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Experimental and theoretical analysis of solar still with glass basin

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ABSTRACT

A single-slope solar still with a basin size of $1 \times 1 \times 0.2\,\mathrm{m}^3$ has been fabricated with glass of 6 mm thickness. The glass basin consists of two compartments, upper and lower compartments. The lower compartment (heating zone) has glass strips and the upper compartment (evaporating zone) has a hole through which the water comes in from the lower compartment. The performance of the still is compared by placing ethylene glycol and zinc nitrate solutions and heat storage materials like sand and wax were kept in between the glass strips. Aluminum cubes and sponges were also made to float in the upper compartment. The results illustrate that the still with corrugated sheet was more productive. The theoretical evaluation was also made. Then the still was modeled using gambit and fluent for high and low solar intensities. Thermal analysis using fluent overlaps with the experimental and theoretical production rates.

Keywords: Solar still; Heat storage materials; Desalination; Aluminum cubes; Exposure area; Fluent

1. Introduction

Fresh water scarcity in arid and semi-arid regions remains to be a long-term existing problem due to increased population, and agricultural and industrial activities. The distribution of consumable water is a major problem faced by the developing countries. There is always a vital need for clean, pure drinking water to be supplied for the livelihood of the living beings. Often water sources are brackish and contain harmful bacteria and therefore cannot be used for drinking. Besides, there are many coastal locations where seawater is abundant but potable water in scarce. Pure water is also essential in hospitals, schools, and batteries. Man has been dependent on rivers, lakes, and underground water reservoirs for fresh water requirements in domestic life, agriculture, and industry. However, rapid industrial growth and the worldwide population explosion have resulted in a large escalation of demand for fresh water, both for the household needs and for vegetation to produce adequate quantities of food. Most of these countries which are characterized by a high intensity solar radiation make the direct use of solar energy a promising option for their arid communities to reduce the major operating cost for the distillation plant. Solar distillation is one of the available methods to produce potable water. This process has the advantage of zero

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fuel cost, renewable, but requires more space (for collection).

Desalination refers to the process of removing salt and other minerals from water. Water is desalinated in order to convert salt water into fresh water to make it suitable for human consumption or irrigation. Most of the modern technologies involving desalination focus on developing cost-effective ways of providing fresh water for human use in regions where there is scarcity for fresh water. A solar still essentially separates saline water into two streams: one with a low concentration of dissolved salts (the fresh water stream) and the other containing the remaining dissolved salts (the concentrate or the brine stream). The device makes use of solar energy to convert impure water into pure form. The salt content is expressed in terms of salinity. Salinity is alternatively expressed as total dissolved solids (TDS). TDS content is varied with respect to water type, seawater has a TDS concentration of about 35,000 mg/L, and brackish water has a TDS concentration of 1,000–10,000 mg/L. Water is considered fresh when its TDS concentration is below 500 mg/L, which is the secondary (voluntary) drinking water standard.

