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Experimental testing method for solar light simulator with an attached evacuated solar collector

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Abstract
This paper describes a novel solar simulator of high solar irradiation. It consists of an array of 30 halogen lamps of 400W each, covering a gross area of 2.32 m^2. A standardized empirical method for solar simulator testing facility based on an experimental performance is presented. A uniform geometrical configuration design for a solar simulator was evaluated by its illuminance distribution to optimize the maximum source-to-target transfer efficiency of irradiative power. 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 the solar collector is about 23 cm at different solar irradiance. The unevenness of solar radiation values were investigated at different points under the simulator facility and the maximum unevenness error percentage was found to be about 9.1%, which is well within the allowable limits of 15% set by British Standards for testing a solar simulator . The performance of an evacuated solar collector with an aperture area of 1.73 m^2 to simulate solar insolation during March in the Middle East region was investigated and it was proved that the efficiency of the solar collector was closely correlated with the efficiency data provided by the manufacturer. The design of such a solar light simulator associated with the development of a standardized test procedure can be utilized as a reliable and efficient experimental platform to investigate various solar collectors and materials.

Keywords: Solar intensity fluctuations; Solar simulator; Vacuum tube solar collector; Light.

1. Introduction
The sun was adored by many ancient civilizations as a powerful God. Solar energy has been utilized by humans for various purposes, including heating, cooling systems, food and pharmaceutical industries, agriculture, wastewater treatment and water desalination. Indeed, most forms of energy are solar in origin since oil, coal, natural gas and wood were produced by photosynthetic processes [1]. Scientists have long tried to convert solar radiation into an energy source for direct utilization [2]. Currently, there is extensive research on the utilization of renewable energy sources, and of solar energy in particular.
Hence the need for testing facilities for these technologies has become a pressing need. The development of solar light simulators enables researchers and industrialists to carry out experimental testing of material or product rigs without the exposure to the outdoor weather fluctuations. This accelerates research in areas of low solar energy intensities such as northern Europe. The main purpose of the solar simulator is to provide a controllable indoor test facility under laboratory conditions [3]. Solar simulators can be designed for both non-concentrating and concentrating solar applications by delivering high-flux thermal radiation onto the target. They are mainly employed for testing components and materials for high-temperature thermal and the rmochemical applications. With a simulator, tests can be carried out at

any chosen time, continued for 24 hours a day, and controlled for humidity and other aspects of a local environment. Simulators enable the same test to be repeated in the laboratory or at any other site and exposure can be related to the internationally accepted solar irradiation levels. In addition, the beam can be concentrated 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 the performance. As a consequence, there is some confusion about how to compare simulators that have been validated using these different methods [4]. Measures of the efficiency of a solar collector and the photocurrent of its solar cells are required in order to determine the comparative value of any 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 solar simulators using different sources 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 a small solar simulator using LED lamps has been investigated by Kohraku and Kurokawa [5] for solar cell measurements and it was found that the unevenness was about 3% for testing a small illuminated area of $100x100mm^2$ of photovoltaic cells. Similarly a Solar Simulator and I-V Measurement system for solar cell testing has been studied by Guvench et al. [6]. In this study, the artificial sunlight was created by combining metal-halide and quartz halogen light sources and the quality and the optimal operational points for maximum electrical output for an area of 8 inch in diameter were determined. However most researchers have focused on 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 cost. There is an urgent need to develop a standardized technique to test the thermal solar collectors associated with low cost large simulators. This paper describes the development of a solar simulator using low cost halogen lamps covering an area of 2.32 m^2 associated with a unique empirical testing method of examining the solar simulator. It presents also the experimental results of investigating an evacuated solar collector under indoor conditions which simulates a whole day of the Middle East solar radiation.

2. System description

The experimental set up, as illustrated in Figure 1, consists of a solar light simulator covering an evacuated solar collector (ESC) of 20 tubes which is connected to 120 litre water storage tank with a circulation pump and flow meter regulator to adjust the mass flow rate of hot water.

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

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 test rig was 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.

