MEASURED PERFORMANCES OF AN AUGMENTED [DOUBLE-EXPOSURE ABSORBER-PLATE] SINGLE-SLOPE SOLAR STILL

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Abstract

Comparative measured performances of a double-exposure absorber-plate single-slope solar still and the conventional single-exposure solar still are reported. The single-slope basin-type solar still (SSBSS) is modified by attaching a semi-cylindrical reflector to its exposed base to obtain the Reverse-side Absorber-plate solar still (RASS). Solar radiation thus impinges on the absorber plate from both the top-side and below. Outdoor tests were conducted on experimental models of both the RASS and the SSBSS of similar dimensions to obtain diurnal variations in absorber-plate temperatures, T_p, glass cover temperatures, T_{gc}, instantaneous distillate outputs, $m_{w,inst}$, cumulative distillate distillate yields, $M_{w,cum}$, and cumulative still efficiencies, η_{cum}. Compared to the SSBSS, significantly higher absorber-plate temperatures were recorded by the RASS, and overall daily distillate yields from the RASS were up to 46% above those obtained from the SSBSS. However, the cumulative efficiencies of the RASS (26-29%) were lower than those of the SSBSS (35-40%). The tests also showed that distillate yields from both stills were improved by increasing the initial masses of water contained in the stills.

1. Introduction

In many rural locations in Nigeria pipe-borne clean portable water, are frequently unavailable. Over 70% of Nigerians live in semi-urban and rural areas; where they face serious healthcare challenges associated with the lack of clean water for basic domestic needs and indeed for drinking. Nigerian healthcare statistics are amongst the worst in the world. In most of the rural homes and many urban homes in Nigeria, the traditional and most popular sources of water, even for drinking, are stagnant pools of muddy ponds, brackish water from shall wells and highly polluted rivers. The high prevalence of dracunculiasis, popularly known as guinea worm disease (GWD) in Africa is associated with the drinking of stagnant water contaminated with copepods infested by the larvae of the guinea worm (http://en.wikipedia.org/wiki/Dracunculiasis). The common name "guinea worm" appeared after Europeans saw the disease on the Guinea coast of West Africa in the 17th century. The challenges posed by dearth of clean portable water are worse during the dry season. Even for many urban dwellers the cost of clean portable water can be prohibitive. Regularly, a large proportion of the family income and/or enormous man-hours that could have been utilised in more productive services are expended in the procurement of water for basic domestic uses. Under these conditions, solar-energy stills appear increasingly attractive as viable alternatives.

The history of solar distillation has been traced to the experiments of Della Porta (1535-1615) (Delyannis, 2003). Since then, tremendous amounts of documented research have been undertaken to bring it to its present status. The investigations undertaken have included the development of novel solar still designs (Ismail, 2009; Abu-Qudais et al., 1996; Zhang et al., 2003; Kumar et al., 2008; Garg, 1987), experimental studies and the improvements of existing designs (Aboabboud et al., 1997; Abdallah et al., 2008), the development of analytical models for analyzing the performance of solar stills and the experimental validation of same (Cooper, 1969; Shawaqfeh and Farid, 1995; Kumar and Tiwari, 1996; Hongfei et al., 2002). The factors that affect the performance of solar stills have also been variously studied (Porta et al., 1997; Dimri et al., 2008).

By far, the most popular solar still type is the *single-slope basin-type solar still* (SSBSS), also known as the *asymmetric greenhouse-type still* (Fig. 1). It consists of a basin which is painted black on the inside, which holds the water to be distilled (the brine). The basin is housed in an insulated casing and is covered airtight with a transparent (glass or plastic) cover inclined at an angle to the horizontal. The solar radiation which gets into the still through the cover is absorbed and converted to thermal energy by the blackened surface of the basin, which then heats up the brine. This induces evaporation from the surface of the brine. The vapour generated condenses on the under-side of the slanted cover and slides down into a channel from which it is collected. Between 3.3 - 5.0 litres $m^{-2}day^{-1}$ of the distillate can be obtained with the typical SSBSS (Garg, 1987).

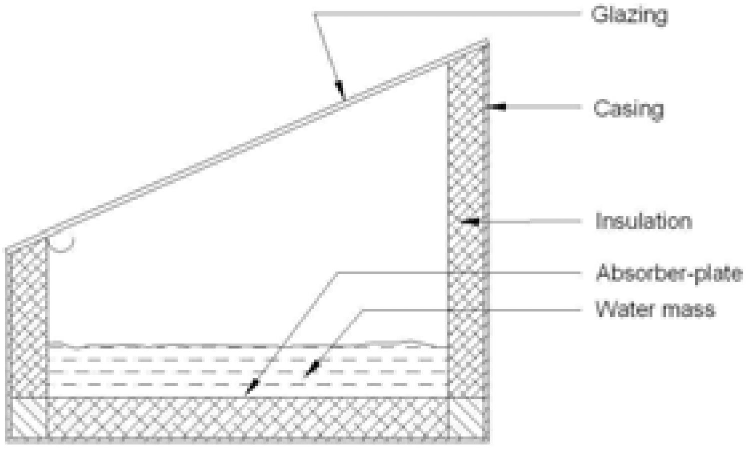

Fig. 1: The single-slope basin-type solar still.

Though the SSBSS has been shown to be a cost effective, easy-to-construct, easy-to-maintain and relatively simple means of producing clean water in locations where other alternatives such as piping and trucking will be unfeasible, certain limitations which attend its usage have been identified. Most prominent among these being the low distillate output which it is capable of. Thus several modifications to the basic SSBSS have been proposed and implemented which have resulted in varying degrees of improvements in its performance. A few of such modifications are listed in Table 1.