Velmurugan et al. [1] used integrated fin type solar still to increase the evaporation rate. They found that when fins were used productivity is maximum with an increment of 45.5%, whereas 29.6% for wick and 15.3% for sponge. They also showed that the experimental results concur well with the theoretical and the deviation was around 10%. Murugavel et al. [2] spotted that the still with black light cotton cloth acting as spread material is found to be more productive. Other basin materials like rubber, gravel, sand, and saw dust are having the properties of absorbing and storing solar radiation in different proportions, and sponge is used to enhance the exposed area for evaporation of water. Badran and Tahaneih [3] found that the output of still was augmented by 36% using a flat plate collector since the saline water fed to the basin becomes preheated in the collector and hence quick evaporation occurs. They also illustrated that decrease of water depth increased the productivity and hence it is a proportional of solar intensity. Murugavel et al. [4] made use of different sensible heat storage materials in the basin along with water to improve the heat capacity and also studied the effect of varying the depth of the basin water. They put forth that still with quartzite rock was the best basin material where theoretical production rate agreed with the experimental production rate. Abu-Hijleh and Rababa'h [5] embarked on the experimental study of a solar still with sponge cubes in basin. The performance of a solar still with different sized sponge cubes placed in the basin was studied experimentally. The raise in distillate production of the still ranged from 18 to 27.3% compared to an identical still without sponge cubes under the same conditions. Tarawneh [6] has studied about the effect of water depth in the basin for the water productivity. The performance characteristics pointed out that the water productivity is closely related to the incident solar radiation intensity. The productivity obtained by them is 6.7 L/day. Boubekri and Chaker [7] learned the effect of the speed wind, the mass flow rate and the water depth in the basin. The results exhibited that productivity of the still is maximum for a flow rate of 0.0009 and 0.0015 kg/s and the wind speed boosts the temperature variation of glass and water on the sunshine period and depth of water in the basin influences the temperature variation during night phase. Singh and Tiwari [8] inferred that the annual yield depends on water depth, inclination of condensing cover and also it increased linearly with the collector area for the given water depth. They concluded that annual yield was maximum when the condensing glass cover inclination was equal to the latitude of the place. Tripathi and Tiwari [9] read the effect of different water depths in the basin to increase the productivity and observed that convective heat transfer coefficient decreases with increase in water depth due to decrease in water temperature. It was inferred that more yield obtained during off-shine hours as compared to day time for higher water depths due to storage effect. Velmurugan et al. [10] have worked on productivity enhancement of stepped solar still performance analysis. To improve productivity, experiments were carried out by integrating small fins in basin plate and adding sponges in the trays. When the fin and sponge-type stepped solar was used, the average daily water production had been discovered to be 80% higher than ordinary single basin solar still. Velmurugan et al. [11] have attempted to produce potable water from industrial effluents. Sponges, pebbles, black rubber, and sand were used in the fin type single basin solar still for enhancing the yield. The evaporation rate increased by about 53% when fins were integrated at the basin plate. El-Sebaii et al. [12] studied the effects of mass flow rate and thickness of the flowing water for different masses of the storage material on the daylight, overnight, and daily productivities and efficiency of the still. It was found that productivity and efficiency decrease as the mass of the storage material increases, due to the increased heat capacity of the storage material. The annual average of daily productivity of the still with storage is found to be 23.8% higher than that when it is used without storage. Ahmed and Tiwari [13] conducted a study about maximum radiation reception for solar collectors by optimizing the tilt angle. They concluded that as tilt angle approaches the latitude of the location, the solar collector receives more radiation. Elminir et al. [14] and Li and Lam [15] results also proved that when the tilt angle is equal to site's latitude, maximum radiation is received. Karatasou et al. [16] suggest that all type of south-facing flat plate collectors can be used which equals the latitude of the site.

2. Objective

The increase of population and human agricultural and industrial activities makes the availability of fresh water in arid and semi-arid regions a problem of great importance all over the world. The supply of drinkable water is a major problem faced by the developing countries. The various methods used for purifying the water are reverse osmosis, ultra filtration, carbon filtering, etc. Solar desalination using solar still is a better choice in the semi-arid regions to purify contaminated water. Though the output of the still is low when compared to other processes, it is used because of it is less expensive and does not use any external source. In this work to increase the productivity, the still basin has been modified and the material chosen was glass because of its high refractive index which transmits more sunlight through it. The saline water from the storage tank enters the lower compartment (namely heating zone) where side loss and direct solar penetration from the upper compartment will be used to preheat the water. The lower compartment has glass partitions placed with equal distance. As the saline water moves in the alternate direction of the glass strips the water will be preheated. Also more heat absorption is possible since glass partition will act as an extended surface. The overflowing water will enter the upper compartment (namely evaporating zone) for evaporation. Also sensible and latent heat storage material like sand, wax, ethylene glycol and zinc nitrate has been placed between the glass strips to enhance the heat transfer and to increase the exposure area of water sponge, and corrugated sheet has been used in the basin to enhance the productivity.

3. Theoretical evaluation

The energy available for utilization by the still is given by the amount of transmitted energy inside the glass cover. Velmurugan et al. [1,11] made theoretical study on the performance of solar still and the theoretical modeling was studied.

The basin water surface continuously absorbs the solar radiation and part of it is transferred to the glass surface due to convection and radiation due to temperature difference. The remaining is transferred to the glass by evaporation due to the partial vapor pressure difference.

The transient energy balance equation for the basin is given by,

$$m_b C_{p,b}\left(\frac{\mathrm{d}T_b}{\mathrm{d}t}\right) = IA_b\alpha_b - Q_{c,b-w} - Q_{\mathrm{loss}} \tag{1}$$

The absorptivity of the still α_b was taken as 0.95.

The convective heat transfer between basin and water is taken as,

$$Q_{c,b-w} = h_{c,b-w}A_b(T_b - T_w) \tag{2}$$

The convective heat transfer coefficient between basin and water is taken as $135\,\mathrm{W/m^2\,K}$.

The heat loss from basin to ambient is obtained from,

$$Q_{\mathrm{loss}} = U_b A_b (T_b - T_a) \tag{3}$$

where U_b was taken as $14\,\mathrm{W/m^2\,K}$.

The transient energy balance equation for water is given by the following equation,

$$m_w C_{p,w}\left(\frac{\mathrm{d}T_w}{\mathrm{d}t}\right) = I\alpha_w A_w + Q_{c,b-w} - Q_{c,w-g} - Q_{r,w-g} - Q_{e,w-g} \tag{4}$$

The absorptivity of the still α_w was taken as 0.05.