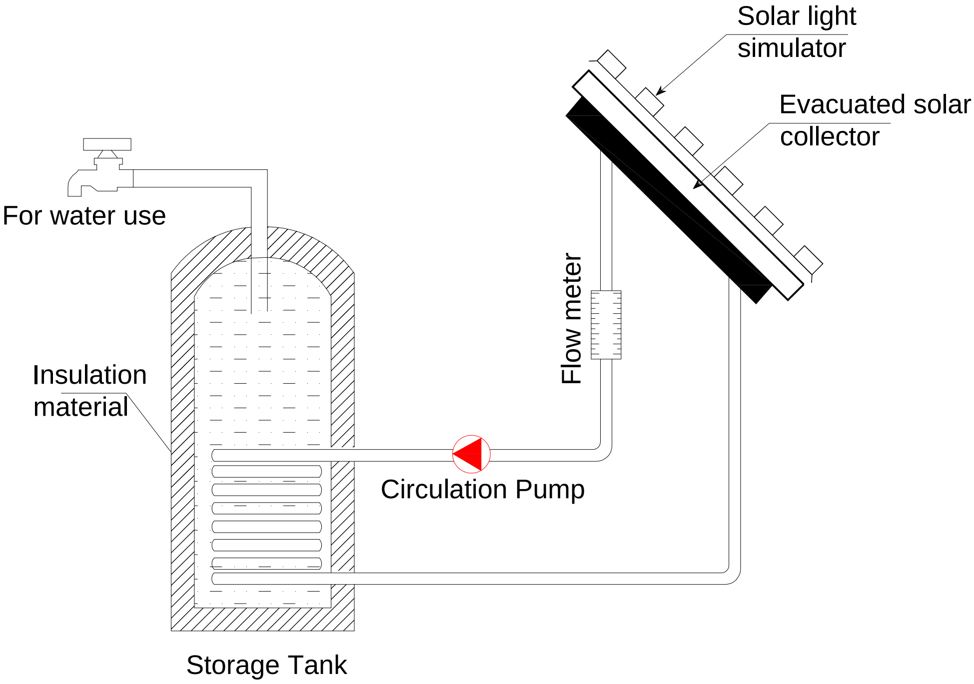

Figure 1. Schematic of experimental set-up of solar simulator with solar collector

