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Productivity enhancement of a-single basin solar still

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ABSTRACT

The rapid increasing need for energy and environmental concern has focused much attention on renewable energy resources. The supply of drinking water is a growing problem for most parts of the world. A solar still is a low-tech way of distilling water, powered by the heat from the sun. Many passive solar stills have been developed to overcome the problem of lower distillate output. This article provides a detailed review of different studies on passive solar distillation systems. In this context, two of the similar-sized solar stills of basin made up of copper sheet were fabricated and experimentally tested in Nazareth climatic condition (9˚N, 77˚E). In this study, the first still is experimentally tested for atmospheric pressure; and in the second still, various modifications were made to enhance the productivity of still like black paint coating, use of pebbles, and introduction of fins, and providing low pressure of 0.1 bar inside the still basin. The modified still made up of copper sheet ensures higher rate of evaporation and in turn increases the efficiency. The performance of the first still and the modified still is compared.

Keywords: Solar still; Distillate; Vacuum pump; Productivity and Still efficiency

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1. Introduction

Water and energy are the two most essential things for sustaining life. The available fresh water is finite on earth and its demand is increasing day by day. The potable water sources from both surface and ground have been increasingly depleted due to increase in worldwide population, intensified agriculture, and industrial development [1]. Hence, there is an essential and earnest need to get fresh water from the saline/brackish water present on or inside the earth. The widely used desalination technologies are generally classified into thermal and membrane processes. Nowadays, various methods of desalination have been developed including Reverse Osmosis, Multi-Stage Flash, Multi-Effect Distillation, and Electrodialysis. These desalination units require fossil/electric energy sources [2]. Scientists all over the world are in search of new and renewable energy sources in the domain of brackish and seawater desalination in developing countries. Fortunately, the regions in most need of additional fresh water are those with the most intense solar radiation. In India, Tamil Nadu lies in the high solar radiation band and the vast solar potential can

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be utilized to convert saline water to potable water [3]. If the water in the basin is heated by only solar radiation, the system is a passive solar still. If additional thermal energy is fed into the basin in addition to the solar radiation, the system is an active solar still. The single-slope solar still is the most popular still due to its simple design, economy, better performance, and operational and constructional easiness when compared to other types of solar stills but has low yield per unit area. Many experimental and theoretical studies were conducted by various researchers on single-basin solar still to increase the productivity [4]. Al-Hussaini and Smith studied the effect of applying vacuum inside the solar still and found that the water productivity increased by 100%. Evaporation at a low temperature using vacuum condition, leads to a good improvement in still productivity. The effect of vacuum inside the still is to avoid any heat transfer due to convection in the still [5].

Velmurugan et al. studied the influence of black gravel on the productivity of the solar still coupled with a mini solar pond. They added pebbles in the solar still and found that the productivity increased by 20% than the conventional solar still [6]. Velmurugan et al. integrated a mini solar pond, a stepped solar still, and a single-basin solar still setup for effluent desalination process. Initially, water from the effluent settling tank is allowed to pass through the mini solar pond where it is heated. Then hot effluent water enters into the stepped solar still and the distilled water is produced. The excess water from the stepped solar still enters into the single-basin solar still. Thus, distilled water is produced in both single-basin solar still and stepped solar still [7]. Velmurugan et al. designed and tested an experimental setup of solar stills with fin and concluded that the temperature difference between water and glass increases if fins were used and in turn average daily productivity increases [8]. Arjunan et al. reviewed the solar status in India and concluded that India being a tropical country receives an average daily solar radiation between 4 and 7 kWh/m^2 in different parts of country with 250–300 clear sunny days per year. Thus, India receives about 5,000 trillion kWh of solar radiation in a year. The solar distillation represents the most attractive and simple technique, especially for small-scale units [9].

Suleiman and Tarawneh carried out the performance evaluation of a double-slope solar still by varying the water depth and observed that the productivity is strongly dependent on the climatic, design, and operational conditions. The decrease in water depth has a significant effect on the increase in the water productivity [10]. Nafey et al. investigated experimentally the use of black rubber or black gravel materials within a single-sloped solar still as a storage medium to improve the still productivity [11]. Sampathkumar et al. described that the still performance can be increased by reducing the water depth and thereby increasing the evaporation rate. The temperature difference between water in the basin and condensing glass cover also has a direct effect in the performance of the still [12]. Aboul-enein et al. [13] investigated on a single-basin solar still with deep basin and proved the influences of cover slope on the daily productivity of the still. They inferred that the productivity of the still decreases with an increase in heat capacity of basin water during daylight and the reverse is the case of overnight [14].