Tab. 1: Performance of some modified Single Slope Basin-type Solar Stills.

Modification	Location	Distillate Yield	Efficiency	Comment
Introduction of a floating absorber plate: Aluminium Mica Copper	 Bahrain Tanta, Egypt Tanta, Egypt	 4.21 litres $m^{-2}day^{-1}$ 4.311 litres $m^{-2}day^{-1}$ 3.325 litres $m^{-2}day^{-1}$	 57% 35.8% 27.6%	 (Rahim, 2003) (El-Sebaii et al., 2000) (El-Sebaii et al., 2000)
Integration of a separate condenser and double glass cover	Ankara, Turkey	4 – 6 kg $m^{-2}day^{-1}$	48-70%	The higher values were obtained when the condenser was cooled with flowing water (El-Bahi and Inan, 1999)
Use of a step-wise water basin with sun-tracking	Amman, Jordan	5.68 litres $m^{-2}day^{-1}$	-	(Abdallah et al., 2008)
Addition of a thermal energy recycle unit	Lab Experiment	12 kg $m^{-2}day^{-1}$	-	(Aboabboud et al., 1997)

The attachment of a semi-cylindrical reflector to the exposed base of solar collectors, variously referred to as *reversed absorber, inverted absorber, reverse-side absorber-plate*, has been suggested (Chandra et al., 1983; Madhusudan et al., 1983; Tiwari, 1986) as a means of improving the performance of such collectors because it enables the absorber plate of the collector to receive solar radiation on both its top- and under-sides, increasing the solar radiation input to the collector. The conclusion of several analytical studies on the application of this concept to solar crop dryers (Goyal and Tiwari 1997; Jain, 2007), air heaters (Chandra et al., 1983), and shallow solar ponds (Njoku et al., 2009) is that reverse-side absorber-plate configurations will deliver higher performances when compared to the conventional ones which receive solar radiation only on the top surfaces of their absorber plates. The *reverse-side absorber-plate solar still* (RASS) which is obtained by attaching a cylindrical reflector to the base of the SSBSS is shown in Fig. 2. It was first suggested by Suneja and Tiwari (1998) (who called it the *inverted absorber solar still*). They developed an analytical model for the inverted absorber solar still which predicted higher distillate outputs from it compared to the SSBSS. The higher temperatures generated in the water basin as a result of the extra solar radiation received on the under-side of the absorber plate led to higher temperature differences between the brine and the cover, and thus higher distillate outputs (Suneja and Tiwari, 1998, 1999).

Two advantages of using a cylindrical reflector to augment the solar radiation received by a solar still (as is the case in the RASS,) are immediately apparent:

- Unlike when a plane reflector is used, where much of the radiation from the reflector bounces off the surface of the titled cover (the glazing), all the radiation reflected from a cylindrical reflector arrives at the absorber-plate.
- Convection heat losses which would otherwise have occurred from the now-exposed base of RASS are suppressed because when the air in contact with the under-side of the absorber-plate gets heated up by conduction, in attempting to rise due to buoyancy, it gets stuck to the absorber-plate, stifling the convection mechanism.

However, in spite of the positive results obtained from analytical studies, reports on experimental work on the RASS, or indeed any other reverse-side absorber-plate-type solar collector device have not appeared in the literature. This paper presents results of experiments which were carried out to evaluate the performance of the RASS. The experiments were done simultaneously on experimental models of the RASS and the SSBSS for comparison.

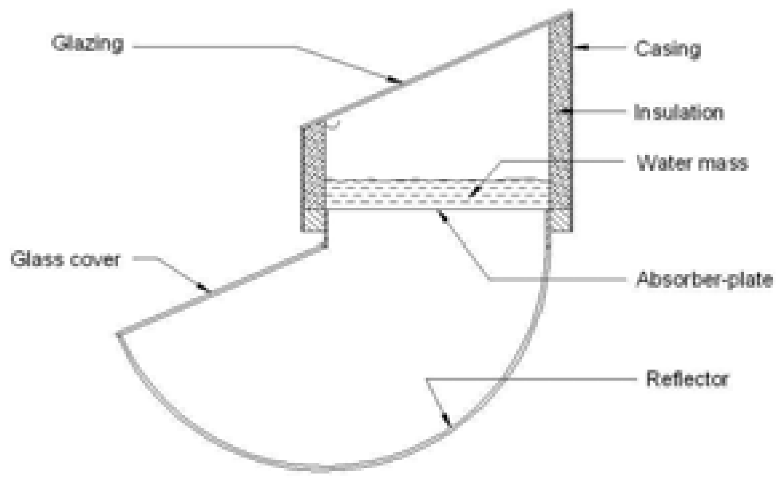

Fig. 2: A schematic of the reverse-side absorber-plate solar still.

2. Experimentation

2.1. Description of the reverse-side absorber-plate solar still unit

The sketch of the experimental unit is as shown in Fig. 2 and a picture is shown in Fig. 3. The basin was constructed of galvanized steel; it had a cross-sectional area of 100cm x 30cm and heights of 25cm and 12cm on the higher and lower sides, respectively. The top- and under-sides of its bottom were painted black, while its sides were lined with a reflective aluminum foil in order that solar radiation falling on the sides may be reflected onto the bottom. It was covered with a 4mm thick sheet of plain glass, fixed to it with silicone glue and making an angle 23.43° to the horizontal. The basin was encased in a wooden box with a 30mm gap between basin and casing which was filled with sawdust insulation. The reflector was formed with particle board and was lined on the inside with a reflective aluminum foil. Its radius, fixed by the width of the solar still basin, was 30cm. the unit was suspended on a frame constructed using mild steel angle bars.

