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A standardized Empirical Method of Testing Solar Simulator Coupled with Solar Tube and Concentrator Collectors

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Abstract

This paper describes a novel an empirical method for testing a solar simulator testing facility based on an experimental performance. A uniform geometrical configuration design for solar simulator was preliminary evaluated by illuminance distribution to optimize the maximum source-to-target transfer efficiency of irradiative power. A number of experimental tests were carried out for various distances from the simulator surface. It was determined that the optimal distance between the light surface simulator and solar collector is about 23 cm at different solar irradiance. The unevenness difference of solar radiation values were investigated at different points under the simulator facility where the maximum unevenness error percentages was about 9.1% which is in a good agreement within the allowable limits of 15% provided by the British Standards for testing the solar simulator . The performance of solar concentrator and an evacuated solar collector with an aperture area of 1.73 m^2 for real solar insolation during spring in the Middle East region have been investigated and it was proved that the calculated efficiency of solar collector was closely correlated within the efficiency provided by the manufacture. Similarly the thermal efficiency of the combined system (both solar concentrator and water tank) was found to be 38%. The design of such solar simulator associated with the development of standardized test procedure can be utilized as a reliable and efficient experimental platform to investigate various solar collectors and materials.

***Keywords**: Solar intensity fluctuations, light, Solar simulator, solar concentrator.*

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1. Introduction

Scientists have long looked at solar radiation as a source of energy trying to convert it into a useful form for direct utilization [1]. Nowadays, there are an extensive ongoing researches focus on the utilization of renewable energy sources and the solar energy in particular. Solar energy has been utilized by human in many fields of life, such as heating, cooling systems, food industries, agriculture, pharmaceutical industries, wastewater treatment and water desalination. Most forms of energy are solar in origin. Oil, coal, natural gas and wood were originally produced by photosynthetic processes [2,3]. Nowadays, solar energy is become one of the most desirable applications to reduce energy consumption and CO_2 [4]. Consequently the need for testing facilities of renewable energy technologies is increasing. The development of solar light simulators enables the researchers and the industries to carry out experimental testing for any material or product rigs without the exposure to the outdoor weather fluctuations and it accelerates the research in countries of low solar energy intensities such as the northern parts of Europe. The main purpose of the solar simulator is to provide a controllable indoor test facility under laboratory conditions [5]. Solar simulators can be designed for non-concentrating and concentrating solar applications by delivering high-flux thermal radiation onto the target, which are mainly employed for testing components and materials for high-temperature thermal and thermochemical applications. In practice, with a simulator, tests can be carried out when you want to, and continue them 24 hours a day, and you can control the humidity and other aspects of the local environment. It became possible to repeat the same test, in the laboratory or at any other site and you can relate the exposure to the internationally accepted solar irradiation levels. In addition to the capability to concentrate the beam for accelerated testing. Obviously, there are different standards describing the method of solar simulators design. However they are similar, these standards differ significantly in some of their defined metrics to measure

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the performance. As a consequence, confusion has emerged regarding the comparison of simulators that have been validated using these different methods [6]. It is necessary to measure the efficiency of solar collector and photocurrent of solar cells for determining the price and the solar system design. The irradiance of the light source of a general solar simulator changes depending on the lamp type and the usage time. It is well understood that since there is a mismatch in the spectral irradiance between a solar simulator and natural sunlight, some error can be made in the measurement of solar collectors and cells. Many researchers have thoroughly investigated the solar simulators using different source of lights but the disadvantages of such simulators include relatively low performance due to excessive variations and unevenness in solar irradiance distribution. The development of small solar simulator using LED lamps has been investigated by Kohraku, and Kurokawa, 2006 [7] for solar cells measurements and it was found that the unevenness was about 3% for testing a small illuminated area of 100x100mm^2 of photovoltaic cells. Similarly Solar Simulator and I-V Measurement system for a solar cell testing has been studied by Guvench, M. et al., 2004 [8]. In this study, the artificial sunlight was created by combining metal-halide and quartz halogen light sources whereby the quality and the optimal operational points for maximum electrical output for an area of 8 inch in diameter were determined. However most of researchers focused on a relatively small scale solar simulators in order to achieve a uniform distribution of solar irradiance with minimum unevenness values. Recently, LED and halogen lamps have widely been used for a traffic signal and an illuminator because of their longer operating life, high energy efficiency, and low inexpensive cost. The need for low cost large simulators to test the thermal solar collectors associated with a standardized testing technique are demanded. This paper describes the development of solar simulator using low cost halogen associated with a unique empirical testing method of examining solar simulator. Meanwhile it presents also the experimental results of investigating a solar concentrator and an evacuated solar collector under indoor conditions for the whole day of the Middle East solar radiation.

