evaluate the solar radiation prior and post the covering material so that solar intensity is measured before and after penetration of solar collector cover. These values are used to calculate the percentage of solar radiation loss as following [16]:

$$\text{Solar loss} = [(I_{in} - I_{out})/I_{in}] * 100\% \tag{1}$$

where I_{in}, I_{out} are the direct solar incident radiation normal to the surface before and after the transparent covering material respectively. Figure 2 shows a schematic diagram for the layout of the tests performed to calculate solar energy loss through cover sheets. As lower the energy loss as better the cover material since it permits more solar energy to pass through.

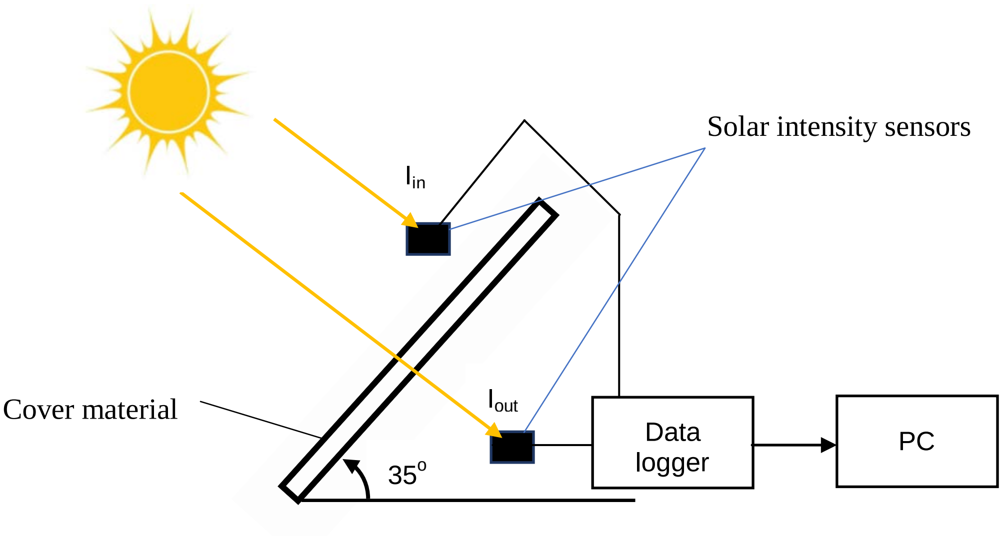

Figure 2. Schematic diagram for the layout used in the tests to calculate solar loss

The tests are performed during clear sunny, and slight dusty weather days. The sheets during these tests are set facing south and inclined with 35° from the horizontal. The results of solar intensity loss with details of the sheets used are shown in table 1. The results from these tests show that the transparent poly carbonite sheets have less solar energy loss than glass sheets. This conclusion indicates higher solar energy transmission through the transparent PC sheets. Based on the results from these tests, the 3 mm transparent PC sheet is chosen as a top covering material to build an evacuated double layer solar collector.

Table 1Solar intensity loss for different transparent covering materials. Sheets are facing south and inclined with 35^o from the horizontal.

Cover type and thickness		**01/03/2019 12:30 PM Clear sunny**	**08/03/2019 12:30 PM Slightly dusty weather**
Type	**Thickness (mm)**	**solar loss %**	**solar loss %**
Polycarbonate	3	10.84	8.21
Polycarbonate	4	17.18	12.56
Polycarbonate	6	18.92	13.52
Glass	4	28.94	26.93
Glass	6	41.18	38.37

Two layers of 3 mm clear Polycarbonate sheet 6mm apart were sealed from all sides and corners. Six spacers are located in three horizontal rows to support the bending of the transparent sheets when air is evacuated from the space in between the sheets. An HVAC service valve is connected to the upper corner for air evacuation. Air is evacuated and kept in a constant vacuum at 0.1 Pa using a vacuum pump that is controlled by an adjustable negative pressure switch (2L Inc. model:11120). This switch turns on the vacuum pump when needed to ensure the vacuum to be maintained at the required level. The purpose of air evacuation is to reduce conduction and convection heat transfer inside the gap between transparent sheets. As a result, to minimize heat energy loss from the solar collector. The cover assembly was securely mounted on the wooden frame. Solar intensity measurements are made using two identical Pyranometers (LI-COR, LI-200R) that measure both direct and diffuse solar radiation in the range of visible light of 400-1100 nm. Temperatures at different locations are measured using calibrated copper-constantan (type T) thermocouples. All data from different sensors are connected to a 16-bit data logger then recorded to a PC in a 1-minute interval for further analysis.

