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An investigation into the effect on the productivity of cascade-type solar distillation systems with varying cover thicknesses and still orientations under tropical Caribbean climatic conditions

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ABSTRACT

Previous investigative work related to solar stills focuses mainly on issues relating to the temperature gradient between the brine and the condensing surface. It is common practice when calculating the efficiencies of solar stills to use the temperature of the outer glass as the condensing surface temperature rather than the temperature of the actual condensing surface. This practice is done due to the fact that the outer glass surface temperature is easily measurable and on the assumption that there is little or no drop in temperature across the thickness of the cover. These conventions in turn create room for misleading results owing to temperature losses across the cover thickness. The main objectives of this research work are to investigate the effect of using different glass cover thicknesses and different solar still orientations on the productivity of cascade-type solar stills tested under tropical Caribbean climatic conditions. In the investigation, three identical units fitted with glass covers of thicknesses 3.18, 4.76 and 6.35 mm are used. Each unit comprised two identical solar stills: one oriented to face north and the other to face south. Results were gathered at the University of the West Indies in St. Augustine, Trinidad and comparative analyses were conducted. The results indicate that the solar still with the glass cover thickness of 4.76 mm facing south produced the highest yield.

Keywords: Distillation; Solar distillation; Solar still; Cascade-type solar still; Desalination; Solar energy; Glazing thickness; Distillation output; Glass cover thickness; Performance

1. Introduction

Water is a basic human necessity with the average daily water consumption of an adult ranging between 2.5 and 3 l d^{-1} [1]. Studies show there is a link between the availability of potable water sources and the settlement of humans across the globe. In 2007, it was reported that approximately 40% of the population of the world would settle in areas that lack

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sufficient quantities of freshwater sources by 2015 [2]. Similarly it is estimated that by 2025, 67% of the global population would have insufficient access to potable water [3]. With the increasing global population and the daily depletion of freshwater resources, it is necessary to search for alternative sources to satisfy the freshwater needs of the global population.

Solar distillation is a process that simulates the naturally occurring hydrological cycle. It employs the use of energy derived from the sun to purify impure water thereby producing potable water for consumption purposes. This technique has been around for centuries as evidenced by numerous pieces penned by Aristotle the great [4].

The productivity of solar stills is dependent on several meteorological and geometrical parameters as outlined by several researchers [5–7]. These parameters include solar radiation, global location, ambient temperature, brine concentration and initial temperature, wind velocity, evaporative area, brine type and depth, type of solar still, orientation of the still, material and thickness of the glazing.

There are several types of solar stills which include of the basin type, the concentrating collector, the multiple try tilted (cascade) and the tilted wick. In this investigation, the cascade-type still is employed due to the reported higher efficiency to collector area ratios [8,9]. Headley and Springer report an increase of 30% in efficiency when cascade-type stills are used [10]. Similar results were obtained in Singapore with stepped-type solar stills producing 25% more distillate than regular basin-type stills [11] and in Iran, where cascade-type solar stills yielded 26% more production both theoretically and experimentally [12]. Additionally, a 77.35% thermal efficiency was reported for stepped solar stills tested under Egyptian climatic conditions [13].

The tilt of the solar still cover and the orientation of the still are of high importance and greatly affect the performance of solar thermal systems. The optimum tilt for solar still covers is dependent on global location as evidenced by the range in the optimum tilt values between 10˚ and 56˚ displayed in the literature. The literature clearly states that the best suited tilt is one which coincides with the latitude of the country where the system is being used. For Trinidad and Tobago, it is recommended that solar thermal systems be oriented at between 10.5˚ and 11˚ to coincide with the latitude of the country [14]. Similarly, the best suited orientation of solar thermal systems is dependent on global location.

The objectives of this research paper are to investigate the effect of using varying orientations and glass cover thicknesses on the productivity of cascade-type solar stills under tropical Caribbean climatic conditions. As such, the main focus is to determine the best suited glass cover thickness and solar still orientation for the identified location. During the winter months in India, a comparable investigation was conducted where glass cover thicknesses of 4, 8 and 12 mm were used. The results of that experiment identified the solar still fitted with glass cover of thickness 4 mm to be the best performing. In another study, the effect of glazing thickness on productivity was investigated for both passive and active hybrid solar stills for glazing thicknesses ranging from 2 to 6 mm and a decrease in daily productivity was noted as the thickness of the glazing increased [15].