2. System Description

Two solar simulators have been developed and investigated to simulate an evacuated solar collector and solar concentrator. However these two simulators have been tested under the same methodology and criteria concept. The experimental set up as illustrated in Figure 1 consists of solar light simulator covering solar concentrator and an evacuated solar collector (ESC) of 20 tubes and solar concentrator respectively which are connected to 120 litre water storage tank with a circulation pump and flow meter regulator to adjust the mass flow rate of the medium fluid.

Initially and during the trial tests, a sunlight simulator comprising of an array of 16 halogen floodlights with the maximum electrical power consumed by each floodlight of 400 W covering an area of 2.32m^2 has been assembled and tested for unevenness but it was found that the values of unevenness were high with inhomogeneous distribution of light intensity due to the abundance of large shaded areas. Therefore the number of lights have been increased for 30 lights. Then, the new solar sunlight simulator has significantly extended the range of insolation values in the experiment as illustrated in Figure 2. The tungsten halogen lamps are widely used in the solar beam experiment (SBE) for solar simulator applications because it provides a very stable and smooth spectral output. The wavelength ranges between 360-2500 nm which is nearly similar to sunlight especially in terms of thermal radiation. They are inexpensive and require only simple power supply units. The natural sunlight has a color temperature of approximately 5600 , whereas halogen lamps radiate at a black body temperature of about 3200K. The array of lights is divided into three groups and it is connected to the grid via a 3-phase transformer, which enables the level of the radiation flux to be gradually regulated. The maximum electrical power consumed by each floodlight is 400 W.

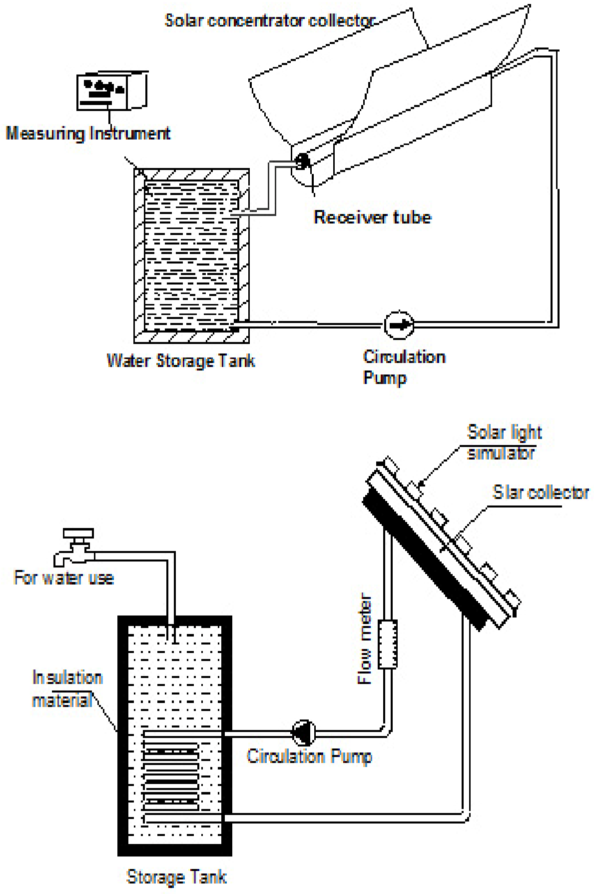

Fig 1: Schematic configurations of experimental set-up of solar simulator with solar collector (concentrator, evacuated tube collector)

A pyranometer with sensitivity of 17.99x10-6 Volts/W/m^2 was mounted on the solar collector to measure the intensity of solar irradiation (radiation flux) at evenly spaced points on the surface of the evacuated tubes. The results were analyzed and averaged as presented in Figure 6. The test rig is also equipped with a circulation pump and a set of K-type thermocouples with an accuracy of 0.1°C to measure the surface temperature of the collector, the inlet and outlet temperatures of fluid in the ESC and finally the ambient temperature under the solar simulator. A water flow meter was installed to measure the flow of the fluid inside the solar collector manifold. The collector consisted of a copper manifold header pipe which is a long horizontal cylinder with a volume of approximately 0.45 litre. The header pipe also contains twenty small cylindrical heat pipe housing ports, as shown in Figure 4 [9].