To simplify the thermal analysis of the solar collector, few assumptions adopted by some researchers [10], [17] are considered during the theoretical approach and data analysis where heat losses by convection and radiation from exterior parts of the system are neglected. This assumption becomes reasonable knowing that adequate insulation materials are used to cover the internal surfaces of the solar collector to minimize heat transfer from different collector parts to the surrounding.

3 EXPERIMENTAL PROCEDURE

Tests are conducted on this system to calculate the thermal efficiency of a solar collector with different cover cases. All tests are performed at the University of Kirkuk, Iraq, with the geographic location of latitude 35.39N, longitude 44.34E, and 350 m elevation during May 2019. All tests are performed outdoors in an open space where no solar irradiance obstacles were present. The collector is faced south with a tilt angle equal to a latitude angle of 35^o [18], [19]. Figure 1 shows a schematic diagram for the test rig used in experiments. To ensure a constant water flow rate, water from a constant head tank is supplied to the water channel. The flow rate of the water stream is measured using a volumetric method and is kept constant at 0.1 LPM with an uncertainty of 0.01 LPM. Temperatures at different locations, including water inlet and outlet, heat pipe surface, pipe surrounding, and ambient air temperatures, are measured using calibrated T-type thermocouples with an accuracy of 0.5^{o}C in the one-minute interval. One solar intensity sensor is mounted to the frame of the collector at the same angle of inclination to record the overall incident irradiance with an accuracy of 0.1 W/m^2. The uncertainty of area measurement is found to be 1x10^{-4} m^2.

Three tests are conducted to investigate the effect of double-layer transparent cover evacuation on the effectiveness of a heat pipe solar panel. The first test was conducted without transparent cover, which is the case that the heat pipes were directly exposed to solar radiation. The second test was performed with a double layer transparent cover installed without air evacuation. The third test was a double layer cover installed with a vacuum maintained between two transparent layers. Comparing the thermal efficiency of the solar collector with these operating conditions willgive a clear statement about the effect of transparent cover evacuation on the overall efficiency of the solar collector.

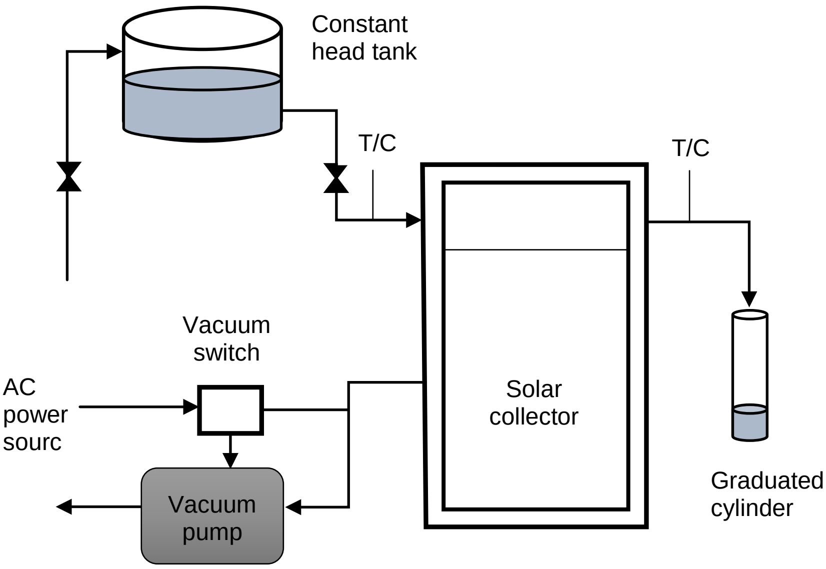

Figure 3. Schematic diagram of the experimental system

4 DATA ANALYSIS

4.1 Solar collector thermal efficiency

To compare the effect of cover design on the thermal performance of the solar collector, the overall thermal efficacy is calculated following the procedure followed by Yousefi [20]. The useful energy that the water stream gains is expressed in the following equation [20]:

$$Q_w = m' C_p (T_{wo} - T_{wi}) \quad (2)$$

whereas the total efficiency of the solar collector is calculated as following [20]:

$$\eta = Q_w/(\text{I. A}) \quad (3)$$

where Q_w represents the useful heat energy transferred to the water flowing in the external water channel. This quantity is calculated using multiplication of the mass flow rate (m') in kg/s, specific heat of water (C_p) at the average water inlet and outlet temperatures in J/kg. K, and (T_{wo}, T_{wi}) represents outlet and inlet water temperatures in ^{o}C. In the denominator, (I) represents the total solar energy irradiant to solar collector surface in W/m^2, and (A) is the solar surface effective area in m^2. The values of irradiant solar energy, water inlet and outlet temperatures, air space temperature between the heat pipe and collector cover, are recorded in a one-minute interval; therefore, the thermal efficiency calculated from equation 3 represents the instantaneous efficiency. Uncertainty analysis is conducted according to the propagation of error method described by Hollman [21]. Uncertainty of each instrument mentioned in the previous section is used to calculate the uncertainty of overall thermal efficiency according to the following equation [21]:

$$\Delta\eta = \sqrt{\left(\frac{\partial\eta}{\partial m'}\Delta m'\right)^2 + \left(\frac{\partial\eta}{\partial T}\Delta T\right)^2 + \left(\frac{\partial\eta}{\partial I}\Delta I\right)^2 + \left(\frac{\partial\eta}{\partial A}\Delta A\right)^2} \quad (4)$$

where $\Delta_{m'}$, ΔT, ΔI, and ΔA represents uncertainties of water flow rate, temperature, incident solar radiation, and collector surface area respectively. Uncertainty analysis data show that the uncertainty of thermal efficiency ranges between 3% to 5.4%.

5 RESULTS AND DISCUSSIONS

This section presents the results of the tests conducted to investigate the effect of cover type on the performance of a heat pipe solar collector.

5.1 Temperatures and solar radiation

Figure 4 shows experimental data for the temperatures of the heat pipe surface and the air surrounding the heat pipe as well as the incoming total solar radiation intensity for the solar collector with no cover.

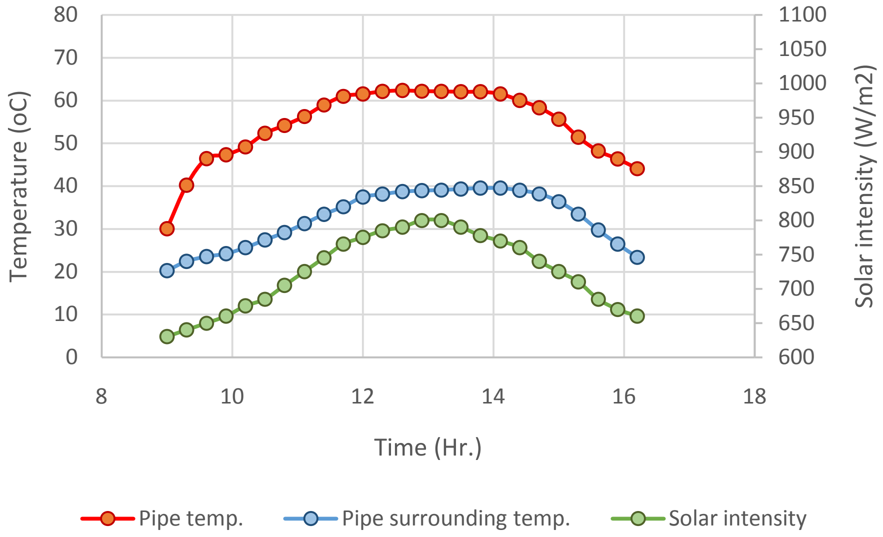

Figure 4. Heat pipe system temperatures and incoming solar intensity with no cover case