Fig. 3: Picture of experimental model of the RASS.

2.2. Measurements

The experiments were conducted at the Solar Energy test ground of the Department of Mechanical Engineering, University of Nigeria, Nsukka (lat. 6.87° N and long. 7.38°E). The first set of the observation started at 8.00 a.m. 9th December, 2009 and continued non-stop till 8.00 a.m.13th December, 2009, while the second set of observations started at 8.00 a.m. 14th December, 2009 and continued non-stop till 8.00 a.m. 18th December, 2009. Data of solar radiation intensity and ambient temperature were obtained from the weather stations of the Center for Basic Space Science and the Department of Geography, University of Nigeria, Nsukka. The arrangement of the test set-up for both RASS and SSBSS is shown in Fig. 4.

At the beginning of each test day, at 8.00 a.m., equal masses of water were poured into both stills. These initial masses of water, M_{ini} , poured into the stills, however varied from one day to another as shown in

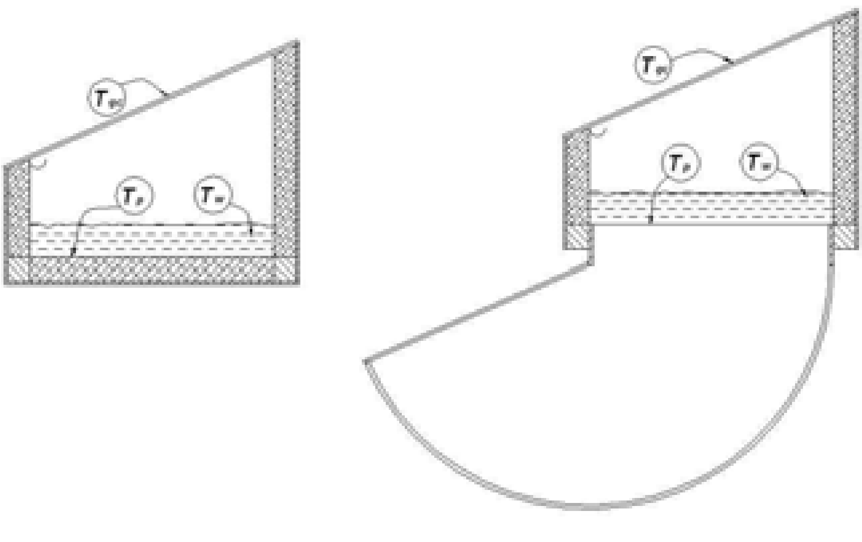

Fig. 4: Experimental set-up of the RASS and SSBSS. (T_p = Absorber-plate temperature sensor; T_w = Water temperature sensor; T_{gc} = Glass cover temperature sensor.)

Table 2. K-type thermocouples (Fig. 4) were used to measure temperatures in the glass covers, water masses and absorber plates of both solar stills. One thermocouple sensor each was attached to the glass covers and immersed in the water masses, while two each were attached to the absorber plates. The sensors were connected through a multi-input selector switch to a digital meter (accuracy of ±0.01.) from which temperatures were read off every half-hour during daytime (from 8.00 a.m. - 8.00 p.m.) and every hour during night-time (from 8.00 p.m. - 8.00 a.m.). Distillate outputs were measured with measuring cylinders which were emptied after each set of recordings.

Tab. 2: Initial water masses daily contained in the stills

Initial water mass, M_{ini}	**Day**
5 kg	9th, 10th and 11th December
10 kg	12th, 14th and 15th December
15 kg	16th and 17th December

2.3. Measures of performance

The instantaneous rate of distillate yield $\dot{m}_{w,inst}$ (kg/m^2·hr) was computed using Equation 1. M_{dist} (kg) is the mass of distillate collected after the time interval, Δt. (Δt is equal to 0.5 or 1 hour, depending on whether intervals of the measurements were half-hourly or hourly, respectively.) A_p is the area of the absorber, taken to be equal to the area of the bottom of the basin (i.e. $A_p = 0.3m^2$).

$$\dot{m}_{w,inst} = \frac{M_{dist}}{A_p \times \Delta t} \qquad (1)$$

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The cumulative distillate yield up to a given time instant $M_{w,cum}(t)$ (kg/m^2) is the sum of all distillate outputs collected from the start of the day's operation till that time. It was computed using Equation 2:

$$M_{w,cum}(t) = \frac{\left(\sum_{t=0}^{t} M_{dist}\right)}{A_p} \qquad (2)$$

The overall efficiency up to any given instant η_o is the efficiency of the still from the start of its operation for the day till that time. It is given by equation 3.

$$\eta_o = \frac{M_{w,cum}(t) \times L}{A_p H_{cum}} \qquad (3)$$

Where, L is the latent heat of water (2430J/kg) and for the SSBSS, $H_{cum} = \sum_{t=0}^{t}\left(G(t)\cdot\Delta t\right)$, while for the RASS, $H_{cum} = \sum_{t=0}^{t}\left(2G(t)\cdot\Delta t\right)$, since the RASS receives twice the quantity of solar radiation received by the SSBSS. $G(t)$ (W/m^2) is the total solar flux intensity over a time interval, Δt.

3. Results and discussions

Data of ambient temperature, insolation and wind speed for the location used were obtained at 30 minute intervals. Wind speeds during the period of the tests were in the range of 0-2.992m/s.