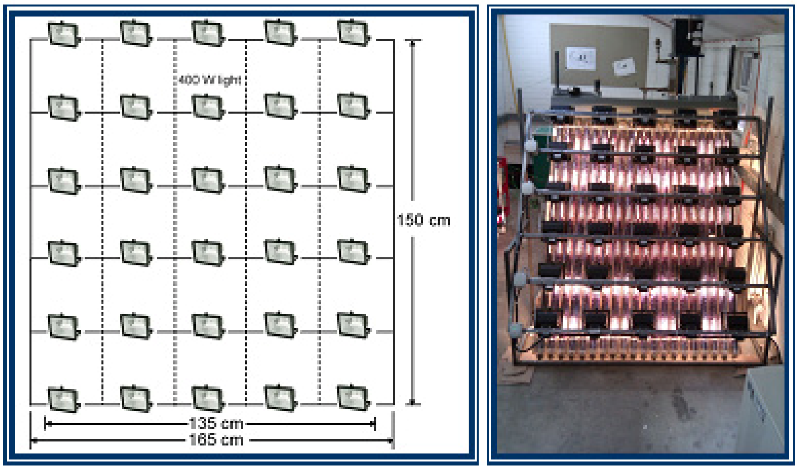

Figure 2. Test rig components

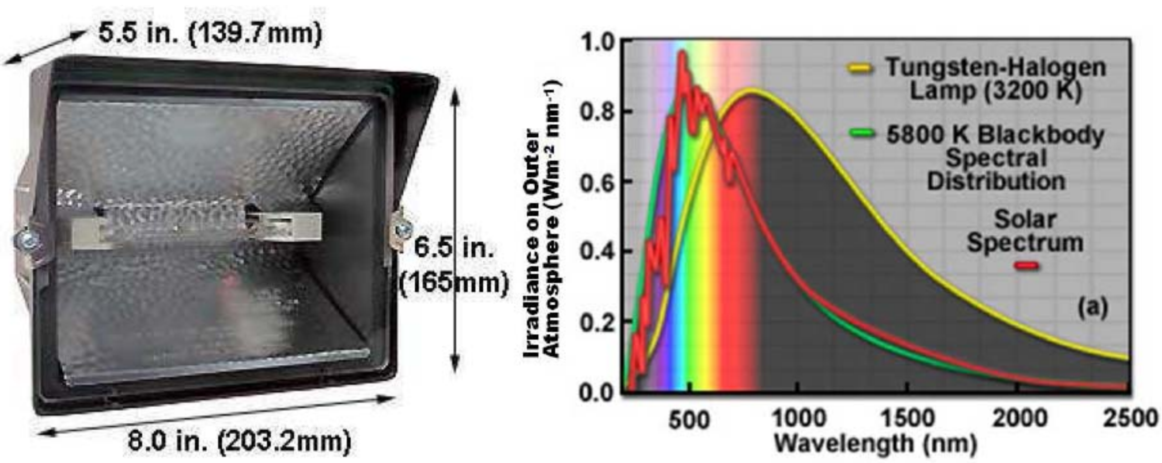

Figure 3. Tungsten halogen lamp spectrum distribution used for solar simulator

The collector consisted of a copper manifold header pipe which is a long horizontal cylinder with a volume of approximately 0.45 litres. The header pipe also contains twenty small cylindrical heat pipe housing ports, as shown in Figure 4 [7]. 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 a special metallic glue compound.

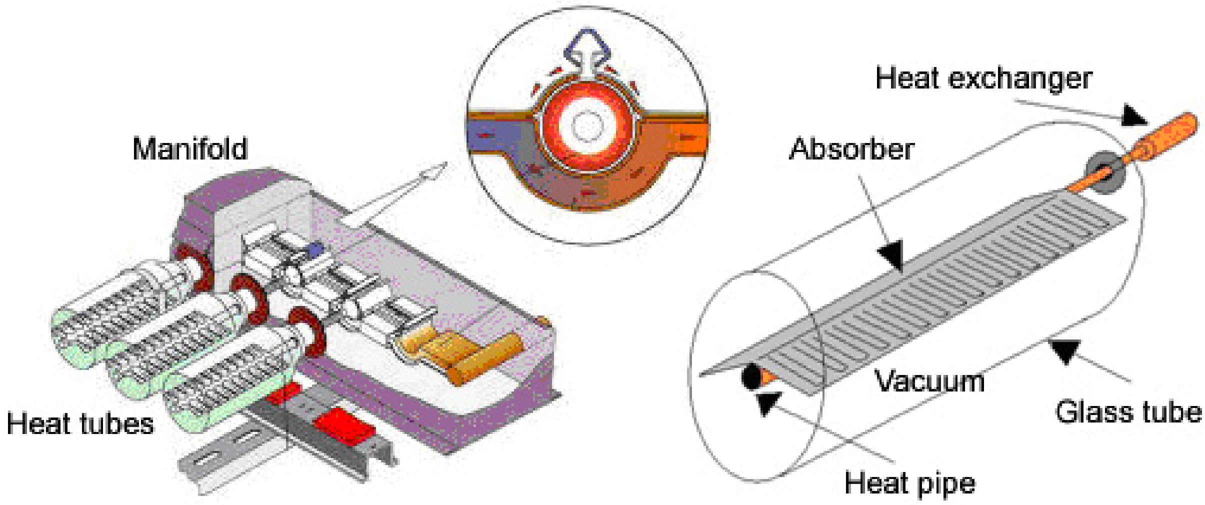

Figure 4. Evacuated solar collector manifolds and heat tubes assembly

An expansion vessel was 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 the heat exchanger is 5.73m with 6 turns. The inlet and outlet of the 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; an electrical pump circulates the water in the loop.