2. Experimental set-up

2.1. System description, methodology and governing equations

2.1.1. Description of the cascade design solar distillation systems

In this investigation, three cascade design solar distillation units are employed and used under Caribbean tropical climatic conditions. Data are collected over a 10-d period at the Department of Physics, Faculty of Science and Technology at the University of the West Indies (UWI), St. Augustine Campus in Trinidad, West Indies during the months of November and December 2012.

Each unit comprises two independent anti-parallel North–South-oriented stills conjoined along the vertices as depicted in Fig. 1. The units were fabricated using glass fibre-reinforced concrete and each solar still encompasses four shallow rectangular basins each merged together in a cascading effect with total external area of 2.446 m^2. The effective collector area amounts to 1.995 m^2 which was first coated with 9800 System DTM Urethane Mastic and then painted with matte black paint to increase the absorptive properties of the surface. The stills are fitted with two transparent glass sheets, each measuring 1.115 m^2 at an inclination of 10.5˚ to the horizontal. Each unit is fixed with sheets of different thicknesses, namely: 3.18, 4.76 and 6.35 mm. To curtail heat losses to the ambient, the system is sealed with silicone sealant.

Affixed to the lower base of the still is a stainless steel collection channel to facilitate acquisition of the distillate. The distillate exits the still via a stainless steel pipe and is fed to a large air-tight plastic bottle via a hose. Silicon sealant is utilized to create a vapour tight system. For purposes of measuring the temperature variations within the system, a total of 12 calibrated copper–constantan (Type-T) thermocouples are fixed at strategic points on the collector area and

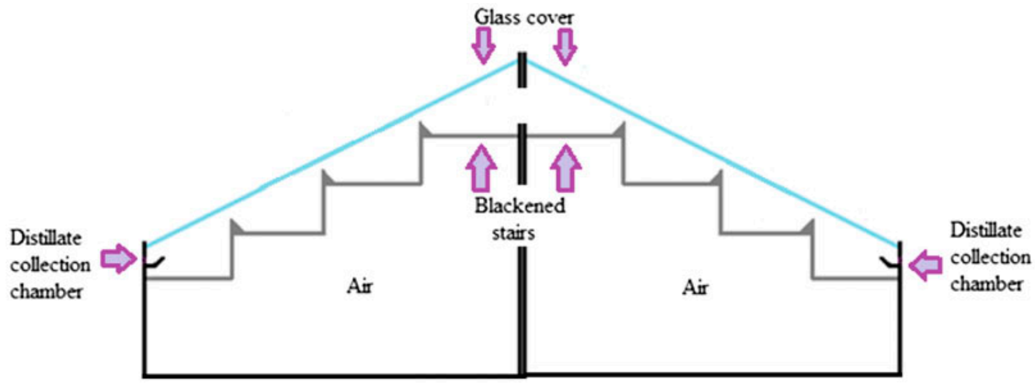

Fig. 1. Schematic of double-sided cascade-type solar distillation system.

another 12 are attached to the inner glass surface as depicted in Fig. 2.

All 24 thermocouples are fed to a multi-channel rotary-switching temperature monitoring box. Once coupled with an appropriate temperature measurement enabled metre, temperature values may be obtained from all the points. A mobile thermocouple point is used to measure the temperature on the external glass surface when necessary.

2.1.2. Methodology

The parameters measured on an hourly basis between 8 am and 5 pm comprised the following:

- Distillate quantity.
- Temperatures of the brine, inner and outer glazing surface and ambient.
- Global solar radiation.
- Observations of state of the atmosphere—monitoring of cloud cover, rainfall, wind speed and direction.

Fig. 2. Picture depicting the thermocouples fixed onto the inner glass surface.