The convective heat transfer between water and glass is taken as,

$$Q_{c,w-g} = h_{c,w-g}A_w(T_w - T_g) \tag{5}$$

where $h_{c,w-g}$

$$= 0.884\left[(T_w - T_g) + \frac{(p_w - p_g)(T_w + 273.15)}{269800 - p_w}\right]^{\frac{1}{3}}$$

The evaporative heat transfer from the basin water to glass is taken as,

$$Q_{e,w-g} = h_{e,w-g}A_w(T_w - T_g) \tag{7}$$

$$\text{where } h_{e,w-g} = 0.0162 h_{c,w-g} \frac{(p_w - p_g)}{T_w - T_g} \quad (8)$$

The radiative heat transfer from the basin to glass cover is given by,

$$Q_{r,w-g} = \sigma \varepsilon_{w-g} A_g [(T_w + 273.15)^4 - (T_g + 273.15)^4] \quad (9)$$

The latent heat of evaporation of water in J/kg at a given basin water temperature (℃) is given by the following correlation,

$$h_{fg} = (2503.3 - 2.398 \times T) \times 1000 \quad (10)$$

The partial pressure of water vapor in air in $\frac{\text{N}}{\text{m}^2}$ is estimated for a given temperature (℃) by,

$$p = 7235 - 431.43T + 10.76T^2 \quad (11)$$

The specific heat capacity of the air inside the still is in J/kg K is calculated using the following correlation in terms of average temperature (T_{av} in ℃) between glass and basin water is given by,

$$C_{p,a} = 999.2 + 0.14339 \times T_{av} + 0.0001101 T_{av}^2 - 0.000000067581 \times T_{av}^3 \quad (12)$$

The transient energy balance equation for glass is calculated from,

$$m_g C_{p,g} \left(\frac{dT_g}{dt} \right) = I \alpha_g A_g + Q_{c,w-g} + Q_{r,w-g} + Q_{e,w-g} - Q_{r,g-\text{sky}} \quad (13)$$

The radiative heat transfer between glass and sky is taken as,

$$Q_{r,g-\text{sky}} = h_{r,g-\text{sky}} A_g (T_g - T_{\text{sky}}) \quad (14)$$

$$\text{where } h_{r,g-\text{sky}} = \varepsilon \sigma \frac{[(T_g + 273)^4 - (T_{\text{sky}} + 273)^4]}{T_g - T_{\text{sky}}} \quad (15)$$

The instantaneous water production is given by,

$$m_e = \frac{Q_{e,w-g}}{h_{fg}} \quad (16)$$

$$\text{The overall production of the still} = \Sigma m_e(t) \Delta t \quad (17)$$

Initially, the time interval is assumed as 5 s and water temperature, glass temperature and plate temperature are taken as ambient temperature. The change in basin temperature (dT_b), increase in saline water temperature (dT_w) and glass temperature (dT_g) were computed by solving Eqs. (1), (4), and (13), respectively. For evaluating, the above-mentioned temperatures in the simulation, the experimentally measured values of solar radiation and ambient temperature of the corresponding day and hour were used.

For the next time step, the parameter is redefined as:

$$T_g = T_g + dT_g$$
$$T_w = T_w + dT_w$$
$$T_b = T_b + dT_b$$

The iteration was continued for 8 h duration from 9 am to 5 pm using the actual metrological and operational data.

4. Experimental procedure

A single-slope solar still consists of a wooden box made of plywood having four sides with dimensions 1.1 × 1.1 m^2 and thickness of 0.025 m. Its height is 0.61 m at one end and 0.40 m at other end as shown in Fig. 1. The outer sides of the wooden box are covered by the sheet metal, in order to protect it from solar radiation and rain. The gap of 0.1 m between the sides of the tray and the wooden box is filled with saw dust. This acts as insulation and prevents the side loss of heat through conduction. The basin of the still was made of glass for its good refractive index and transmits more light through it, so it can increase the water temperature at a faster rate. The size of the basin was1 × 1 × 0.02 m^3. The basin consists of two compartments, upper and lower compartments. The lower compartment has five glass strips of size 0.7 × 0.05 × 0.1 m^3 and the upper compartment has a hole through which the feed water comes in the lower compartment as shown in Figs. 2 and 3. The glass strips in the bottom compartment acts as an extended surface because the water moves in the alternate direction, due to which the exposure area increases. The space in the glass strips is filled with heat storage materials like sand, wax, ethylene glycol, and zinc nitrate, so that it enhances the heat transfer. The entire basin is rigidly fixed on a black-coated absorber basin made up of galvanized iron sheet. However, the interface basin