3.1 Temperatures

Plots of temperatures in the solar stills when $M_{ini} = 5\text{kg}$ are shown in Figure 5. Temperatures peaked at about midday when the insolation was highest. Plots of temperatures when $M_{ini} = 10\text{kg}$ and when $M_{ini} = 15\text{kg}$ are also shown in Figures 6 and 7, respectively. It is seen from these figures that as M_{ini} increased, the time-lag between the peak ambient temperatures and peak temperatures in the stills also increased due to the higher thermal inertias of the water masses contained in the stills. The temperatures recorded in the RASS were always higher than those in the SSBSS irrespective of the M_{ini}. When $M_{ini} = 5\text{kg}$, the maximum absorber-plate and glass cover temperatures in the RASS were greater than those in the SSBSS by up to 7.86ºC and 5.50ºC respectively. The difference between the maximum absorber-plate temperature in the RASS and that in the SSBSS was 8.15ºC when $M_{ini} = 10\text{kg}$, and 12.70ºC when $M_{ini} = 15\text{kg}$. The effect of M_{ini} on the glass cover temperatures however, were not apparent from the results obtained. Furthermore, and in support of the findings of Tiwari and Suneja (1999), higher temperatures were recorded in the stills with greater M_{ini} at the end of the 24 hour test period because of their greater thermal inertias which resulted in longer retention of heat. This is seen from Figures 5, 6 and 7 in which the absorber-plate temperatures at the end of the 24 hour periods in the SSBSS are higher than those in the RASS, by 0.6ºC, 1.3ºC and 4.35ºC, respectively, corresponding to M_{ini} of 5kg, 10kg and 15kg, respectively.

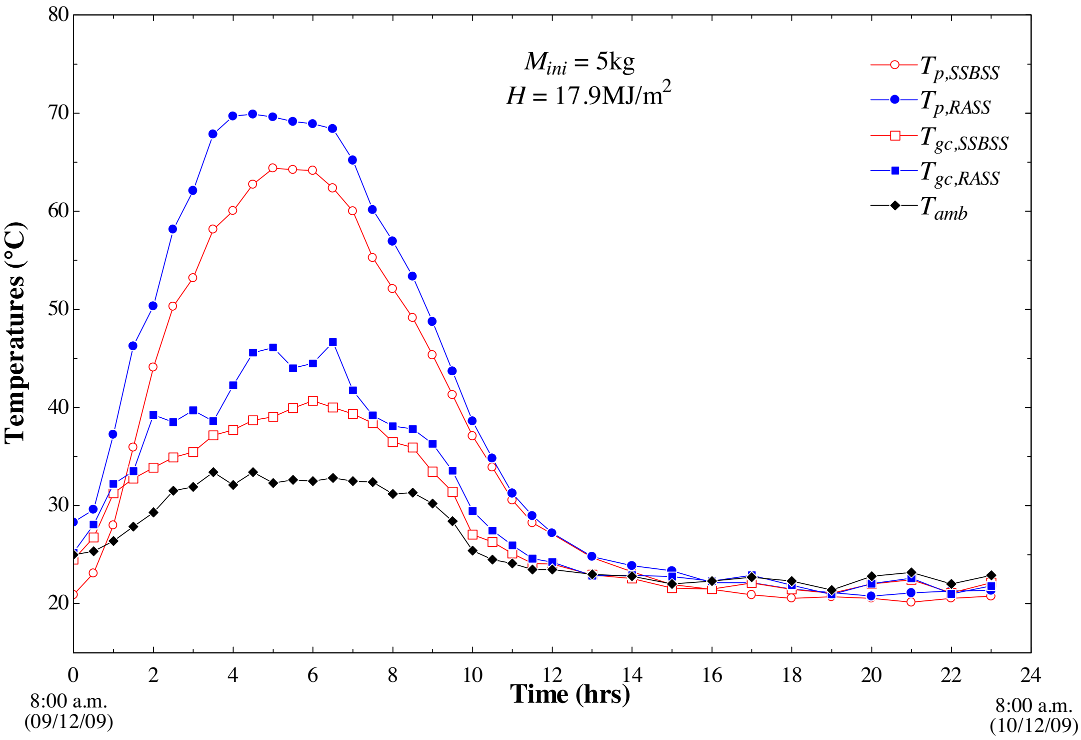

Fig. 5: Plots of variations in absorber-plate temperatures, $T_{p,SSBSS}$ and $T_{p,RASS}$, glass cover temperatures, $T_{gc,SSBSS}$ and $T_{gc,RASS}$ in the SSBSS and RASS, respectively, together with prevailing ambient temperatures, T_{amb}, when $M_{ini} = 5\text{kg}$ and total insolation for the day, $H = 17.9\text{MJ/m}^2$ (Test started 8 a.m. 09/12/2009).