The temperatures of brine and inner glazing surface are measured with the aid of calibrated copper–constantan thermocouples and a digital multimeter capable of obtaining temperature readings. The ambient temperature; global solar radiation on a horizontal surface; wind speed and direction; total rainfall and other meteorological parameters were measured with utilizing a Davis Weather Station located at the same location of the stills. A glass cylinder of 1 l capacity is utilized to quantify the hourly distillate produced from the solar stills.

2.1.3. Governing equations of solar stills

The heat transfer occurs via the humid area within the solar still that is the area between the brine and the condensing surface. This occurs via convection which is due to the effect of buoyancy due to the density variation of the humid fluid. This density variation occurs due to the temperature gradient within the fluid.

The radiation and convection heat transfer may be obtained from the equations [12]:

$$Q_{rw} = \sigma\epsilon_w A_b \left(T_w{}^4 - T_g{}^4\right) \tag{1}$$

$$Q_{cw} = h_{cw} A_b \left(T_w - T_g\right) \tag{2}$$

The rate of heat transfer in the evaporation process (brine to condensing surface) Q_{ew} may be estimated using the equation:

$$Q_{ew} = h_{cw} A_b \left(T_w - T_g\right) \tag{3}$$

The convective loss coefficient from the water surface to the glass h_{cw} is given by Tiwari [16]:

$$h_{cw} = 0.884\left[(T_w - T_g) + \frac{(P_w - P_g)(T_w + 273)}{268.9 \times 10^3 - P_w}\right]^{1/3} \tag{4}$$

The values of P_w and P_g within the range of interest may be obtained from the expression [17]:

$$P(T) = exp^{\left(25.317 - \frac{5.144}{T+273}\right)} \tag{5}$$

The hourly yield of the solar still is given by [18]:

$$m_{ew} = h_{ew}\frac{(T_w - T_g)}{L} \times 3{,}600 \tag{6}$$

For instantaneous efficiency of the still η_i is calculated by:

$$\eta_i = \frac{q}{I(t)} = \frac{h_{ew}(T_w - T_g)}{I(t)} \times 100 \tag{7}$$

The term h_{ew}, the mass transfer coefficient is found using the equation [19]:

$$h_{ew} = 16.273 \times 10^{-3} h_{cw}\left(\frac{P_w - P_g}{T_w - T_g}\right) \tag{8}$$

The various heat transfer processes taking place within the cascade design system in this research are depicted in Fig. 3.

The daily efficiency of the solar still may be calculated using the equation [20]:

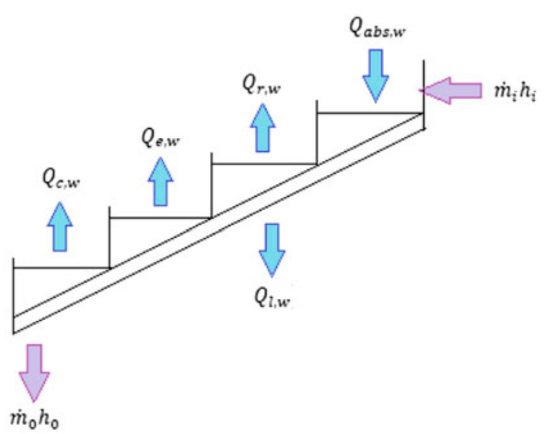

Fig. 3. Schematic depicting the energy balances in the cascade solar still used.

$$\text{Efficiency} = \frac{h_{fg} P_d}{I} \tag{9}$$

h_{fg} is the latent heat of evaporation of water (2,260 kJ kg^{-1}), P_d is the daily yield measured in kg m^{-2}, I is the average daily solar intensity measured in W m^{-2}.

3. Results, analysis and discussion

3.1. Results and analysis

The results obtained throughout the duration of testing period are depicted in the graphs in Fig. 4(a)–(j).

From the graphs depicted in Fig. 4(a)–(j), it is noted that the solar still with glass of thickness 4.76 mm yields better results overall than the stills fitted with glass covers of thicknesses 3.18 and 6.35 mm. These results may be accounted for by examining the geometrical properties of the glass covers.