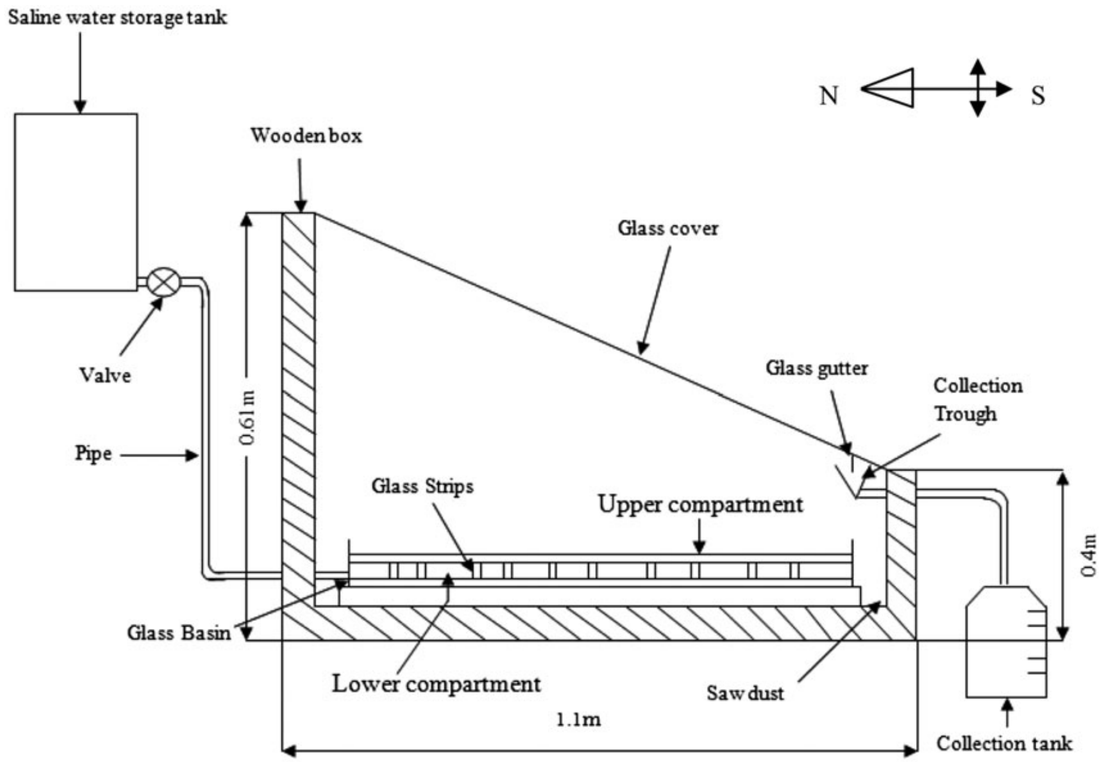


Fig. 1. Sectional view of the setup.

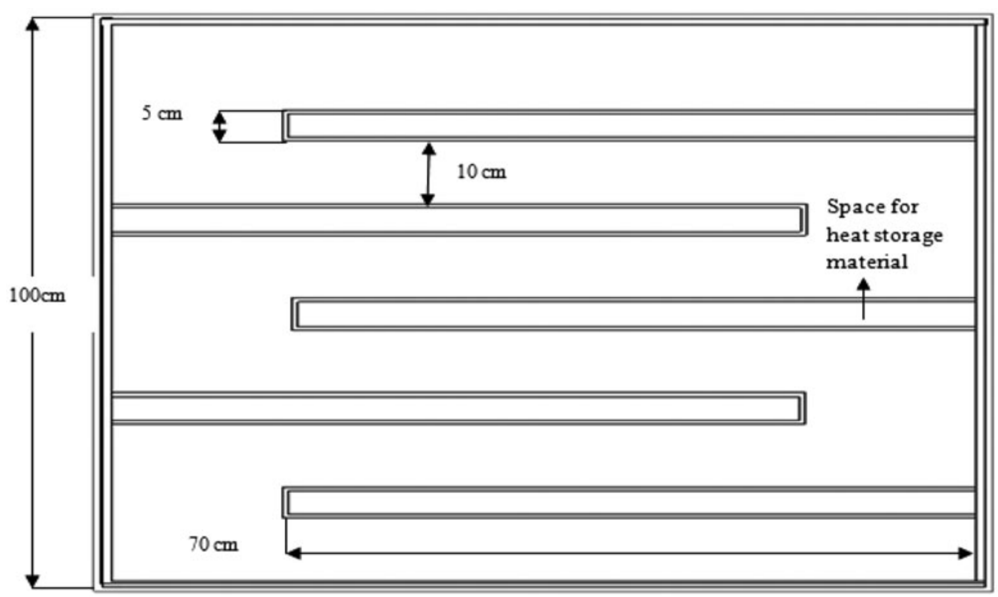


Fig. 2. Top view of basin.