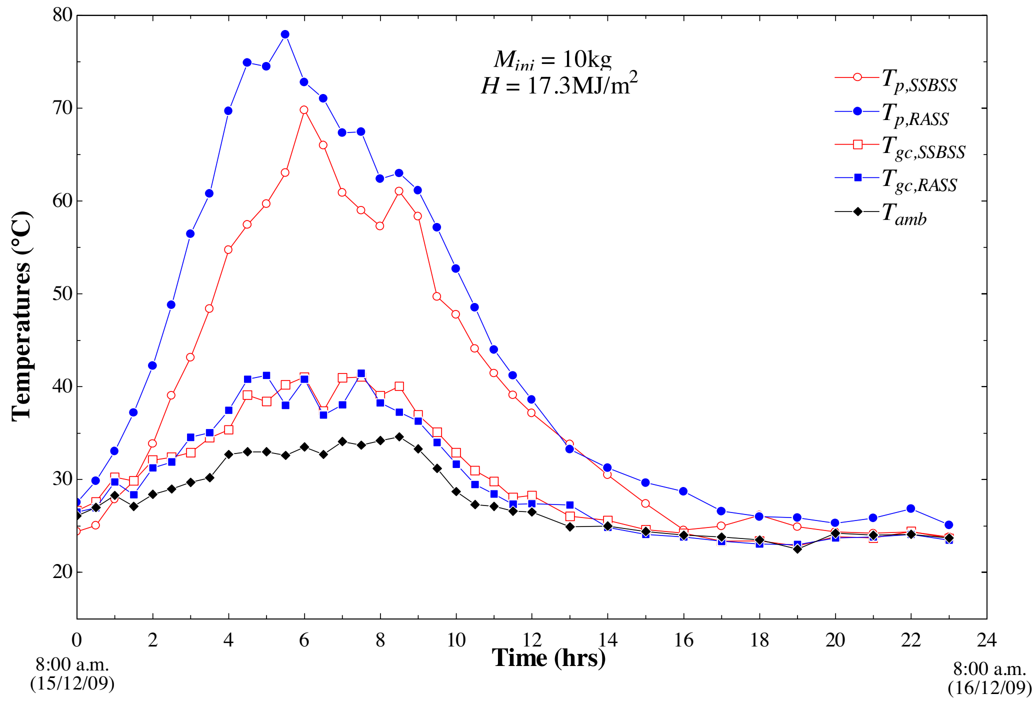

Fig. 6: Plots of variations in absorber-plate temperatures, $T_{p,SSBSS}$ and $T_{p,RASS}$, glass cover temperatures, $T_{gc,SSBSS}$ and $T_{gc,RASS}$ in the SSBSS and RASS, respectively, together with prevailing ambient temperatures, T_{amb}, when $M_{ini} = 10\text{kg}$ and total insolation for the day, $H = 17.3\text{MJ/m}^2$ (Test started 8 a.m. 15/12/2009).

3.2 Distillate yields

The instantaneous rates of distillate yields, $\dot{m}_{w,inst}$ from both stills generally increased from the start of the day's operation till it peaked at about 14:00hrs local time, lagging behind the peak insolation by about 2 hours due to the thermal inertia of the water masses. $\dot{m}_{w,inst}$. Figures 8, 9 and 10 show the rate of instantaneous distillate yields when M_{ini} was 5kg, 10kg and 15kg, respectively, in the two solar stills. For all cases, the distillate outputs from the RASS were higher than those from the SSBSS, and the difference between the distillate outputs from the two stills kept increasing from the start of the day till midday when the peak rates of distillate yield were achieved. Thereafter, the difference reduced till outputs from both stills became almost equal during night-time operation. As was alluded to in section 3.1, the plots show that with higher M_{ini} , distillate production from both stills extended further into the off-sunshine periods of operation: when M_{ini} was 5kg, distillate production in both stills ceased after about 15 hours of operation (11.00 p.m. local time Figure 8); when M_{ini} was 10kg yield from the stills continued till after 20 hours of operation (4.00 a,m local time, Figure 9); and when M_{ini} was 15kg yield continued till after 24 hours of operation (8 a.m local time, Figure 10).

The cumulative distillate yields for three representative days – 11th, 15th and 17th December 2009 are plotted in Figure 11, corresponding to M_{ini} equal to 5kg, 10kg and 15kg, respectively. The plots show clearly that for the same M_{ini} in the stills, the RASS yielded higher overall distillate outputs at the end of a 24 hour period of operation. This agrees with the results of Tiwari and Suneja (1998, 1999).

The overall outputs from the RASS and SSBSS respectively were 3.203 and 1.97kgm^{-2}day^{-1} when M_{ini} was 5kg, 3.723 and 2.762 kgm^{-2}day^{-1} when M_{ini} was 10kg, and 4.263 and 2.923 kgm^{-2}day^{-1} when M_{ini} was 15kg, showing that, on the average, the RASS produced about 46% more distillate per day than the SSBSS. These are comparable to the outputs shown in Table 1, in spite of the RASS being a passive-type still while most of the stills listed in the table are active stills.