Kalidasa Murugavel et al. analyzed the effectiveness of the single-basin passive solar still and suggested that the orientation of the glass cover depends on the latitude and surface heating of water mass [2]. Gnanadason et al. experimented and concluded that the still productivity is improved significantly if copper is used as material for still basin instead of galvanized iron (GI) sheet. The black paint coated inside the bottom of the basin absorbs all the incident solar radiation. Thus, the temperature of the water increases and it has direct effect on the still productivity [15]. Velmurugan et al. experimented on fin-type passive solar still and found that the yield was increased by 52%. Productivity of the solar still increases with increase in absorber area [16]. The authors Kalidasa Murugavel et al. fabricated and tested a double-slope single-basin passive-type still. Thin layer of water is maintained in the basin, by spreading the water throughout the basin by wick materials or porous materials. It was found that the still productivity depends on parameters like solar radiation intensity, atmospheric temperature, basin water depth, glass cover material, thickness and its inclination, wind velocity, and the heat capacity of the still [16].

From the literature review, it is concluded that the performance of a solar still could neither be predicted nor improved by some of the uncontrollable parameters like intensity of solar radiation, ambient temperature, and wind velocity. Moreover, the still productivity depends on parameters like basin water depth, glass cover material, thickness and its inclination, and heat capacity of the still. The objective of this work is to improve the distilled water evaporation rate by designing a solar still built with copper sheet. The productivity and in turn efficiency is further improved by means of painting black coating inside the bottom of the still basin, using pebbles (gravels), incorporating the fins, and by applying vacuum inside the solar still.

2. Materials and methods

2.1. System description and operating principle

Solar energy heats water, evaporates it (salts and microbes left behind), and the evaporated water rises above the surface and is moved by the wind. Once this vapor cools down to its dew point, condensation occurs and the fresh water comes down as rain. The same principle is used in all man-made distillation systems. This natural process is copied on a small-scale basin-type solar still [17].

Fig. 1 shows the skeleton of the single-basin solar still. The conventional solar still consists of an air-tight chamber in which evaporation and condensation of water take place simultaneously. It is made up of concrete/cement, fibre-reinforced plastic, glass-reinforced plastic, or GI sheet. The traditional single-slope solar still has an inclined top. The top cover is made up of transparent material-like glass. The provision is made at the lower end of the glass cover to collect the distillate output.

Brackish or saline water was poured into the basin of the solar still to partially fill the basin. The incident solar radiation passes through the transparent glass cover. The transmitted radiation comes into contact with the water surface and part of it gets reflected and absorbed in the water mass. Consequently, the water mass gets heated, leading to an increased temperature of water and glass cover. The brackish water starts heating and evaporating, the formed vapor on the water surface starts moving in an upward direction caused by the created driving force (convective currents) due to the temperature difference between the water and glass cover ($T_w - T_g$). The water in the basin gets evaporated and it leaves all contaminates and microbes in the basin. The evaporated water gets condensed over the inner surface of the glass after releasing the latent heat. Condensed water trickles down the inclined glass cover under gravity to an interior collection trough and gets collected.

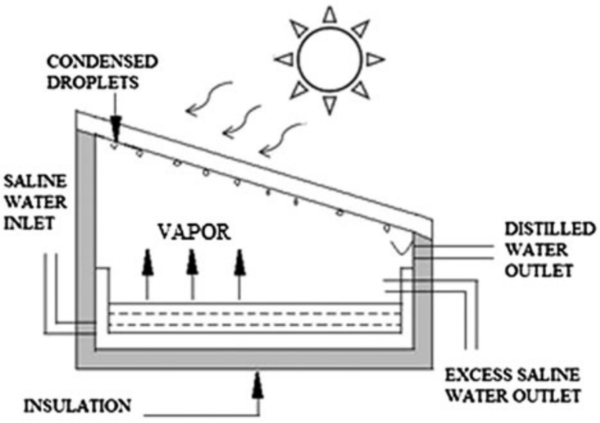

Fig. 1. Skeleton of a single-basin solar still.