between the lower and upper zones is not coated with black. This will allow more solar radiation in all direction in to the lower compartment which will augment the temperature of the saline water at the bottom zone. No evaporation takes place in the bottom zone as it is completely filled with saline water, whereas

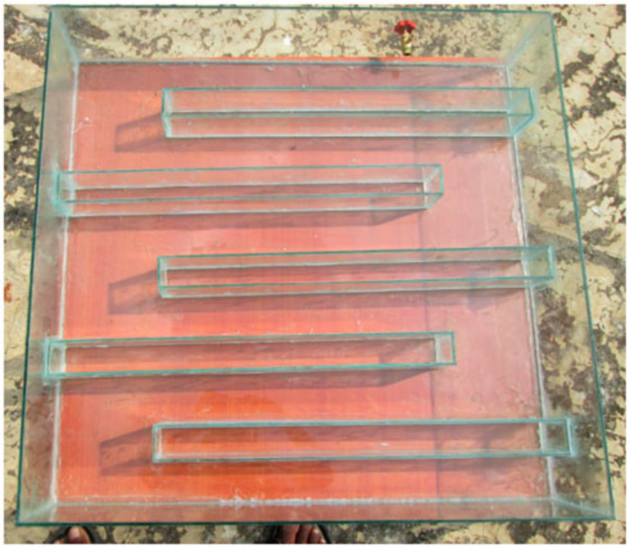


Fig. 3. Photographic view of the basin.

the upper compartment (evaporating zone) is open and the saline water is filled at various depths ranging between 1 and 4 cm, evaporation takes place.

The plastic storage tank of 50 L capacity was used as the storage tank. The water from the saline water storage tank enters the lower compartment of the glass basin though the valve, to control the water level in the still. Due to the baffle plates, the water in lower compartment moves in the alternate direction and finally the heated excess water enter the upper compartment through a hole. Since the bottom compartment is filled completely with water it acts as a conductive zone. This increases the saline water temperature, whereas in the upper compartment it is partially filled and exposed to solar radiation. This induces the convective current between water and heated air inside the still and causes the evaporation. The minimum amount of water like 1, 2, and 4 cm is maintained in the upper compartment by marking with the help of marker on four sides of glass. A small glass gutter was fixed on the inside surface of the glass cover, to facilitate the deflection of the condensate return in to the collection trough, which is fixed with the wooden box. The gliding water from the trough was transferred to the collection tank through the pipe. Copper–constantan thermocouples were used for temperature measurement. These thermocouples were fixed at still basin, water, and inside of the glass cover. The evaporation rate was noted for every half an hour and the makeup water was added with the help of a valve. Each time the makeup saline water from storage tank pushes the heated saline water present in the lower compartment to the upper compartment through the hole provided at the interface of the basin. This will ensure the preheated water supply to the upper compartment always.

The whole experimental setup was kept in the north–south direction, with the inclination of 10˚, which is the latitude [13–16] of Madurai. A similar procedure was carried out for all modifications in the solar still. Latent heat storage materials like wax, zinc nitrate, and sensible heat storage materials like sand, ethylene glycol were placed inside the glass strips for enhancing the heat transfer. Materials like corrugated sheet and sponge were made to float on the upper compartment for increasing the exposure area of water. The problem using saline water is salt deposition at the basins of the inner and upper compartments. This will reduce the solar radiation penetration. Also the conduction resistance formed in both the basins reduces the heat transfer from basin to water. To avoid such problems, at the end of each day of experiments the glass basin are cleaned properly.

This experimental setup was designed, installed and tested at Thiagarajar College of Engineering, Madurai, Tamil Nadu, India. All the experiments were started at 9 am local time and lasted for 8 h till 5 pm. The experiments were performed during the months of February, March, and April of 2013.

5. Results and discussion

5.1. Variation of output for various depths

From Fig. 4, it is proved that the productivity has increased in the still when water depth is decreased. For a given solar intensity, the lower depth basin has low heat capacity ($m\ C_p$) which rises the heat transfer rate as shown in Eq. (4). Thus only less time is

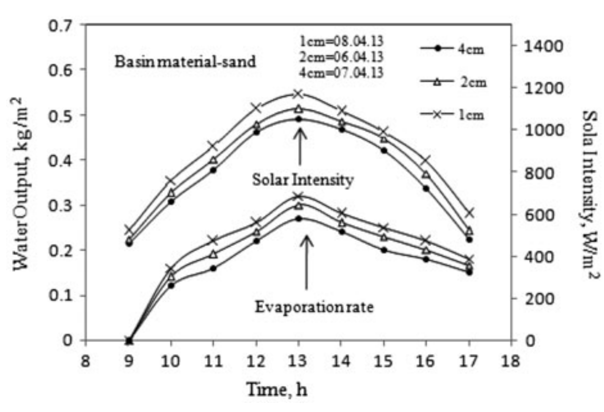


Fig. 4. Effect of water output on various depths.

required to heat the water and hence water evaporates at a faster rate which increases productivity. Thus the productivity is maximum for the still with 1 cm depth.