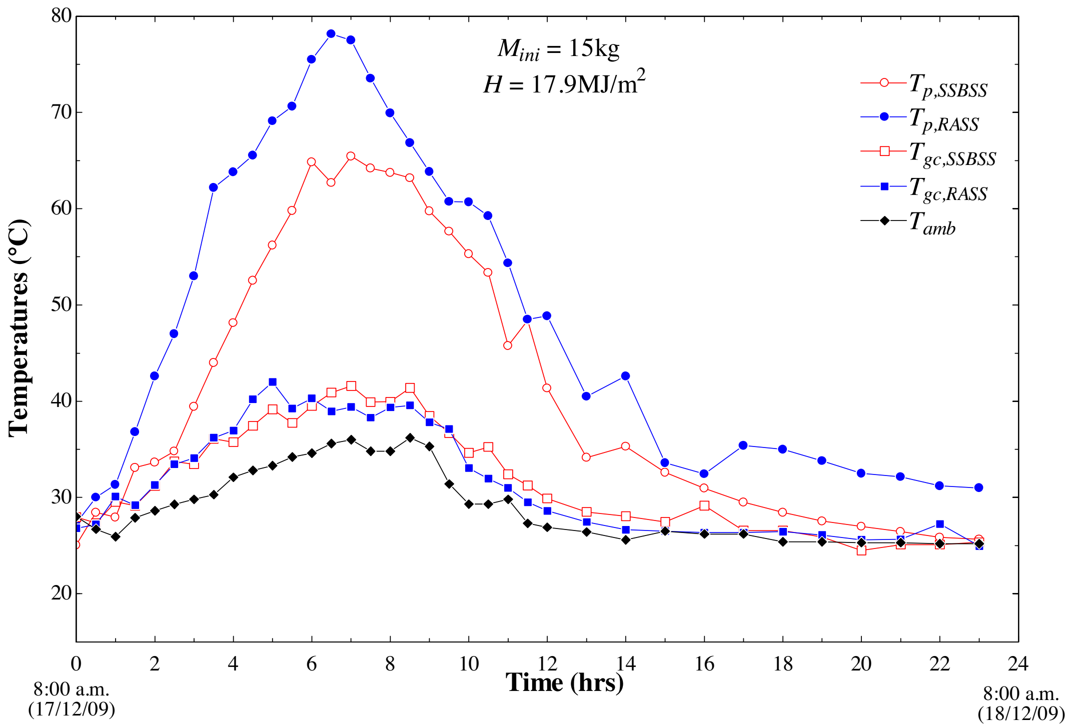

Fig. 7: Plots of variations in absorber-plate temperatures, $T_{p,SSBSS}$ and $T_{p,RASS}$, glass cover temperatures, $T_{gc,SSBSS}$ and $T_{gc,RASS}$ in the SSBSS and RASS, respectively, together with prevailing ambient temperatures, T_{amb} , when $M_{ini} = 15\text{kg}$ and total insolation for the day, $H = 17.9\text{MJ/m}^2$ (Test started 8 a.m. 17/12/2009).

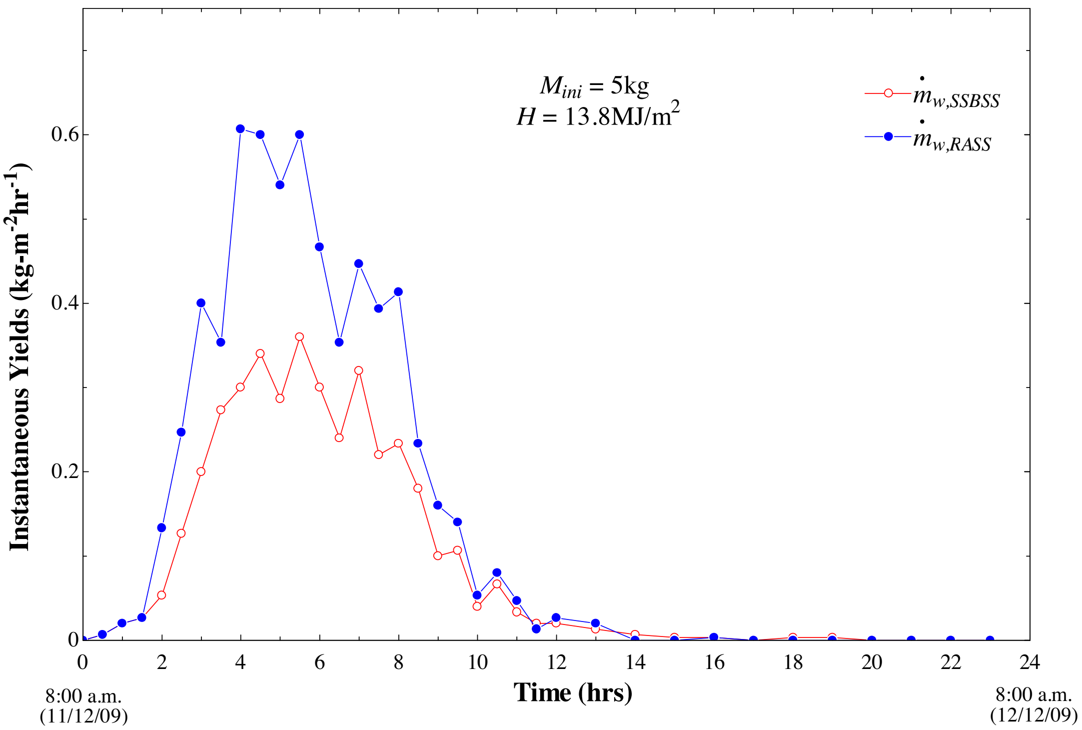

Fig. 8: Plots of instantaneous yields, $\dot{m}_{w,SSBSS}$ and $\dot{m}_{w,RASS}$ in the SSBSS and RASS, respectively, when $M_{ini} = 5\text{kg}$ and total insolation for the day, $H = 13.8\text{MJ/m}^2$ (Test started 8 a.m. 11/12/2009).