Theoretically, we know that the thicker the glass, the longer the time it takes to transverse the medium and the greater the losses that occur and, the thinner the glass cover, the greater the losses that occur from within the system. Thus, the thinnest glass covers (3.18 mm), while allowing the most incoming solar radiation into the still, also allows for more thermal losses occurring from the system. The 6.35 mm thick glass cover however does the complete opposite by limiting the quantity of solar radiation that enters the interior of the still but trapping more thermal radiation within the system. The solar still fitted with glass of thickness 4.76 mm however was able to allow more solar radiation to enter the system than the 6.35 mm glass but less that the 3.18 mm. However, the 4.76 mm thick covered still experienced less losses than the one covered with the 3.18 mm glass due to the increased thickness. This subsequently makes those stills the better performing ones.

Examining the yields depicted in Fig. 5, it is clear that the still with the overall best performance was the one fitted with glass of thickness 4.76 mm facing south. The still with the lowest yield over the duration of the period was consistently the one fitted with the 6.35 mm thick glass cover and oriented to face north. On the 7th d, the still with the 3.18 mm thick glass cover facing south produced the highest yield. Careful examination of the results and the meteorological data collected on that day show this performance is due to an anomaly.

Fig. 6 depicts the average total daily yields obtained over the duration of the 10 d. For the solar stills oriented facing north, it was noted that the still fitted with glass cover of thickness 4.76 mm showed