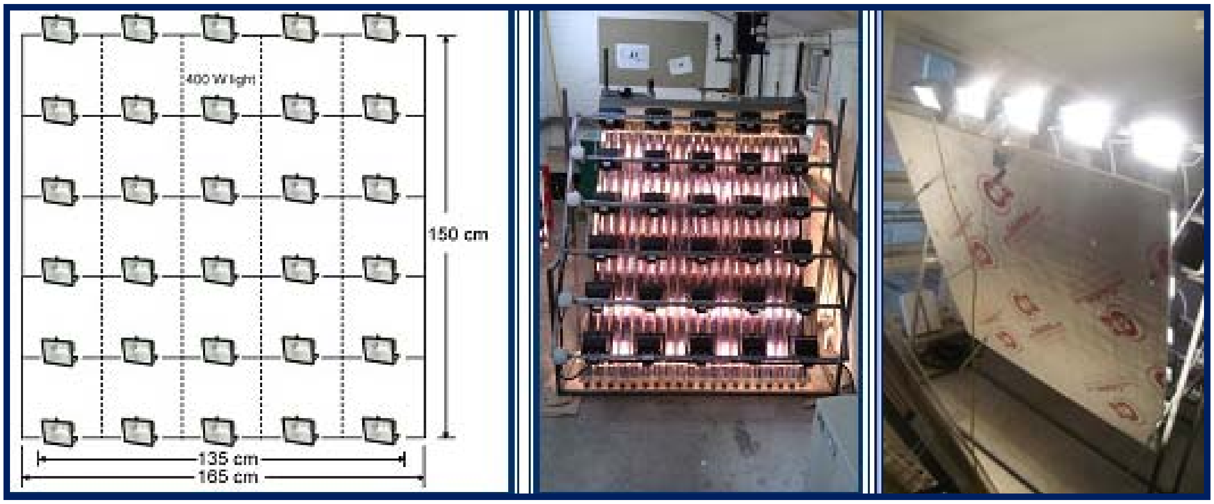

Fig 2: Evacuated solar collector and solar simulator test rig

The axis of each housing port is perpendicular to the flow direction in the header pipe. In the solar collector, the head of each evacuated tube heat pipe is inserted into a separate housing port and the heat from the heater pipes is transferred to the flow inside the header pipe through the walls of the housing ports. The thermal contact between the heads of the heat pipes and the housing ports is provided by using a special metallic glue compound. Similarly The experimental set up as shown in Figure 3 consists of the solar concentrator which includes the multi-curved surface concentrator and the high temperature receiver tube. It also consists of a solar tracking device (for outdoor test) which is mounted on the collector, receiver fluid (HTF) circulation tank measuring 0.15m height by 0.22m diameter, pump (pump flow rate range between 3-8L/min, 4 bar max pressure and 150°C maximum temperature) and a water storage tank for heat exchange with 80L capacity (for outdoor test only).

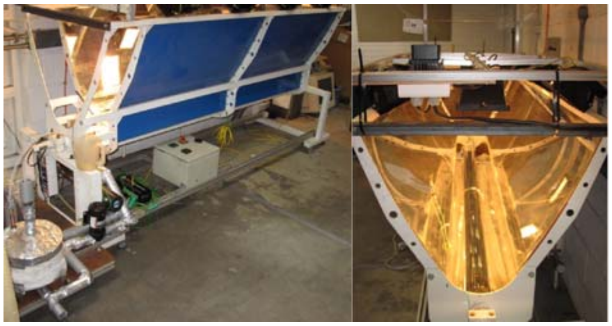

Fig 3: Solar concentrator collector and solar simulator test rig

An expansion vessel is also incorporated into system in order to prevent the possibility of system damage due to an increase in pressure. The vessel has two halves: one half connects directly to the water system while the second, separated by a special diaphragm, contains air. As pressure rises and the volume increases, the diaphragm is displaced. In addition, the fluid pressure in the solar collector manifold is monitored by a pressure gauge. A 120 Litre water storage tank is fully insulated with foam insulation materials to reduce the heat losses. The water inside the storage tank is heated by a helical copper tubular heat exchanger fixed inside the storage tank as shown in Figure 2. The outer diameter of copper pipe is 22mm and the total length of heat exchanger is 5.73m with 6 turns. The inlet and outlet of heat exchanger are connected, respectively, to the outlet and inlet of the manifold at the top of evacuated solar collector so that these form a closed loop and an electrical pump circulates the water in the loop.