2.2. Solar still made up of copper

Fig. 2 shows the experimental setup consisting of a saline water storage tank and a still made up of copper sheet. The proper material selection and fabrication of the absorbing plate has a positive effect on the increased basin water temperature. In this work, the material used for the still basin is copper because of its high thermal conductivity. Therefore, the rate of heat transfer to water in the still is more. Two similar single-basin solar stills made up of copper sheet were designed for the same basin size of 900 × 300 × 50 mm and 1.5 mm thick. The basin is enclosed inside an outer box made up of plywood. The gap of 25 mm between the sides of the tray and the wooden box is filled with thermocol to prevent heat loss. The copper sheet was made into a rectangular tray by sheet metal work of bending and cutting of an effective area 0.27 m^2. The height of the solar still was 15 cm for the lower end of glass. The top of the basin is covered with a 5 mm thick transparent glass cover. The cover is sealed tightly using silicon sealant to reduce the vapor leakage and the basin becomes air tight. The material

Fig. 2. Solar still made up of copper.

selection and its reason for selection and the design specification are shown in Table 1.

This experimental setup was designed, installed, and tested at Jayaraj Annapackiam CSI College of Engineering, Nazareth, Tamil Nadu, India. The stills are positioned in such a way that the sloping sides always face the sun. The whole experimental setup was kept in the north–south direction, with the inclination of 9°. The solar stills were properly oriented, and directly exposed to solar radiation. The measured parameters and quantities were; the solar radiation intensity $I(t)$, the glass temperature (T_g), the basin water temperature (T_w), and the ambient air temperature (T_a).

2.3. Instrumentation and error analysis

To measure the temperatures of basin plate, saline water, glass and vapor, copper constantine thermocouples (J-type) integrated with a temperature indicator and selector switch were used. To measure solar radiation, a calibrated Kipp–Zonen pyranometer was used. An electronic weighing machine of 5 kg capacity was used to measure the hourly yield. Vane type digital anemometer was used to measure the wind velocity. The thermocouples were fixed at the following locations: still basin plate, basin water, water vapor, and inside and outside glass covers. The accuracy of various measuring instruments used during experimentation is given in Table 2. The hourly reading of wind velocity, wet bulb temperature, dry bulb temperature, anemometer, and pyronometer are tabulated.

2.4. Modification in solar still

The productivity of the solar still is improved significantly because copper is used as the material for the still basin. To augment the evaporation rate of solar still made of copper, four types of modifications are tried in this work.

2.4.1. Still with black coating

The attempts were made to increase the productivity of the solar still made up of copper sheet by painting black coating inside the still basin. This will help absorb the incident solar radiation falling on it effectively and to convert it into heat. Therefore, the rate of heat transfer to water in the still is increased.

2.4.2. Still with pebbles

The schematic of solar still with gravel is shown in Fig. 3. To absorb and retain the heat obtained by solar radiations, sensible heat storage materials like pebbles are used to increase the temperature of water. Black pebbles of 20–30 mm size are used. Pebbles absorb more energy due to their high heat capacity. Addition of pebbles in the basin surface increases the water temperature thereby increasing the evaporation rate.

2.4.3. Still with fins

To increase the absorber plate area, circular rods are used as fins as shown in Fig. 4. The bottom of the rod is welded at the top surface of the trays. In the present work, the productivity is improved by integrating the solar still with fins at the basin plate. The diameter and length of the fins are 10 and 50 mm, respectively. Totally 30 fins are used. Depending on the level of water in the basin a portion of the fin is placed inside the saline water and the rest is exposed over the water level.