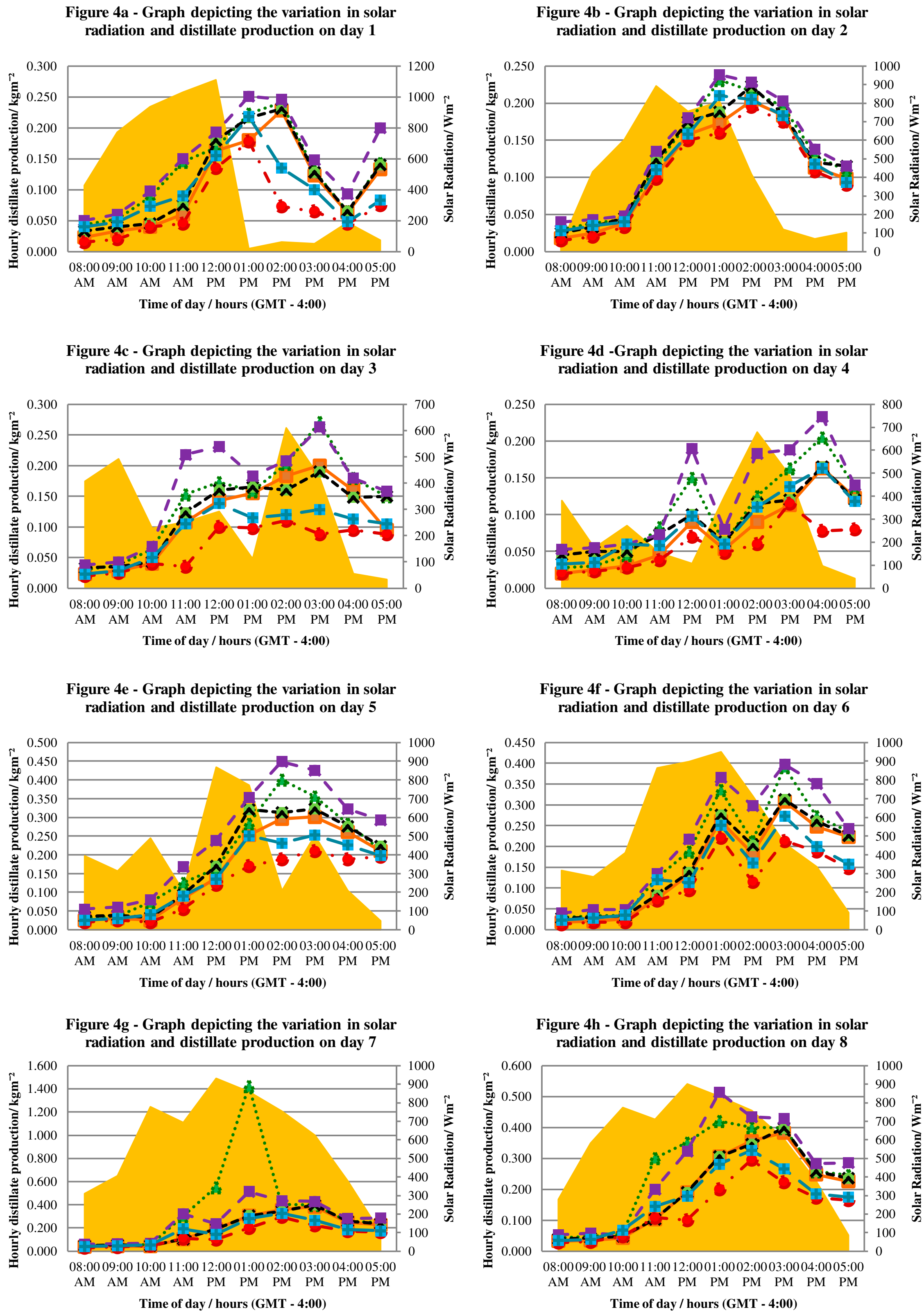

Fig. 4. Graphs showing the daily hourly variation in solar radiation and distillate yield.

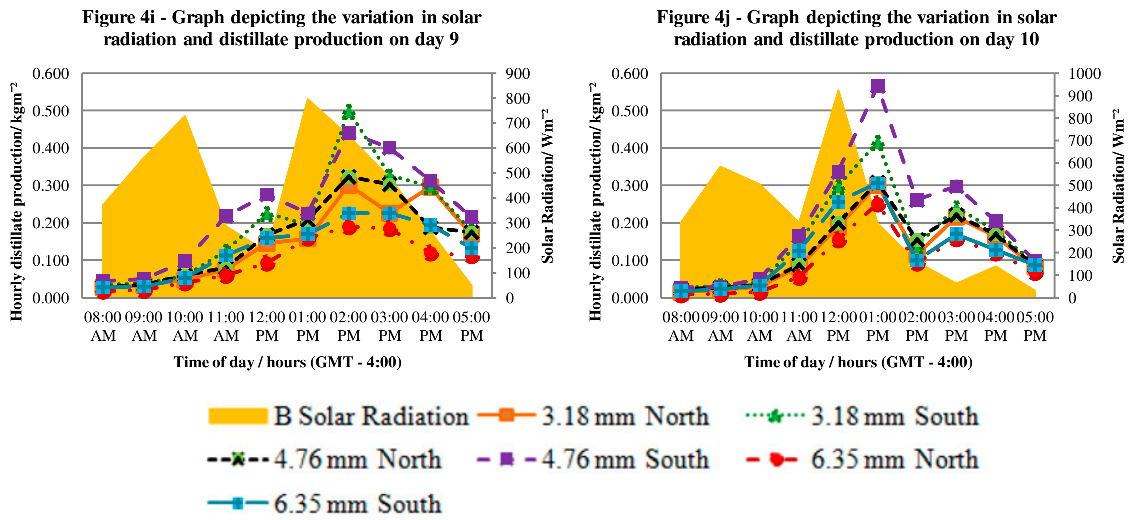

Fig. 4. (*Continued*)

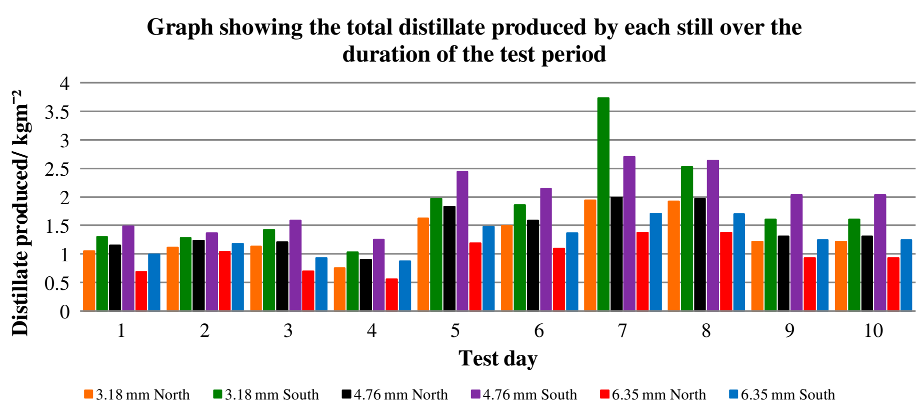

Fig. 5. Graph showing the total daily yields for each still over the 10-d test period.