3. Test Procedure and Method Presentation

The experimental devices and instruments have been fabricated and assembled as illustrated in Figures 1, 2 & 3. The floodlights are evenly spaced on a frame installed above and in parallel to the flat board covering the area of solar light simulator. This flat board has been divided horizontally and vertically into evenly spaced grid points with a maximum spacing of 150 mm in order to maintain constant solar irradiance variations as recommended by the British Standards for testing the solar simulator. The light intensity was measured using the CMP 3 pyranometer with sensitivity of 17.99x10-6 Volts/W/m^2 at evenly spaced points under the light simulator for four different distances: 15, 25, 35, and 45 cm between the simulator and the target perpendicular to the flat board. This was in order to achieve the optimal distance based on the lowest unevenness value. All experimental parameters, such as ambient temperature, surface temperature, and solar intensity (insolation), under the solar simulator, were measured and recorded using a data logger (DT500). Temperatures were recorded using K-type thermocouples with an accuracy of 0.1°C. To ensure that all the sensors provided approximately the same reading, they were exposed to the ambient temperature and compared to a mercury-in-glass thermometer with ±1 division accuracy.

They were also immersed in a hot water bath and the same readings were obtained. The accuracy of the thermometer was checked with a handheld digital thermometer which has 0.1°C accuracy. Prior to the experiments, the solar simulator covering the solar collector (concentrator and evacuated tube solar collector) with the storage tank were assembled so that all the piping system was covered by thermo-insulation materials as shown in Figures 1 & 2.

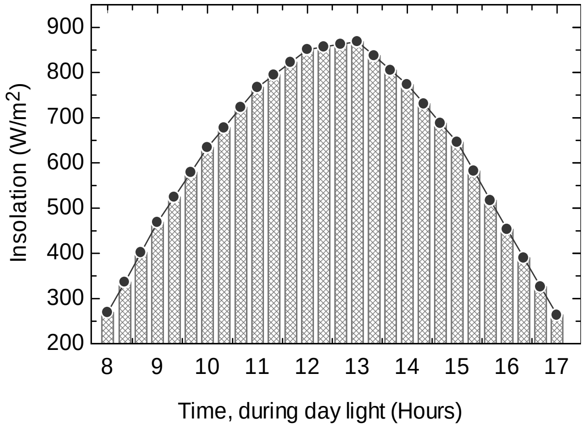

Fig 4: Solar insolation variation in the Middle East region [10]

This was to reduce the heat losses. Several experimental tests have been conducted under different conditions especially for various distances from the solar light simulator to the top surface of the glass tube of the ESC. The evaluation and analysis were performed and the most appropriate optimal distance was determined. These figures were then used to test the performance of the evacuated solar collector under different schemes, it was also tested in conditions simulating a typical spring semester in the Middle East region with an average irradiance of 6.2 KW/m^2 day as shown in Figure 4. The regulator dimmer level of electrical power supplied to floodlights was changed every 20 minutes using the floodlight irradiation measurement results which have been evaluated and verified experimentally as shown in Figure 5. Similarly the for mentioned test procedure and testing method has been applied to investigate the solar concentrator but with constant solar irradiance at various levels of solar insulations.

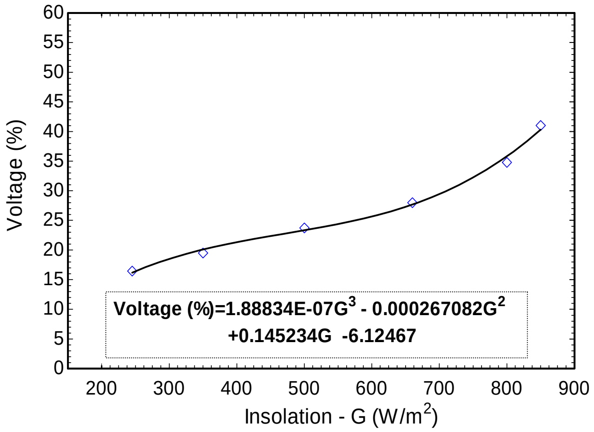

Fig 5: Solar insolation level versus transformer voltage calibration results [10]

4. RESULTS AND DISCUSSIONS

4.1 Light unevenness

The solar simulator steady state light is a very essential factor for reliable measurements, however during the preliminary tests and evaluation of the light simulator, it was noticed that the halogen light intensities were variable and unstable. In order to remedy this problem, thus the lights were left working for 30 minutes prior to the commencement of the experimental tests. Continuous observations showed that the simulator's lights took 20 – 30 minutes to reach a constant intensity, i.e. the steady state condition.

Figure 6 shows the results of the unevenness calculation of the irradiation as a function of the light-source and distance between the evacuated solar collector and the light source. It can be noticed that the unevenness decreases as the interval distances between the light-source and the solar collector increases, before the minimum value is obtained. However, the unevenness increases reversely when the distance is larger than the minimum value which complies with The ASTM procedure for testing solar simulators [11]. It can be observed that ambient temperatures under the solar simulator increases as the distance between the solar collector and the light source decreases. Similarly the solar intensity decreases with the increase of the distance as illustrated in Figure 7.