2.4.4. Vacuum solar still

Fig. 5 shows the schematic of the vacuum solar still. The effect of vacuum inside the still avoids any heat transfer due to convection in the still. In the presence of vacuum, the rate of evaporation and the rate of condensation are increased. The working pressure inside the distiller is reduced using a small-sized vacuum pump so that the boiling point of water in the still basin is decreased. Vacuum enables the distillation of water at a lower temperature, requires less thermal energy. During the vacuum pump operation a portion of the evaporated water vapor is absorbed by the vacuum pump. The additional condensation chamber is used to condense and collect the condensed

Table 1
Specification

Parts	Material	Size	Purpose
Still outer box	Plywood (Water proof)	1,050 × 350 × 430 mm	Low cost and easy availability
Still basin	Copper	900 × 300 × 50 mm thickness 1.5 mm	High thermal conductivity
Top cover	Glass	1,175 × 320 × 5 mm	Good transparence
Insulation	Thermocol	25 mm thick	Insulation, low cost

Table 2
Error analysis of measuring instruments

S. No.	Instrument	Range	Accuracy	Expected error (%)
1	Solar meter	0–1,200 W/m^2	±5 W/m^2	5
2	Thermocouple (J-type)	0–100℃	±0.1℃	0.4
3	Electronic weighing machine	0–5 kg	±1 g	2
4	Anemometer	0–15 m/s	±0.1 m/s	10
5	Vacuum gauge	0.01–100 kN/m^2	±0.01 kN/m^2	1

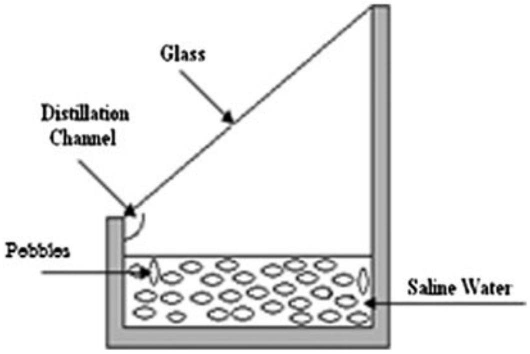

Fig. 3. Schematic of the still with pebbles.

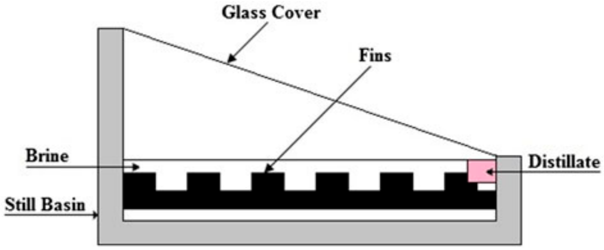

Fig. 4. Schematic of the still with fins.

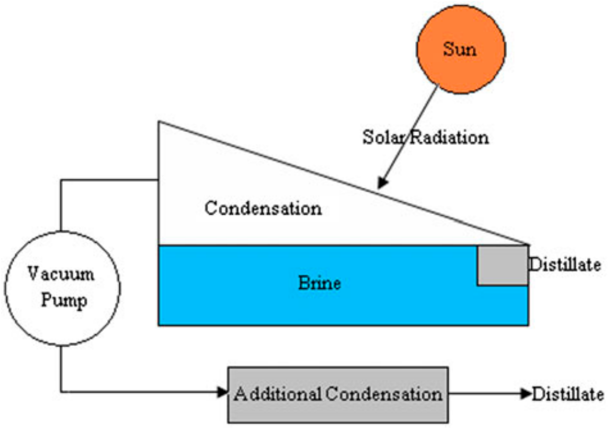

Fig. 5. Schematic of the vacuum solar still.

vapor coming out of the vacuum pump. Around 10–20% of the total distillate output is collected in the additional condensation chamber.

2.4.5. Vacuum solar still setup

Fig. 6 shows the experimental setup of a vacuum single-basin solar still made up of copper. In this design, a simple vacuum pump is incorporated to reduce pressure inside the distillation chamber. This pump is operated intermittently to maintain the vacuum constantly. During that time, an additional condensation chamber is used to condense the vapor leaving through the vacuum pump. An operating condition of about 45℃ is maintained to ensure low heat transfer losses. At this temperature, the vapor pressure of water is 10 kPa. So, the vacuum pump is operated till the pressure is reduced to this value and then made inoperative till the pressure rises again.

A reciprocating piston-type vacuum pump is used to produce low pressure inside the still basin. A smaller sized motor of 1/16 H.P is mounted over the pump itself. It has a capacity of three litres per minute and a speed of 300 rpm. In this work, the vacuum pump casing is removed for the ease of fitting. The pump unit is fitted on the inside wall of the still basin and the motor is fitted on the outside wall of the still basin. The pump is made operative for 10 min continuously and then it is stopped for another 20 min and thus the desired low pressure of 0.1 bar (10 kN/m^2) is maintained inside the still basin. The motor is driven by a DC supply of 12 V battery. The provision is made for battery re-charging from solar inverter setup as shown in the Fig. 7.