3. Test procedure and method presentation

The experimental devices and instruments were fabricated and assembled as illustrated in Figures 1 and 2. The floodlights were evenly spaced on a frame installed above and in parallel to the flat board covering the area of solar light simulator. This flat board was 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 British Standards for testing the solar simulator. The light intensity was measured using a CMP 3 pyranometer with sensitivity of $17.99\text{x}10^{-6}$ 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 with 0.1°C accuracy. Prior to the experiments, the solar simulator covering the evacuated solar collector with the storage tank was assembled so that all the piping system was covered by thermo-insulation materials, as shown in Figure 2. This was to reduce heat losses. Several experimental tests were carried out 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 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 period in the Middle East region with an average irradiance of 6.2 KW/m^2 day. Solar radiation during March 2004 was simulated, as shown in Figure 5. Using the regulator dimmer, the level of electrical power supplied to floodlights was changed every 20 minutes using the floodlight irradiation measurement results which were evaluated and verified experimentally, and the results then were analyzed and averaged as presented in Figure 6.

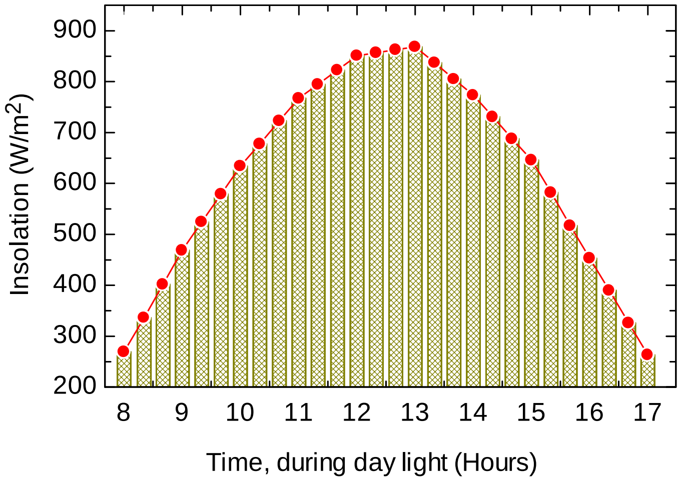

Figure 5. Solar insolation variation in the Middle East region

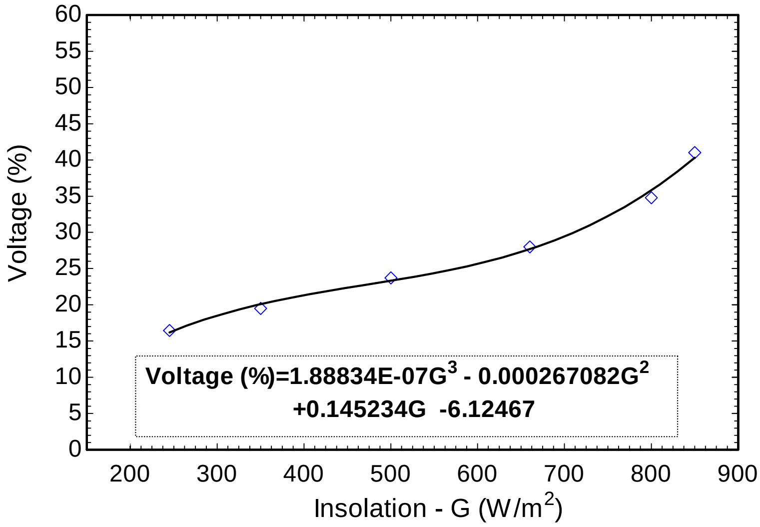

Figure 6. Solar insolation level versus transformer voltage calibration results

4. Results and discussions

4.1 Light unevenness

The solar simulator steady state light is essential 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, 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 7 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 [8]. 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 in distance, as illustrated in Figure 8.