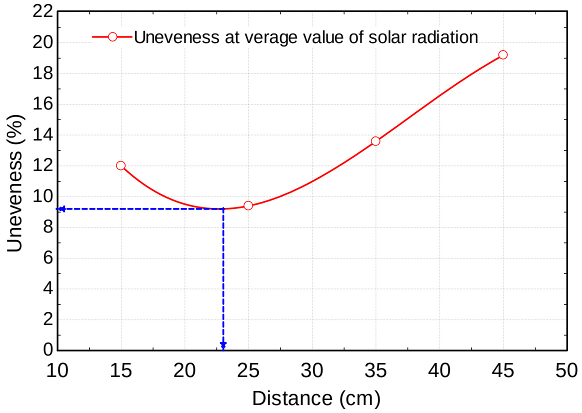

Fig 6: The unevenness percentages versus distance

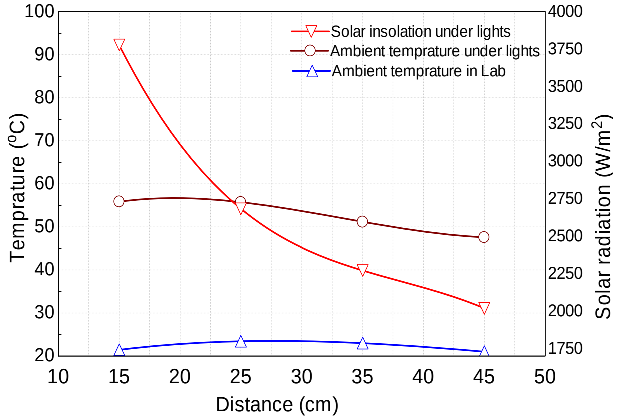

Fig 7: Solar insolation and ambient temperatures

The unevenness is expressed in terms of the uniformity which can be defined as a measure of how the solar irradiance varies over a selected area. This value usually expressed as non-uniformity and it can be calculated as the maximum and minimum percentage differences from the mean irradiance as presented in Equation 1.

$$Unevenness\quad(\%) = \pm 100\left(\frac{E_{\max} - E_{\min}}{E_{\max} + E_{\min}}\right) \quad (1)$$

The preliminary distribution of the solar insolations showed a high fluctuations and un acceptable difference in solar radiation as shown in Figure 8. Consequently several experimental tests have been carried out and based on the experimental results, it was determined that the minimum achieved optimal distance between the target and the light source was about 23 cm with respect to the minimum unevenness percentage value of 9.1% as shown in Figure 6.

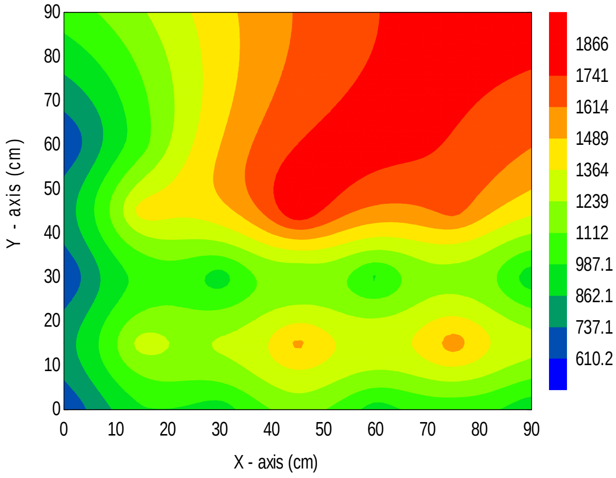

Fig 8: Preliminary distribution of solar insolation

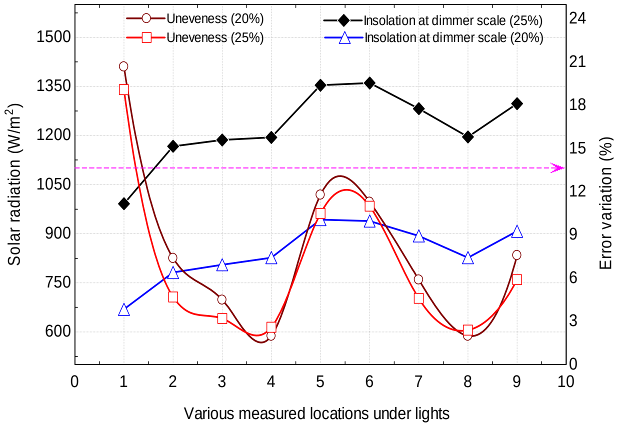

Fig 9: The unevenness and insolations under solar simulator at various spaced points