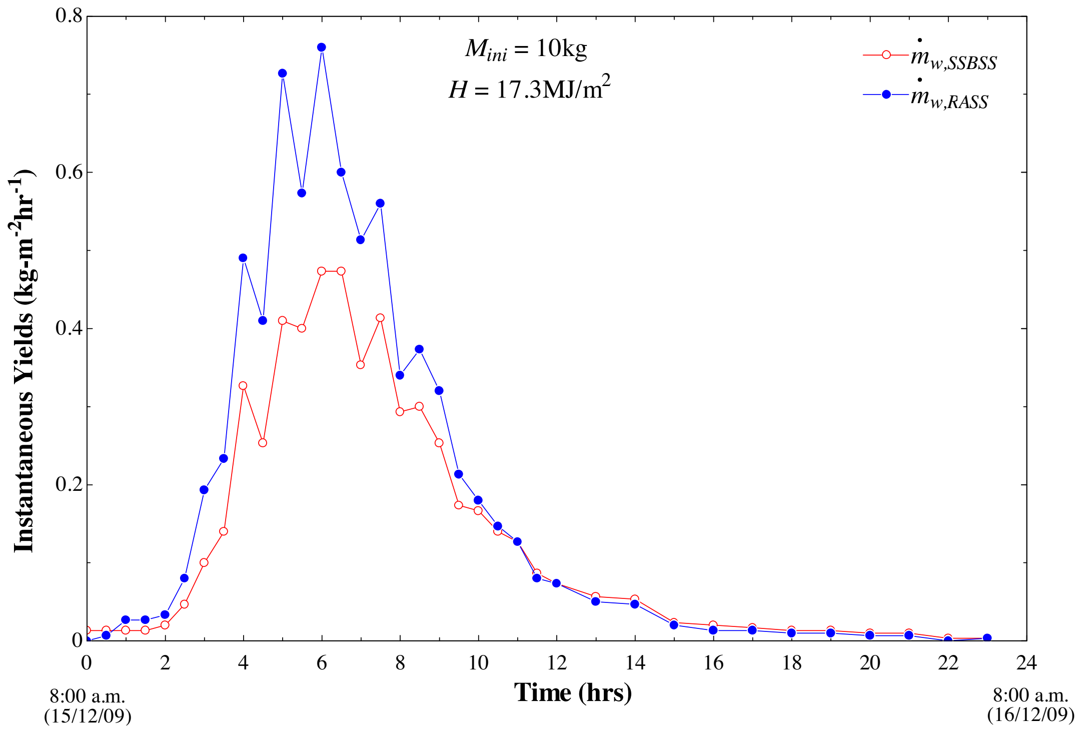

Fig. 9: Plots of instantaneous yields, $\dot{m}_{w,SSBSS}$ and $\dot{m}_{w,RASS}$ in the SSBSS and RASS, respectively, when $M_{ini} = 10$kg and total insolation for the day, $H = 17.3$MJ/m^2 (Test started 8 a.m. 15/12/2009).

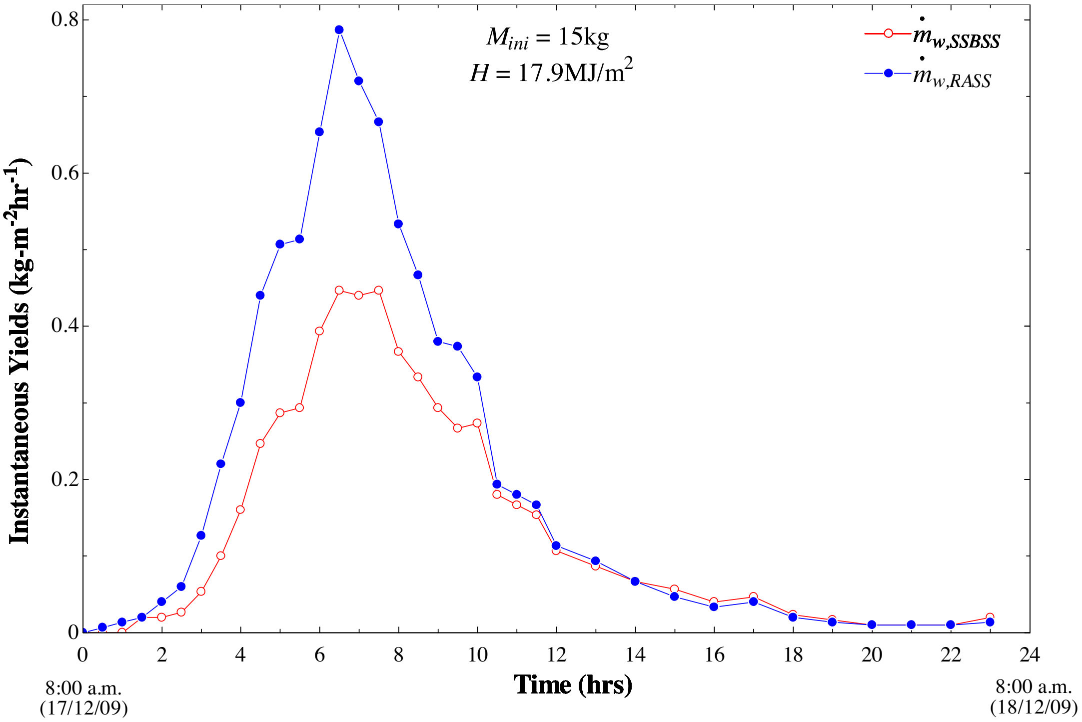

Fig. 10: Plots of instantaneous yields, $\dot{m}_{w,SSBSS}$ and $\dot{m}_{w,RASS}$ in the SSBSS and RASS, respectively, when $M_{ini} = 15$kg and total insolation for the day, $H = 17.9$MJ/m^2 (Test started 8 a.m. 15/12/2009).