The figure shows that the solar intensity increases gradually in the morning time till reaching the peak value of about 810 W/m^2 at around 2 PM. Similarly, the heat pipe surface temperature shows a rapid increase reaching a maximum surface temperature of 62^{o}C at around noon and stays constant for about two hours before starting to decline as the incident solar energy values drop. Since the solar collector had no cover as a first test, the pipe surrounding air temperature is the temperature of air adjacent to the heat pipe surface. Experimental data show that air temperature is lower than heat pipe surface temperature by about 20^{o}C at peak solar intensity time.

Figure 5 shows the same parameters but for the solar collector with a double transparent PC cover without applying a vacuum in the spacing between cover layers. The test was performed in clear sky conditions one day following the no cover test. Therefore, the solar intensity in figure 4 shows a similar trend with close values recorded in no cover test.

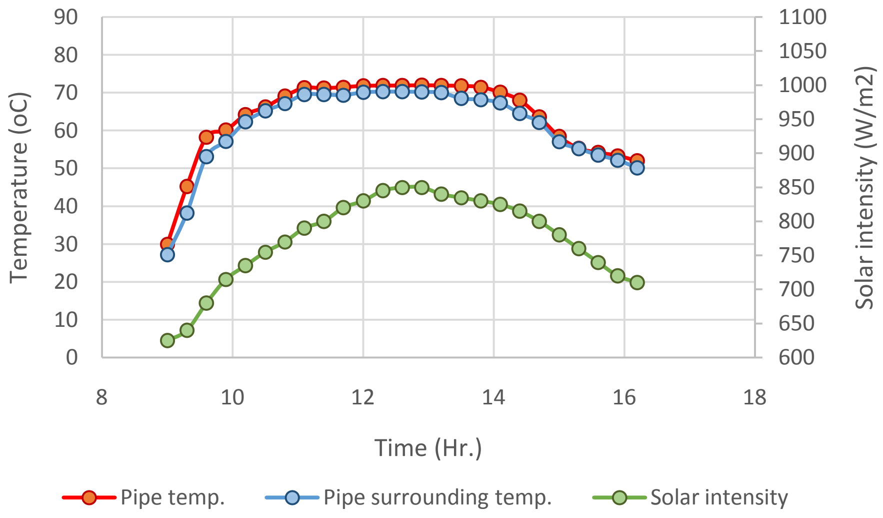

Figure 5. Heat pipe system temperatures and incoming solar intensity with the double cover case.

However, the heat pipe surface temperature shows a higher peak temperature of about 72^{o}C verses 62^{o}C for the no cover test. Additionally, the air temperature adjacent to the heat pipe shows a few degrees lower than the heat pipe temperature. This condition is due to that incident solar energy will heat both the heat pipes and the air surrounding them. Besides, the double layer cover will work as an excellent thermal insulator by reducing conduction and convection heat transfer losses from the heat pipe tubing system to the environment.

Figure 6 shows temperature and incident solar intensity data for the case of a solar collector with a vacuum applied between the double transparent cover. The test with vacuumed cover is conducted in a day with weathering conditions similar to the two previous tests; therefore, the solar intensity values are close in values to the previous two tests. For both heat pipe and its surrounding temperatures, few remarkable notices can be seen if compared with cases in figures 3 and 4. The first is that there is a faster increase in both heat pipe and surrounding air temperatures in comparison with no cover, and not vacuumed cover tests. The second observation is that higher temperatures are seen for pipe surface and surrounding air temperatures. As numeric values, the figure shows that the maximum pipe surface temperature reaches 84^{o}C, and the surrounding air temperature reaches about 82^{o}C. These data clearly indicate that vacuuming the gap between the double layer covering will raise the working temperature of heat pipes, which consequently leads to better thermal performance, as will be shown later in thermal efficiency curves.