5.2. Temperatures and production rate variations for the still

Fig. 5 shows the variation of water temperature (T_w), glass temperature (T_g), the difference between the water and glass temperatures ($T_w - T_g$) and production rate (m_e) for the still with basin material sponge. For all basin materials, the production rate increases with the increase in difference between the water and glass temperature as shown in the Eq. (16). Basin temperature in the glass basin still is higher in the range of 6–20% more than conventional basin. Also the temperature difference between the water and glass increases the bulk motion of the air mixture inside the still which increases the evaporation and condensation. Hence the production rate is a function of water, glass, and the difference between water and glass temperatures.

5.3. Effect of total water production on the still

Fig. 6 shows the variation of the accumulated water production of the still for various basin materials. The accumulated production rate is higher for the still when corrugated sheets are placed at the basin material. Due to increase in exposure area, for the same solar intensity the minimum accumulated evaporation rate in the glass basin still is 1.9 L/m^2 which is 26% higher than the conventional still (1.4 L/m^2). Maximum productivity is achieved (43%) by using corrugated sheets.

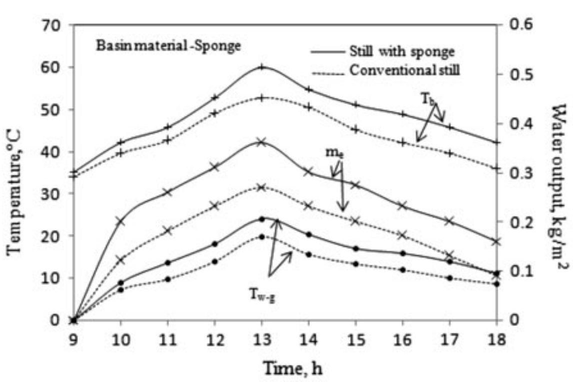


Fig. 5. Temperature and water output as a function of time.

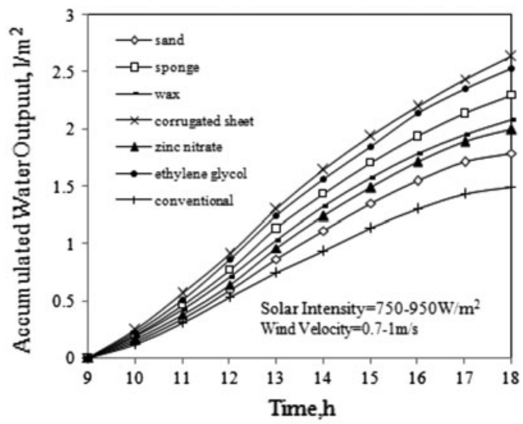


Fig. 6. Comparison of total water output for various materials.

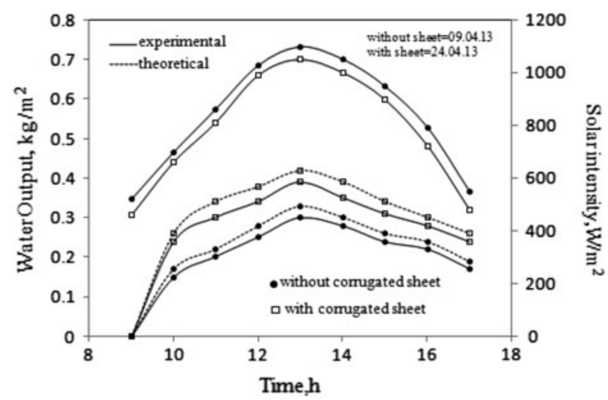


Fig. 7. Comparison of experimental and theoretical results.

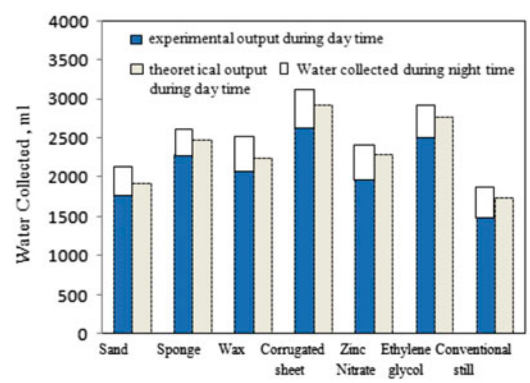


Fig. 8. Effect of water output on various materials.