The simulator was then investigated under the optimal distance of 23cm at different points and it was noticed that the unevenness percentage reaches 20% at one point, This is due to the fact that this point is slightly deviated away from the edge of the light. However the unevenness at most points were found to be less than 15%, as shown in Figure 9. This is compatible with the British Standards values for testing the solar simulator. The simulator was tested under different solar irradiations namely 200, 400,600, 800, 1000, 1200 W/m^2 and It was found that the magnitude of light's unevenness increases with the increase of solar intensities, however it can be noted that the unevenness error in both conditions are uniformly distributed as shown in Figure 9 which indicates a reliable experimental measurement. Further research will be conducted using different types of lights for system improvements.

4.2 Testing the Evacuated solar collector

The evacuated solar collector was tested under different solar intensities starting from low intensities of 245 W/m^2 to the higher values of 850 W/m^2 and it can be noticed from Figure 11 that the efficiency of the solar collector is inversely proportional to the values of solar intensities. This is a reasonable observation due to the fact that the increase of solar intensities will result in an increase of ambient temperature under the simulator. This has influenced significantly its performance efficiency. Figure 10 presents the ambient temperature changes under the simulator as a function of time. It can be seen that the higher the solar irradiation the greater the ambient temperatures. It was also found that the average measured results of efficiency varies between 70% and 81%, which was in a good agreement with the calculated efficiency diagram provided by the manufacturer.

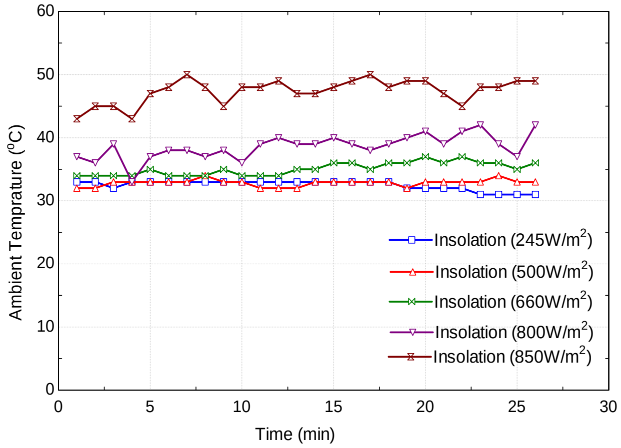

Fig 10: Ambient temperature under the solar simulator

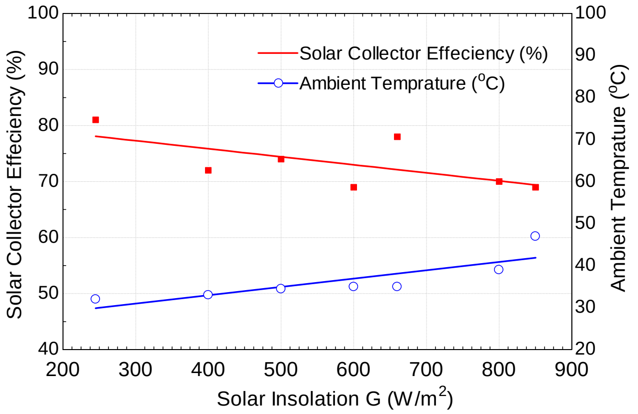

Fig 11: Variation of solar collector experimental efficiency and ambient temperature of (ESC)

4.3 Solar collector efficiency

The efficiency of solar collector was calculated in different ways based on the inlet and the outlet of water temperatures of the solar collector and the ambient temperatures as follows: In this method the efficiency was determined in terms of the inlet and outlet temperatures of the collector manifold, the area of the collector, and the mass flow rate, as shown in Equation 2

$$\eta_i = \frac{\dot{m}_c C_p (T_{SCi} - T_{SCo})}{\overline{G} A_{col}} \qquad (2)$$

The efficiency was determined using the derived formula based on experimental results of solar insolation and ambient temperature as presented in Figure 11 and written in Equation 3

$$\eta_i = 83.0583 - 0.628174 \left(\frac{\overline{G}}{T_a}\right)$$

(3)

where:

T_m = mean collector temperature, $\frac{(T_{sci} + T_{sco})}{2}$ [^{o}C].

T_a = ambient air temperature [^{o}C].