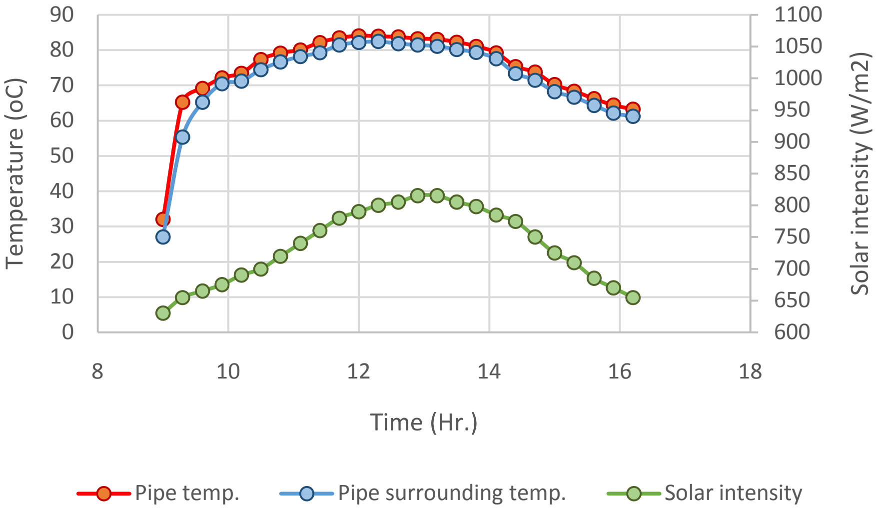

Figure 6. Heat pipe system temperatures and incoming solar intensity with the vacuumed double cover case.

Figure 7 shows the cooling water temperature difference for the three studied cases. The figure shows that the minimum temperature raise is for the coverless solar collector, where the maximum temperature difference between inlet and outlet streams is about 2^{o}C only. With a double cover collector test, the temperature profile shows quicker raise than the first test. In addition, the maximum temperature difference reaches about 5^{o}C. For the third case study, the vacuumed cover, the water temperature rises even faster than the previous two cases. Additionally, the exit water temperature reaches about 6^{o}C, which is the highest value among the three tests. Water temperature difference enhancement can be explained as better cover insulation leads to a reduction in heat loss through the cover leading to more heat energy transfer through heat pipes to the water stream.

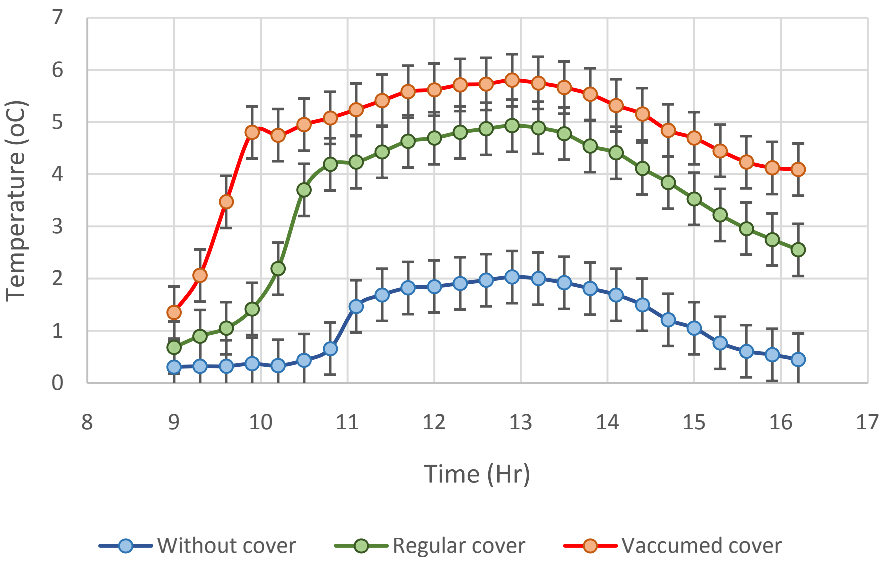

Figure 7. Water temperature difference variation with time for the three solar panel cases