2.5. Experimental procedure

Experiments are carried out from 7 am to 5 pm from April 2011 to March 2012. In the first experiment, the still works as a simple passive still without any

Fig. 6. Vacuum solar still setup.

modification. In the next experiment, the still is modified by painting black coatings, by adding pebbles, by integrating fins, and also coupled with an external vacuum pump. The water level in the solar basin is maintained at a level of 1 cm and the 0% salt concentration for constant basin water mass of 2.7 kg. Readings are taken at an interval of one hour till the sun sets in the evening. The solar intensity, wind velocity, wet bulb temperature, dry bulb temperature, basin temperature, basin water temperature, glass temperature, vapor temperature, and distilled water productivity are measured every hour. The natural water in which no salt is further added is considered as 0% salt concentration. The same measurement process is repeated by varying the water level inside the solar still to 3 and 5 cm for different salt concentrations of 0, 10, and 20%. The performance of the modified still is compared with the base still for same climatic conditions.

Fig. 7. Vacuum solar still with solar inverter.

3. Results and discussion

Copper has higher thermal conductivity and it conducts much heat to the water in the basin. Due to this, the basin water temperature increases. Modifications like black paint coating, pebbles, fins, and vacuum were made on the solar still to improve the productivity further.

3.1. *Effect of solar intensity on productivity*

The wet bulb temperature indicates the amount of moisture content in the atmospheric air. Fig. 8 shows the hourly solar intensity and temperature variation along with the time. The maximum solar radiation is 1,075 W/m^2. It has been observed that solar radiation varies parabolically with time, with its maximum value at 2 pm.

To analyze the effect of solar intensity on productivity, the data were chosen from various days of experiments for constant value of wind velocity 2 m/s, and are plotted as shown in Fig. 9. In the morning, the temperature of water is low; therefore it needs high energy to change its phase from saturated liquid to saturated vapor phase. The results show that temperature and required heat are inversely proportional. In the early afternoon, the temperature of water

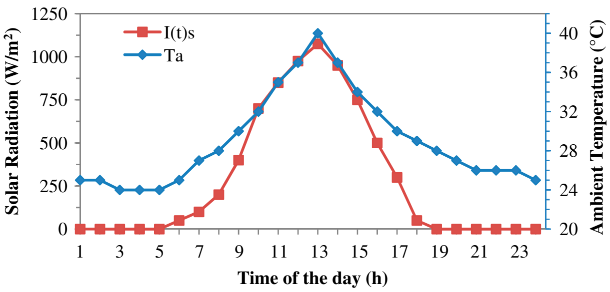

Fig. 8. Variation of solar intensity and ambient temperature vs. time of the day.

reaches the maximum so it needs less heat to vaporize, and vice versa in the late afternoon.

The productivity rate varies as time passes from the early morning until late afternoon and reaches its peak at around 2 pm while the yield reaches its maximum value around 3 pm. Between the hours of 2 pm and 3 pm, although the solar radiation had started declining, the yield was still increasing for the two-hour interval. The efficiency of the solar still increases with the ambient temperature. The yield of solar still is directly proportional to the daily solar radiation. The use of pebbles increases the productivity due to increase in heat capacity.

3.2. Effect of wind velocity on productivity

The wind velocity is an important factor which affects the yield of the solar still through glass cover temperature. It can be concluded that as the solar intensity increases, the heat loss decreases and the water and ambient temperature difference increases considerably due to the increase in the water temperature through conduction process between the black basin and the water. Fig. 10 shows the effect of wind velocity on productivity for the copper still and for the vacuum solar still painted with black coating, with pebbles and with fins, Cu (B,S,F,V) from various days of experiments for a constant solar intensity of 800 W/m^2. The variation of wind velocity fluctuated over the test days from the value of 2 to 8 m/s and corresponding yield for 1 cm water depth. The wind velocity varying from 2 to 4 m/s results in decrease in hourly yield by 15% for the lower water level. If the wind velocity increases, the convective heat transfer coefficient from the glass cover to ambient air increases i.e. convective losses are directly proportional to wind velocity. Hence, wind velocity increases but the productivity decreases. But beyond some level of water mass there is an increase in hourly yield.