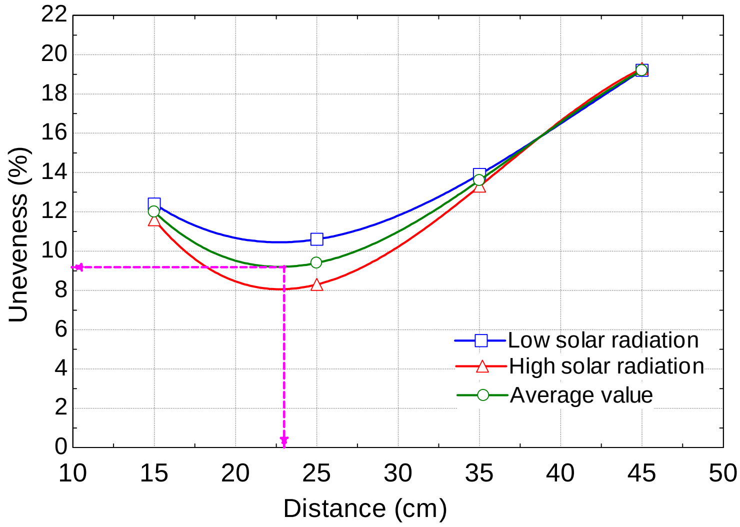

Figure 7. The unevenness percentages versus distance

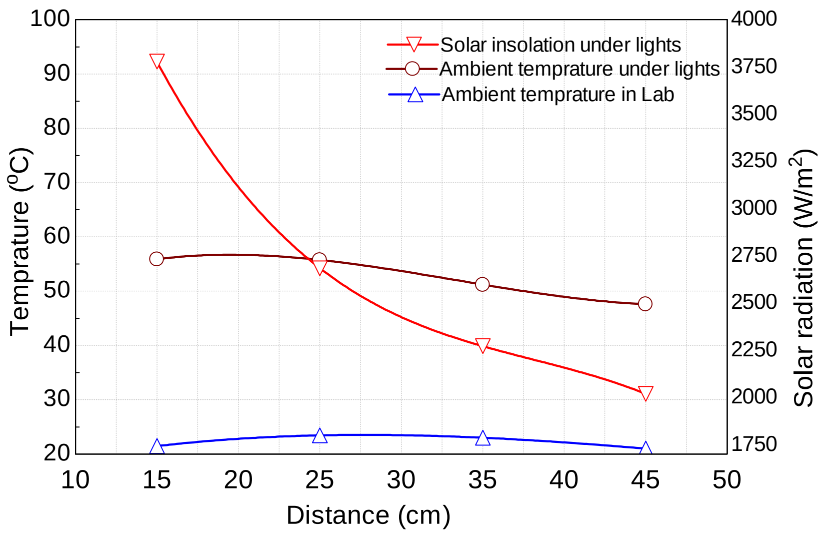

Figure 8. Solar insolation and ambient temperatures

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 is 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.

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

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 7.

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 was found to be less than 15%, as shown in Figure 9. This is compatible with the British Standards values for testing a solar simulator. The simulator was tested under different solar irradiations, namely 200, 400,600, 800, 1000 and 1200 W/m^2 and it was found that the magnitude of light's unevenness increases with the increase of solar intensity. However, it can be noted that the unevenness error in both conditions is 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.

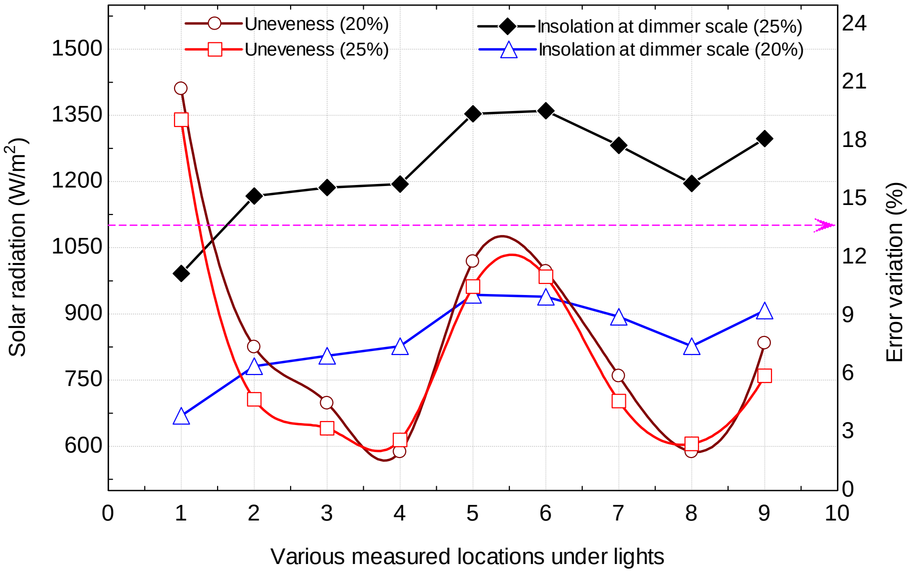

Figure 9. The unevenness and insolations under solar simulator at various spaced points

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 a high of 850 W/m^2. 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 varied between 70% and 81%, which was in good agreement with the calculated efficiency diagram provided by the manufacturer.