5.2 Overall Solar collector efficiency

To compare different cases of solar collector cover types, the overall thermal efficiency is calculated using equation 1. Figure 8 illustrates the instantaneous thermal efficiency change with time for the three cases of study. The figure shows the highest efficiency is about 70% for the vacuumed cover collector. Also, the highest efficiency persists for about 4 hours, which can be referred to as a steady-state zone.

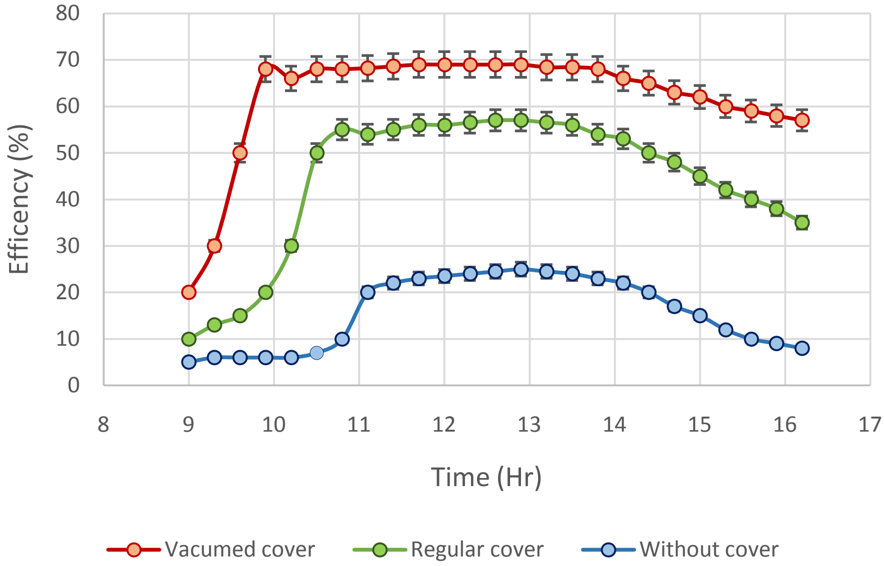

Figure 8. Variation of solar collector efficiency with time for the three cases of the study

For the case of a double-layer cover with no vacuum, the maximum thermal efficiency is lower than the vacuumed cover collector by about 13% in the steady-state period. Also, the duration of persistence of maximum efficiency is less, which is about 2 hours with a maximum efficiency value of 55-58%. For the no cover case, the maximum efficiency is aopbout 25%, which is the least value among the three tests. In addition, the duration of maximum efficiency lasts for less than two hours, which is the least period as well. The vacuumed cover case shows the best performance among the three tests conducted. This result is mainly because using vacuum cover leads to better thermal insulation, which reduces heat energy losses from the higher temperature heat pipe to the lower temperature surrounding.

6 CONCLUSION

In this study, the effect of cover type on the performance of a heat pipe solar collector is studied. Different covering materials like glass and PC sheets with different thicknesses and layers were tested first to calculate solar radiation loss through these materials. The results of this part of the study show that PC sheets have higher solar transmittance than glass sheets with 11% less solar energy loss through Polycarbonate sheets than glass sheets (for 4mm thickness sheets). As a result, a higher thermal efficiency can be achieved if PC sheets are used. This finding encourages using transparent PC sheets instead of glass sheets as covering for solar devices.

The thermal efficiency results reveal that the maximum efficacy of a double layer vacuumed PC covering collector reaches about 70%. On the other hand, the maximum thermal efficiency of non-vacuumed cover reaches about 57%, which is about 12% lower than the vacuumed cover. This behavior indicates that combining both high transmittance PC cover with vacuumed spacing results in a higher thermal efficiency solar collector.

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