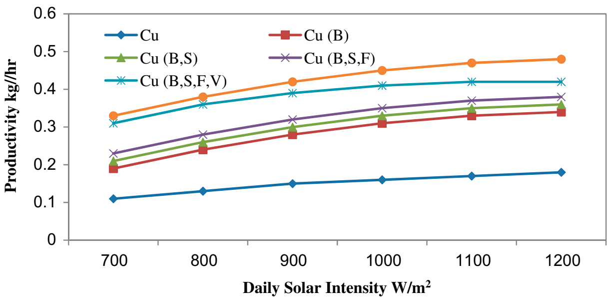

Fig. 9. Effect of solar radiation on yield.

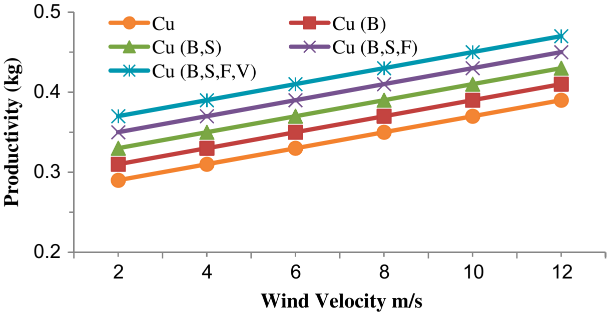

Fig. 10. Effect of wind velocity on productivity.

3.3. Effect of different temperature

The basin and basin water temperatures are almost equal during the morning hours and varied in afternoon hours due to the low heat capacity of the basin material. The highest temperature was recorded during 1 pm to 2 pm, where as the highest solar intensity was recorded between 12 Noon and 3 pm. During experimentation, the variation of temperature was in the order of $T_{\text{go}} < T_{\text{gi}} < T_{\text{v}} < T_{\text{w}} < T_{\text{b}}$. In the morning hours, the glass outside receives solar radiation before the glass inside and gets heated faster than the glass inside. Fig. 11 shows the hourly variation of measured temperature for the vacuum solar still painted with black coating, pebbles, and fins. It was found that the basin temperature was high among all other temperatures. The vacuum inside the still basin reduces the boiling point of water. As the water evaporates at low temperature, the temperature values decrease significantly. The water level in the solar basin is maintained at a level of 1 cm and the salt concentration 0%. The productivity rate varies as time passes from the early morning until late afternoon. It can be noted that the basin temperature gets closer to the water temperature because of the continuous contact between them which leads to heat equilibrium.

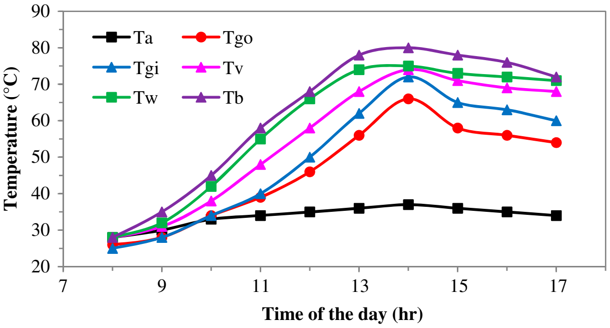

Fig. 11. Variation of different temperatures for the Cu (B,S,F,V).

3.4. Effect of water depth on productivity

For a solar still made up of copper sheet with black coating, gravels, fins, and with vacuum, graphs are drawn for productivity and time for different depths of water level of 1, 3, and 5 cm for 0% salt concentration. The hourly variation of yield against the time of the day is shown in Fig. 12. Higher hourly yield has been observed for lower water depth and opposite relationship has been attained for higher water depth. The maximum hourly yield of 0.4 kg was attained at 1 pm for lower water depth of 0.01 m, 0.17 kg attained at 1 pm in the case of intermediate water depth of 0.03 m, and 0.11 kg attained at 1 pm in the case of higher water depth of 0.05 m. It is also noticed that, the solar radiation is intense raising the glass cover temperature during morning hours (8 am–11am) and mostly this is the duration when the glass cover temperature is more than the water temperature. It reveals an increase in the productivity for minimum depths of water level and it decreases with increase in water level.