$\overline{G}$ = Solar irradiance [W/m^2]

A_{col} = Solar collector absorbance area [m^2]

Solar insolation for the Middle East in the month of March was simulated using the developed sunlight simulator to test the evacuated solar collector. The water inside the storage tank was heated through a heat exchanger connected to the outlet and inlet of the solar collector respectively. The data sets from the conducted experiments were collected and analyzed. Figure 13 shows that the efficiency of the solar collector increases with decrease of solar insolation. The efficiency of solar collector has been calculated in three different ways as illustrated in previously. It can be seen that the efficiency of ESC increases with the decrease of solar insolation which complied with the measured efficiency and the efficiency calculated by the experimental formula. However the manufacturer efficiency showed a significant decrease in efficiency after 2:00 pm as illustrated in Figure 14 and this contradiction can be explained due to the fact that manufacturer efficiency formula was produced at certain indoor conditions at solar insolations of 800 and 1000 W/m^2 respectively.

Figure 12, shows that the ambient temperature and the surface tube temperature of the solar collector ranges between 20-45^{o}C, and 20-100 ^{o}C respectively. The change of temperature magnitude is directly proportional to the increase of solar intensities. It was noticed that the difference between the inlet and outlet fluid of the evacuated solar collector manifold ranges between 2 to 5 ^{o}C for insolation values of 245 to 850 W/m^2 as presented in Figure 12. The ambient temperature under the simulator and the tube surface temperatures of ESC increased at higher solar radiations values as shown in Figure 14. It was proved experimentally that this simulator gives a maximum solar radiation of 900 W/m^2 can be utilized by the solar collector. However it can be seen that the additional increase of solar intensities higher than 900 W/m^2 for such simulator results in a slightly small increase in thermal heat output of the solar collector which affected significantly the collectors efficiency. This can be explained due to the fact that the solar collector has reached its saturation capacity point of heat output. Furthermore Figure 14 shows that the maximum achieved temperature at the water storage tank for the Middle East day of operation is about 73.50 ^{o}C and the average evacuated solar collector efficiency is about 72% which is in a good agreement with the manufacturers recommended efficiency.

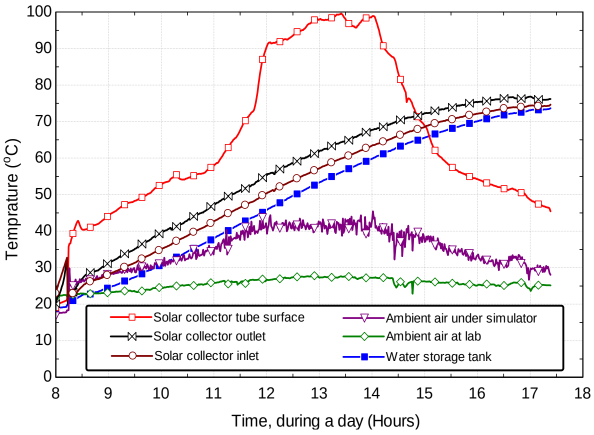

Fig 12: Ambient temperature under the solar simulator for a day light in the Middle East

4.4 Solar concentrator efficiency

Experimental test was carried out in order to determine the efficiency of the concentrator solar collector combined with water storage tank. The test was carried out using 8 m by 0.7 m solar collector with total area of 5.6 m². The tank is made of coil heat exchanger for heat transfer between the HTF in the collector and water in the tank. An organic oil was used as HTF with 2186 J/kg K specific heat capacity. The choice of using oil as HTF was mainly because the aim of the test was to achieve temperatures above 100 °C and oil has lower risk than water in terms of boiling and pressure. The tracking device was constructed. It was set to track the sun from east to west direction. However, the sun was tracked manually due to failure of the tracking device during the experiment. Figure 13 presents experimental data solar intensity, receiver outlet temperature, receiver inside temperature. An average of approximately 700W/m^2 was measured between 08:00 to 18:00 hours. The maximum receiver tube surface temperature measured was around 150 °C. The oil temperature raised to more than 120°C. It can be seen from Figure 14 the water temperature reached 100°C in approximately 4 hours.