superior results with an overall greater yield of 11 and 49% for the stills fitted with glass covers of thicknesses 3.18 and 6.35 mm, respectively. In the south direction, the system with cover of thickness 4.76 mm produced an average of 19 and 54% more distillate than the 3.18 and 6.35 mm ones, respectively.

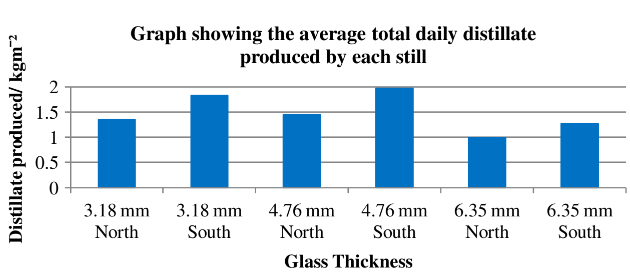

Fig. 6. Graph showing the average total daily yields for each still over the 10-d test period.

Comparing the average daily distillate collected over the 10 d period for the stills fitted with thicknesses 3.18 and 6.35 mm it was observed that when facing north, the one with the 3.18 mm thickness produced 34% more distillate than the one fitted with the glass cover of thickness 6.35 mm. Likewise, when facing south, an increase of 38% yield was noted for the still fitted with glass of thickness 3.18 mm as compared with the one with glass cover of thickness 6.35 mm. The greater production rate of the solar still fitted with glass covers of thickness 3.18 mm may be accounted for by examining the spectral and geometrical properties of the glass medium.

When comparing stills oriented south vs. those oriented to face north, we observe an average of 29% more for the still with glass thickness 3.18 mm, 30% for the still with glass of thickness 4.76 mm and 26% for the still with glass of thickness 6.35 mm. These results are expected theoretically due to the location of Trinidad with respect to the equator.

Depicted in Table 1 are the average daily efficiencies obtained from the solar stills over the duration of the experimental work. The average daily efficiencies ranged from the lowest value of 11.4% for the solar still with glass cover of thickness 6.35 mm oriented facing north to the highest value of 39.3% for the 3.18 mm glass cover fitted solar still oriented to face south. Overall, the solar still fitted with glass cover of thickness 4.76 mm oriented to face north displayed the best average daily efficiency of 29.3%. The second highest average daily efficiency of 26.2% was found for the solar still facing south fitted with glass of cover thickness 3.18 mm.

3.2. Discussion

Throughout the duration of this experimental work, the maximum value of global solar radiation available for usage peaked at 1,124 Wm^{-2} on November 09th and dipped to 818 Wm^{-2} on November 16th. The maximum value averaged at 978 Wm^{-2} over the 10 d period. The highest daily temperature varied from a maximum of 33.1˚C on November 22nd to a minimum of 30.2˚C on 16th November, with an average maximum daily temperature of 31.6˚ throughout the experimental period. The lowest temperature occurred on November 10th during the early morning hours, prior to sunrise.

Analysis of the data obtained from the Davis weather station showed a correlation between the global solar radiation and the ambient temperature. An example of this trend is depicted in Fig. 7. An interesting but expected observation is the time lag between the peaks (and valleys) in the global solar radiation and the ambient temperature. This is accounted for the fact that the earth is warmed via infrared radiation emitted from the sun and thus as the radiation values increase, the thermal radiation warms the atmosphere, subsequently increasing the ambient temperature.