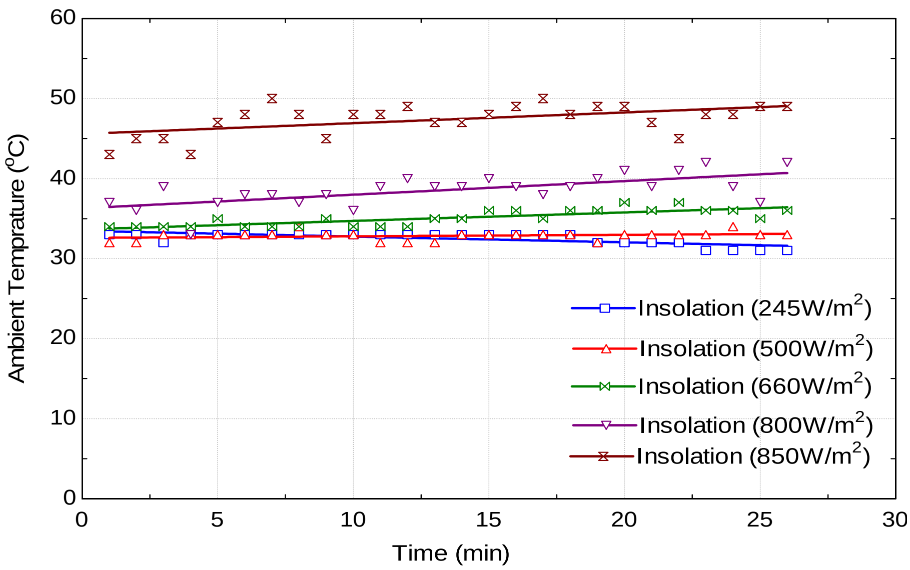

Figure 10. Ambient temperature under the solar simulator

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It can be seen from Figure 11 that the efficiency of the solar collector is inversely proportional to the solar intensity. 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 a significant influence on its performance efficiency.

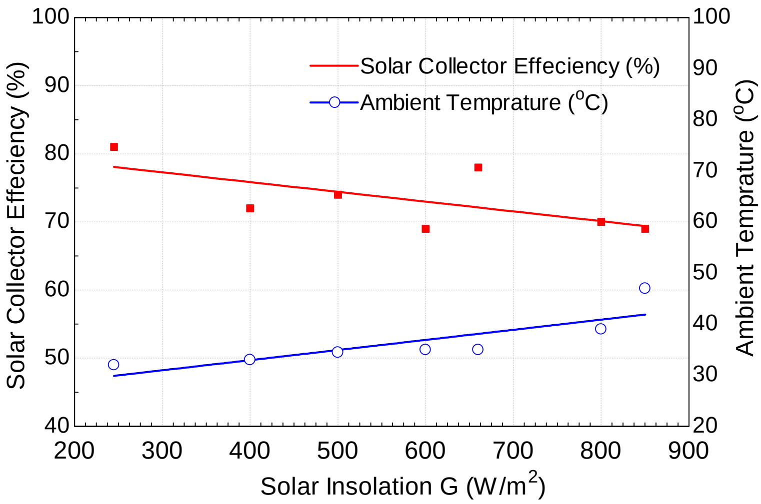

Figure 11. Solar insolation versus solar collector efficiency

4.3 Solar collector efficiency

The efficiency of the solar collector was calculated in different ways based on the inlet and outlet water temperatures of the solar collector and the ambient temperatures as follows:

Thus, 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

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

The efficiency was determined using the derived formula based on experimental results of solar insolation and ambient temperature, as presented in Figure 12 and as written in Equation 3

$$\eta_i = 83.0583 - 0.628174 \left(\frac{\overline{G}}{T_a}\right) \quad (3)$$

The efficiency was also calculated using an equation provided by the manufacturer as represented in Equation 4 [7].

$$\eta_i = 0.84 - 2.02 \frac{T_m - T_a}{\overline{G}} - 0.0046\,\overline{G}\left[\frac{T_m - T_a}{\overline{G}}\right]^2 \quad (4)$$

where: T_m = mean collector temperature, $\frac{(T_{sci} + T_{sco})}{2}$ [°C], T_a = ambient air temperature [°C], $\overline{G}$ = Solar irradiance [W/m^2], A_{col} = Solar collector absorbance area [m^2]

Solar insolation for the Middle East in 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 as solar insolation decreases. The efficiency of solar collector has been calculated in three different ways as illustrated in previously. It can be seen that the efficiency of the 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's suggested efficiency showed a significant decreaseafter 2:00 pm, as illustrated in Figure 14; this can be explained by the fact that the manufacturer's efficiency formula was produced under indoor conditions at solar insolations of 800 and 1000 W/m^2 respectively.

Figure 14 shows that the ambient temperature and the surface tube temperature of the solar collector ranged 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 ranged between 2 and 5 ^{o}C for insolation values of 245 to 850 W/m^{2,} as presented in Figure 10. 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 to be utilized by the solar collector. However, it can be seen that increases of solar intensities above 900 W/m^2 results in only a very small increase in the thermal heat output of the solar collector, and this affected significantly the collector's efficiency. This can be explained by the fact that the solar collector had reached its saturation capacity point of heat output.