3.5. Effect of salt concentration on productivity

The effect of salt concentration on yield is shown in Fig. 13. For a solar still made up of copper sheet with black coating, gravels, fins, and with vacuum, graphs are drawn for Productivity and Time for various concentrations of 0, 10, and 20% for 1 cm depth of water level. The result shows that the lower the salt concentration, the higher will be the productivity. If the level of salt concentration is higher, a portion of incident solar radiation is used for heating the salt rather to heat the water inside the still.

3.6. Effect of various modifications on productivity

Two single-basin solar stills made up of copper sheet were designed and tested for ambient conditions. Copper has higher thermal conductivity and it results a good improvement in productivity of Cu still 1.09 kg/d and hence, the increase in productivity by 45% with copper sheet when compared to the test result obtained in a passive solar still made up of GI sheet of same size [14]. This was further modified to enhance the productivity. First, it was improved by painting black color coating inside the bottom of the still. Due to this, the amount of distillate collected in this still is higher, Cu (B) 1.21 kg/d and hence the increase in productivity by 19% for copper sheet with black coating. Black coating of basin absorbs more heat of the sun and increases the water temperature. Pebble improves the evaporation rate and increases the distillate output to Cu (B,S) 1.48 kg/d and in turn improves the productivity of the still by 22%. To increase the absorber plate area, fins are used which improves the evaporation rate and increases the distillate output to Cu (B,S,F) 1.91 kg/d and in turn improves the productivity of the still by 29%. Due to this vacuum inside the still, the evaporation rate increases further and the productivity increased to Cu (B,S,F,V) 2.56 kg/d, and the productivity further increases by 34% compared with the still working at atmospheric conditions. Furthermore, this still uses the latent heat which is released during condensation to heat up the water at lower temperature. The performances of the various stills are compared in Figs. 14 and 15.

3.7. Variations of theoretical and experimental yield

Fig. 16 shows the hourly variations of theoretically calculated and experimentally measured values of yield of solar still coupled with vacuum. The maximum yield of 0.42 kg and 0.18 kg for the Cu (B,S,F,V) and Cu, respectively, are obtained during the test day at 1 pm. The theoretical results are compared with the experimental results. The deviation of the mean square percentage was high due to the assumption of

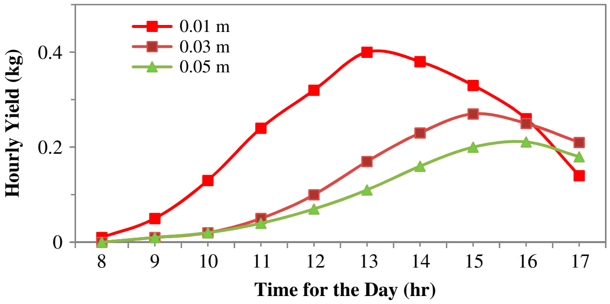

Fig. 12. Variation of distilled water output for different water depths.

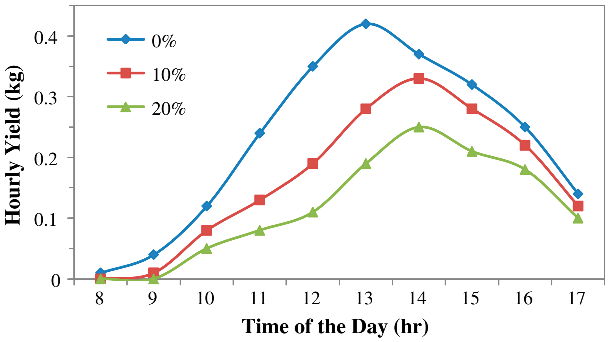

Fig. 13. Effect of salt concentrations on yield.

a constant water temperature in the basin water depth, bottom heat loss, and thermal expansion of the glass cover. The experimentally measured values are also in close agreement with theoretical values.

3.8. Economic analysis

The overall cost of the experimental setup is compared and given in Table 3. The payback period of the solar still setup depends on the overall cost of fabrication, maintenance cost, operating cost, and cost of feed water. The overall fabrication cost is Rs. 12,000 ($200).

The solar inverter cost (not only for this), maintenance cost, operating cost, and cost of feed water are negligible. The overall cost of the project = Rs. 12,000 ($200).

Cost of water produced per day = Cost of water per litre × daily yield = 2.56 litres/day × Rs. 12/L = Rs. 30 ($0.5)

The payback period is less than one year.