Careful analysis of the trend of data displayed in the graphs included in Fig. 4(a)–(j) shows a direct correlation between the quality of global solar radiation available for capture and the total yield of distillate produced. The correlation is accompanied by a time lag such that a peak in the solar radiation values preceded the peak observed in distillate collection. One notes that on days with higher insolation readings, higher distillation yields are produced and vice versa.

The glass cover of the solar still exhibits a vital role in the determination of the quantity of solar radiation allowed to enter the system. One of the functions of the glass cover is to selectively allow the short-wavelength highly energetic solar radiation to enter the system. Once the radiation enters the system it is re-radiated as long-wavelength infrared radiation. However, the properties of the glass do not easily allow for this radiation to escape from the still, resulting in the majority of the re-radiated radiation being trapped within the system. This is subsequently converted to thermal energy which is used in the distillation process. When solar radiation is incident onto the glass surface, both reflection and refraction occurs at the air–glass boundary. The quantity of solar radiation that enters the glass medium via refraction undergoes energy losses as it traverses the medium due to impurities that exist within the glass. As the radiation encounters the glass–air boundary it once more undergoes both reflection and refraction. The refracted quantity then enters the solar still where it is converted to long-wavelength infrared radiation. The spectral properties of the glass do not allow this type of radiation to easily travel through thus, trapping the

Table 1
Average daily efficiencies of the solar stills over the 10-d test period

Day	Average daily efficiencies of solar stills (%)					
	3.18 (mm N)	3.18 (mm S)	4.76 (mm N)	4.76 (mm S)	6.35 (mm N)	6.35 (mm S)
1	16.4	20.1	18.0	22.8	11.4	15.8
2	17.4	19.9	20.2	22.3	15.7	18.0
3	23.4	29.3	26.7	33.1	15.9	19.5
4	17.8	22.4	20.3	26.1	14.6	19.9
5	21.8	26.2	24.5	32.0	16.5	20.0
6	19.0	23.3	21.0	28.2	13.9	17.0
7	22.1	39.3	22.9	30.7	15.8	19.4
8	21.4	27.2	22.2	29.3	15.4	19.0
9	21.8	27.9	23.4	32.1	15.0	20.0
10	20.6	26.6	25.1	36.2	16.1	20.9
	20.17	26.22	22.43	29.28	15.03	18.95

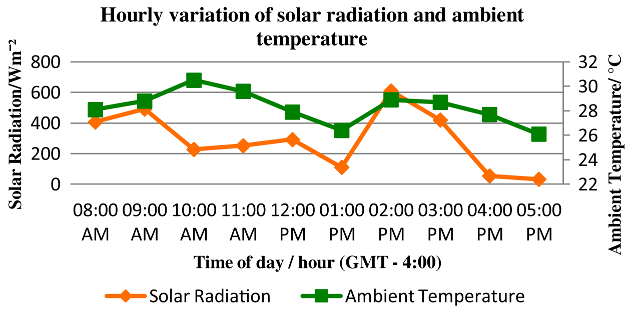

Fig. 7. Graph showing the hourly variation in solar radiation and ambient temperature for a typical day during the testing period.

re-radiated infrared radiation within the solar still. The thinnest of the glass cover allows for a greater quantity of solar radiation to enter the solar still at a much quicker rate. On the other hand, the thicker the glass covers, the better it is able to create a barrier which traps the re-radiated radiation within the still. Thus, it is concluded that the thinner the glass cover, the greater the losses and the thicker the glass surface, the greater the shield which prevents absorption of solar radiation. As such, the ideal glass cover needs to be of optimal thickness that allows the maximum radiation to enter the solar still but at the same time minimizing losses.

4. Conclusion

Overall, it is noted that the solar still fitted with glass of thickness 4.76 mm yielded better results when oriented both in the north direction and the south direction. The average daily efficiency of this still was calculated to be 29.3% over the duration of the experiment. Moreover, it is observed that the stills oriented in the south direction, yielded better results than those in the north direction, which is characteristic of the geographical location of Trinidad. Further investigative work would include investigating the effect on the performance of the still when a wider range of glass cover thicknesses and solar still orientations are used.

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