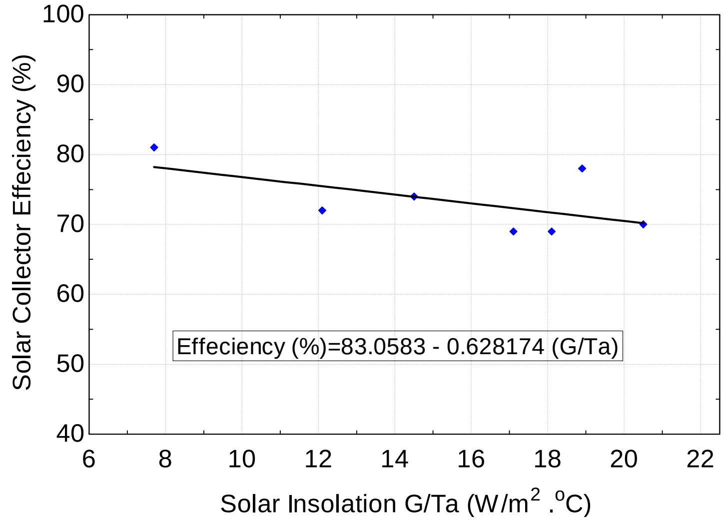

Figure 12. Experimental efficiency formula of solar collector

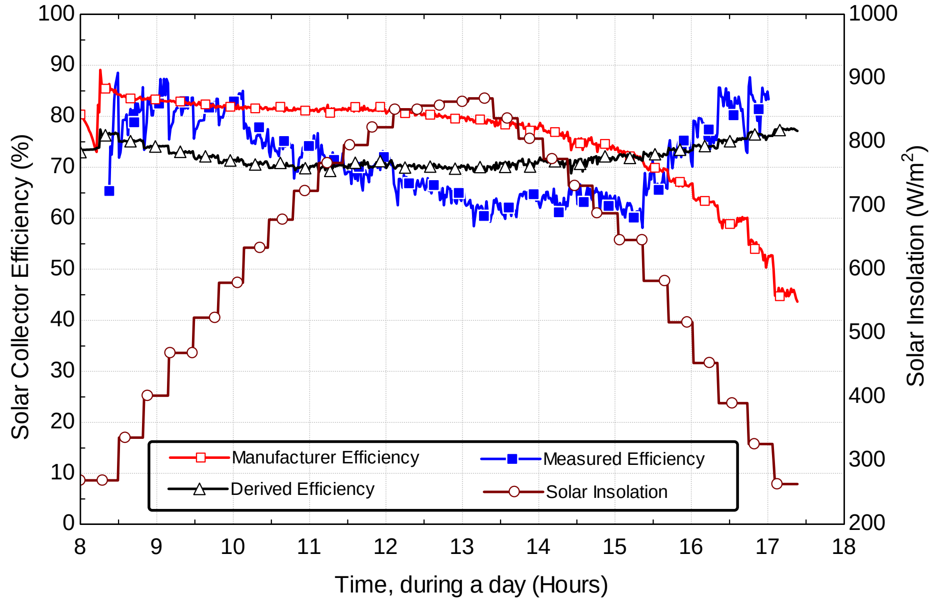

Figure 13. Efficiency of solar collector and solar insolation variations for entire day light in the Middle East

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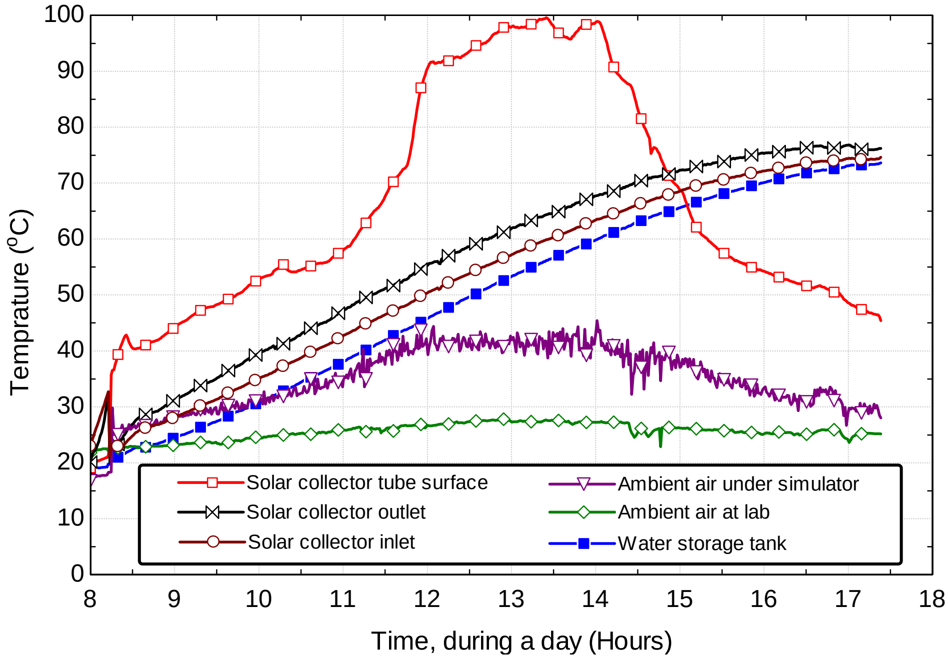

Figure 14. Ambient temperature under the solar simulator for a day light in the Middle East

Furthermore, Figure 14 shows that the maximum achieved temperature at the water storage tank for the Middle East day of operation was 73.50 °C and the average evacuated solar collector efficiency was about 72%, which is in good agreement with the manufacturer's recommended efficiency.

5. Conclusion

A solar light simulator of high flux solar irradiation connected to a water heating system comprising an evacuated solar collector and water storage tank was 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 of the light source from the simulator surface in order to investigate the problem of variations in light distribution. 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 good agreement within the permissible limits of 15% provided by British Standards for testing a solar simulator. The performance of an evacuated solar collector of 20 tubes with an aperture area of about 1.73 m^2 was tested in indoor conditions to simulate solar insolation during March in the Middle East region. It was determined that the average efficiency of the solar collector was 72% and this correlated closely with the efficiency data provided by the manufacturer.
It can be concluded that the development of such solar light simulators would be a significant advantage to R & D work in solar energy technologies because it would enable researchers to carry out and repeat experimental tests under various conditions without exposure to unpredictable outdoor weather fluctuations and limited availability of solar radiation, especially in northern Europe. Further, less expensive and high performance of solar simulators can be fabricated with tungsten halogen lamps light sources.

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Nomenclature

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

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