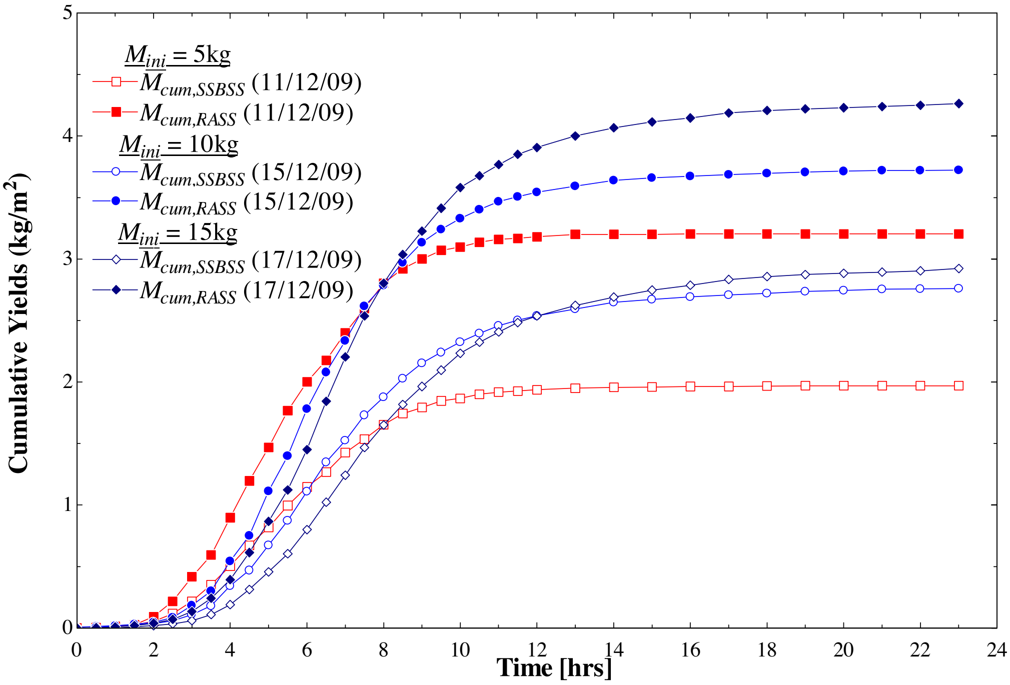

Fig. 11: Plots of cumulative yields, $\dot{m}_{w,SSBSS}$ and $\dot{m}_{w,RASS}$ in the SSBSS and RASS, respectively, when $M_{ini} = 15\text{kg}$ and total insolation for the day, $H = 17.9\text{MJ/m}^2$ (Test started 8 a.m. 15/12/2009).

3.3 Efficiencies

The overall efficiencies for three representative days -11th, 15th and 17th December 2009, corresponding to M_{ini} of 5kg, 10kg and 15kg, respectively, are plotted in Figure 12. The overall daily efficiencies of the RASS were always lower than those of the SSBSS – as is the case for all other solar thermal collectors, this is because higher temperatures in the RASS resulted in higher rates of heat loss and thus lower efficiencies. The overall efficiencies of the RASS at the end of the day's operation are between 26-29%, while those of the SSBSS increase from about 34.75% to 39.85% as M_{ini} increases from 5kg to 15kg.

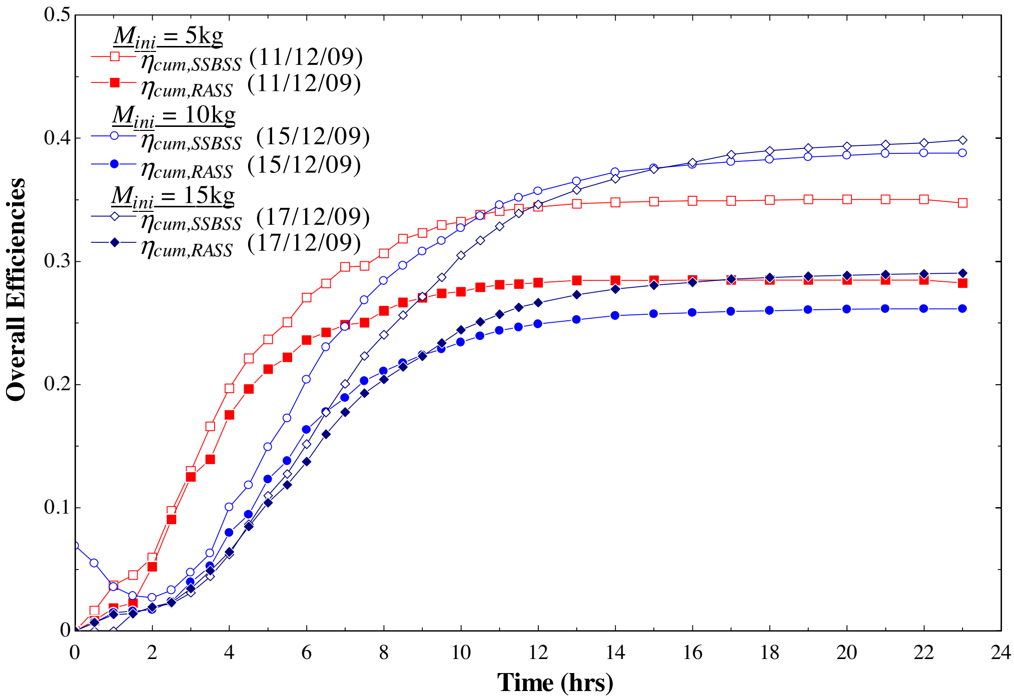

Fig. 12: Overall efficiencies

4. Conclusions

The conventional Single Slope Basin-type solar still has been modified by adding a cylindrical reflector to its exposed underside to obtain the Reserve-side Absorber-plate Solar Still. Experimental models of both stills of identical dimensions were built and tested side-by-side in order to determine the extent of performance improvements that may be obtained from the modification to the SSBSS, while varying the initial water mass, M_{ini} contained in the stills. For all test days, higher temperatures were recorded in the RASS, and it was able to achieve a 46% increase in overall daily distillate yield compared to the SSBSS. The distillate yields and the efficiencies of the two stills over 24 hour periods were shown to improve as the initial mass of water in the stills was increased because of the accompanying increase in thermal inertia. However, the efficiency of the RASS was found to be lower than that of the SSBSS due to the higher temperatures encountered in them.

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