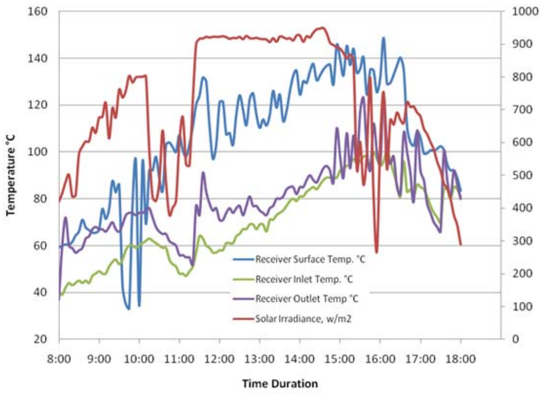

Fig 13: Variation of various temperature and solar irradiation with time

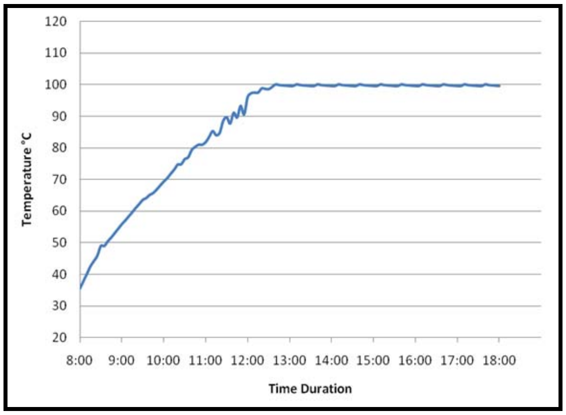

Fig 14: Variation of water temperature in storage tank with time for concentrator

After the useful data was extracted, the thermal energy and efficiency of the system were calculated using Equation 2 utilizing the experimental results obtained. It was found that the thermal energy delivered by the solar collector in order to raise water temperature from 35 to 100. 100°C was around 1.5 kW. The thermal efficiency of the combined system (both collector and water tank) was found to be 38%. The plot of the efficiency of the system is presented in Figure 15.

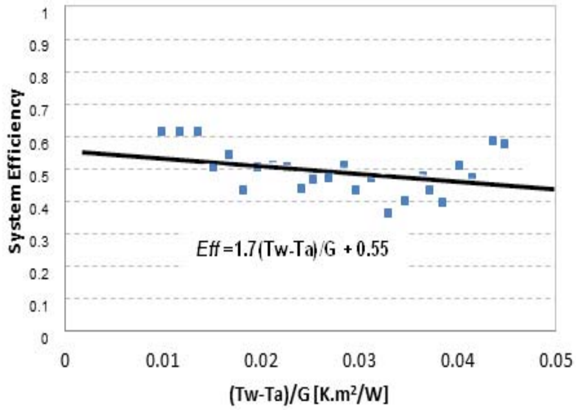

Fig 15: Experimental efficiency formula of solar concentrator

A solar light simulator of high flux solar irradiation connected to a water heating system comprising solar concentrator and an evacuated solar collector and water storage tank have been developed and assembled at the Institute of Sustainable Energy Technology at Nottingham University - UK. An experimental method of solar simulator testing was presented. A number of experimental tests were carried out for various distances from the simulator surface, in order to tackle the light in homogeneity fluctuations. It was determined that the optimal distance between the light surface simulator and solar collector is about 23 cm. The unevenness difference of solar radiation values were investigated at different points under the simulator facility where the maximum unevenness error percentage is about 9.1% at a distance of 23cm which is in a good agreement within the permissible limits of 15% provided by the British Standards for testing the solar simulator . The performance of an evacuated solar collector of 20 tubes with an aperture area of about 1.73 m2 was tested under real indoor solar insolation during March in the Middle East region, it was determined that the calculated average efficiency of the solar collector is equal to 72% and found to be closely correlated within the efficiency provided by the manufacture. The efficiency of the concentrator solar collector was compared with the non concentrating flat plate collector (FPC) and the concentrating compound parabolic collector (CPC). It was found that the newly designed concentrator solar collector performed better than both the FPC and CPC as expected. The concentrating collectors are more competitive than the non-concentrating collectors at temperatures above 80 °C. It was found that the newly tested concentrator solar collector is more competitive with the CPC at high operating temperatures about 120 °C. The new collector is more economical in terms of cost and land requirement compared to both the CPC and FPC. It can be concluded that the development of such solar light simulators would have a significant impact on the R & D of solar energy technologies which shall enable researchers and industries to carry out and repeat experimental tests under various conditions without the exposure to the unpredictable variation of the outdoor weather fluctuations and limited availability of solar radiation especially in the northern parts of Europe. Further less expensive and excellent performance solar simulators can be fabricated with tungsten halogen lamps light sources.

Acknowledgments

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Nomenclature

T_a	Ambient air temperature (^{o}C)
T_m	Mean collector temperature, (^{o}C)
T_{SCi}	Solar collector inlet temperature (^{o}C)
T_{SCo}	Solar collector outlet temperature (^{o}C))
C_p	Specific heat capacity of water (J/kg.K)
A_{col}	Solar collector area (m^2)
$\overline{G}$	Daily average insolation (W/m^2)
ηi	Solar collector efficiency
ESC	Evacuated solar collector
SBE	Solar beam experiment
BS	British standards
DT	Data taker

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