5.4. Effect of corrugated sheets on productivity in the solar still

Fig. 7 shows the effect of using corrugated sheets on productivity in the solar still. The use of corrugated sheets increases the exposure area and decreases the preheating time of saline water. It was found that

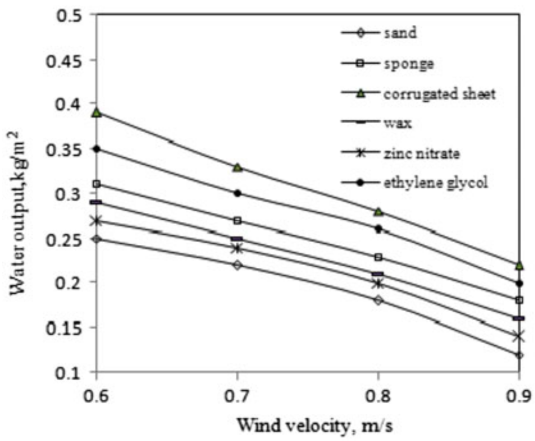


Fig. 9. Comparison of wind velocity with water output.

productivity increased by 32% when sheets were used as the basin material.

5.5. Comparison of output for various materials

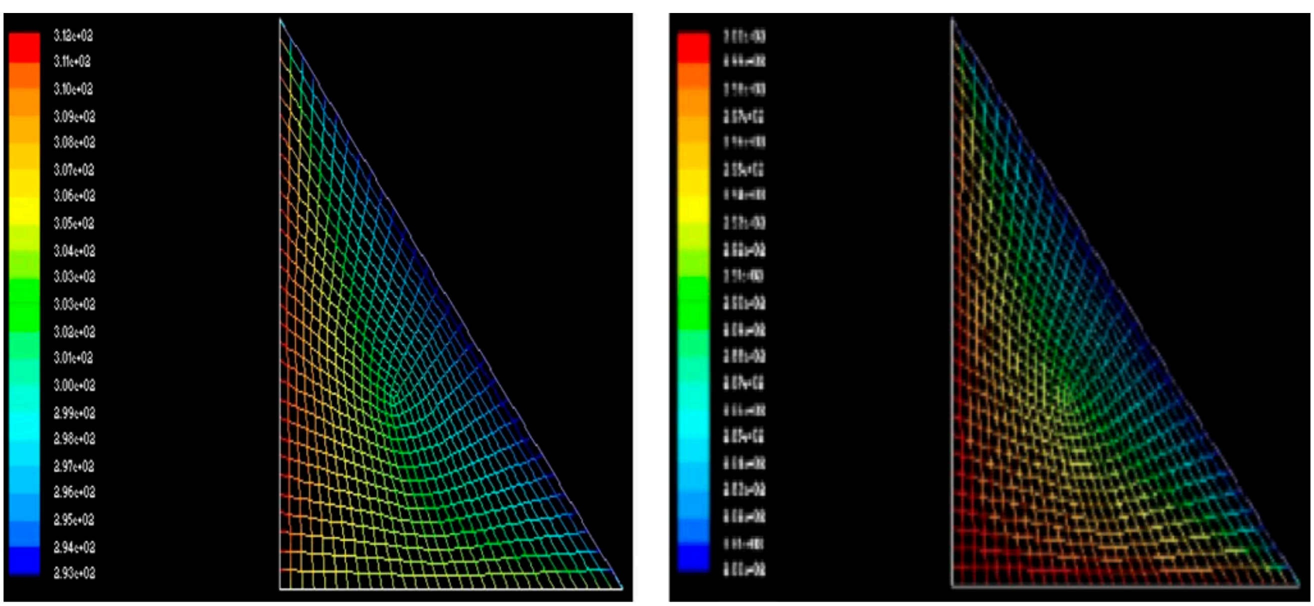
Fig. 8 shows the variation of water production rate for the still with different basin materials. When corrugated sheet is used as basin material, the production rate is more during heating and cooling period because it increases the exposure area as well as decrease the preheating time for water. But the production rate for sand, ethylene glycol, zinc nitrate and wax is more during cooling period than heating period. Similarly for sponge the productivity is more during heating period and less during cooling period. So from the above figure it is shown that when energy storing materials are used, the evaporation rate will be more during night time and thus the productivity is more when corrugated sheet is used.

5.6. Effect of wind velocity on productivity

The effect of wind velocity on productivity is shown in Fig. 9. Data from various days of experiments with various modifications were chosen with constant solar intensity (700 W/m^2) and water depth (1 cm). Increase in wind velocity increases the convective heat losses at the top surface of the glass. This reduces the water–glass temperature difference and hence productivity rate gets decreased. A maximum increase in productivity occurs, when corrugated sheets are used in the single basin solar still.

5.7. Temperature variation of water and glass using fluent

Fig. 10 shows the variation of difference in water and glass temperatures with high and low solar intensities. As the diagram in left side shows the still has a



(a) Solar intensity=700-950W/m^2
Date= 03-04-13

(b) Solar intensity=800-1050W/m^2
Date=14-04-13

Fig. 10. (a) Temperature variation of glass. (b) Temperature variation of glass and water with low solar intensity.

Table 1
Mineral content in the saline and distilled water

Sl. No.	Parameter	Acceptable range of limits as per guidelines (mg/L)	Available minerals in raw water at stills (mg/L)	Available minerals in distilled water produced in the still (mg/L)
1	Total alkalinity	200–600	800	66
2	Total hardness	200–600	1,200	60
3	Calcium	75–200	190	20
4	Magnesium	30–150	250	2
5	Iron	0.1–1	0.1	0.07
6	Manganese	0.05–0.5	0.0	0.00
7	Nitrate	45–100	0.0	0.00
8	Chloride	200–1,000	1,500	8
9	Fluoride	1–1.5	0.0	0.00
10	Sulphate	200–400		3

low region of temperature difference between water and glass because the solar intensity is less. The glass temperature was 39 ℃ and water temperature was 49 ℃. So the difference between them is 10 ℃, whereas the high solar intensity range shows high difference in water–glass temperatures. The maximum difference in temperature is observed at 20 ℃. So from the above analysis, it is shown that evaporation rate depends on solar intensity and difference in water–glass temperature. Thus the thermal analysis using fluent accords well with the theoretical and experimental results.

6. Conclusion

A single-slope solar still with glass basin was fabricated and tested with different heat storage materials like sand, wax, ethylene glycol, and zinc nitrate. To augment the evaporation rate further materials like a corrugated sheet of size $0.2 \times 0.2\,m^2$ and a sponge of size $0.04 \times 0.04 \times 0.04\,m^3$ were used in the basin. In all cases, the minimum amount of water maintained was 1, 2, and 4 cm. Working out with different basin materials, finally still with corrugated sheet yielded highest for 1 cm water level in the basin the following results were obtained, 2.64 kg/m^2 for corrugated sheets, 2.53 kg/m^2 for ethylene glycol, 2.29 kg/m^2 for sponge, 2.08 kg/m^2 for wax, 2 kg/m^2 for zinc nitrate, 1.79 kg/m^2 for sand. So the percentage increase in output, when corrugated sheet was used as basin material, was nearly 43% than the conventional still.

Bore well water is used as the feed. Table 1 shows the various mineral contents in the raw water as well as treated distilled water. It is found that the minerals present in the desalinated water are very low. To make the water potable, additional minerals are to be added as per the guidelines given by the Tamil Nadu Water supply and Drainage Board. The cost of production of one litre of potable water including the addition of minerals comes around Rs. 10 ($0.2).

Also the material and fabrication cost of 1 m^2 galvanized iron basin comes around Rs. 5000 ($83), whereas the material and fabrication cost of 1 m^2 of 5 m thick glass basin comes around Rs. 1500 ($25) only and even fabricated with the help of locally available fish-pot fabricator.

The still is also theoretically modeled and its performance was compared with the original still. The theoretical results agreed well with the experimental ones. The still was also modeled using fluent for high and low solar intensities and shows that for high intensity the difference in temperature region is more. Thus the modeling agreed with the experimental and theoretical results.

Nomenclature

A	—	area (m^2)
C_p	—	specific heat (J/kg K)
I	—	solar flux on an inclined collector (W/m^2)
I_g	—	global radiation intensity on a horizontal plate (W/m^2)
I_d	—	diffuse radiation intensity on a horizontal plane (W/m^2)
p	—	partial pressure (N/m^2)
Q	—	heat transfer (W)
T	—	temperature (℃)
dt	—	time interval (s)
h	—	heat transfer coefficient (W/m^2 K)
h_{fg}	—	enthalpy of evaporation at T_w (J/kg)

m_c — condensate (kg/m^2)
m — mass (kg)
U — side heat loss coefficient from basin to ambient (W/m^2 K)

Greeks
ε — emissivity
α — absorptivity
σ — Stefan–Boltzmann constant (W/m^2 K^4)

Subscripts
a — ambient
b — basin
c — convective
e — evaporative
g — glass
r — radiative
w — water
loss — side loss

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