3.9. Theoretical analysis

In this section, a complete mathematical model that describes the processes in the basin of the solar still is presented. These models will assist in determining the hourly saturated vapor pressures of water and glass, the convective and evaporative loss coefficients from the water surface to the glass, the distillate output, and the instantaneous efficiency of the still.

3.9.1. Conventional basin solar still

The energy received by the basin plate is equal to the summation of the energy gained by the basin plate, energy lost by convective heat transfer between basin, water, and side losses.

$$I(t)A_b\alpha_b = m_bC_{pb}\left(\frac{\mathrm{d}T_b}{\mathrm{d}t}\right) + Q_{c.b-w} + Q_{loss} \tag{1}$$

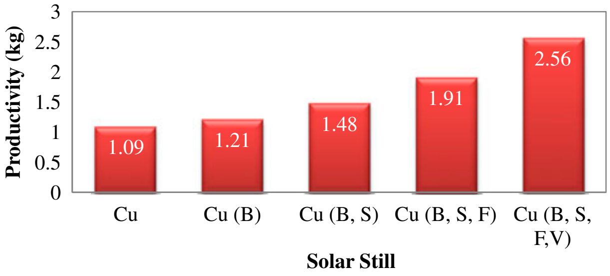

Fig. 14. Productivity for various stills.

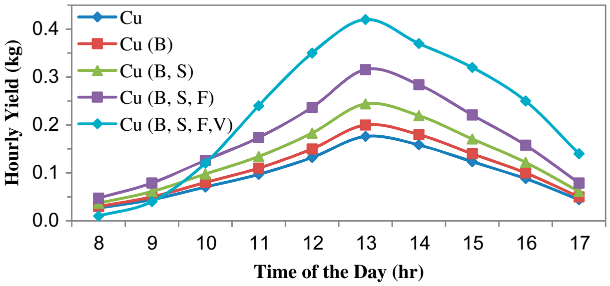

Fig. 15. Comparison of hourly yield for various modifications.

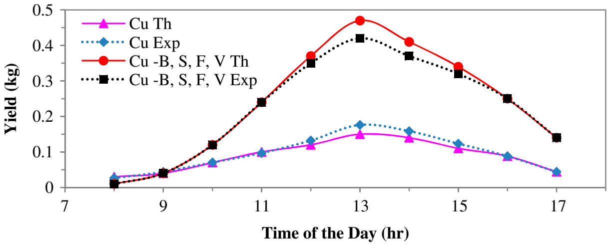

Fig. 16. Hourly variations of theoretical and experimental yield.

The energy received by the saline water in the still $I(t)$ solar radiation and $Q_{c.b-w}$ convective heat transfer between basin and water are equal to the summation of energy lost by $Q_{c.w-g}$ convective heat transfer between water and glass, $Q_{r.w-g}$ radiative heat transfer between water and glass, $Q_{e.w-g}$ evaporative heat transfer between water and glass and energy gained by the saline water:

$$I(t)A_w\alpha_w + Q_{c.b-w} = Q_{c.w-g} + Q_{r.w-g} + Q_{e.w-g} + mwC_{pw}\left(\frac{\mathrm{d}T_w}{\mathrm{d}t}\right) \tag{2}$$

The energy received by the glass cover (from sun and convective, radiative and evaporative heat transfer between water and glass) is equal to the summation of energy lost by Q_{cw-g} convective Q_{rw-g} and radiative heat transfer between glass and sky, and energy gained by the glass:

$$I(t)A_g\alpha_g + Q_{cw-g} + Q_{rw-g} + Q_{ew-g} = Q_{rg-sky} + Q_{cg-sky} + m_gC_{pg}\left(\frac{\mathrm{d}T_g}{\mathrm{d}t}\right) \tag{3}$$

The change in basin temperature ($\mathrm{d}T_b$), saline water temperature ($\mathrm{d}T_w$), and glass temperature ($\mathrm{d}T_g$) are computed by solving Eqs. (1) and (3).

Table 3
Cost estimation

	Description	Still–Cu Amount (Rs.)	Still–Cu (B,S,F,V) Amount (Rs.)
1	Basin material—Copper Sheet	4,900	4,900
2	Plywood	1,200	1,200
3	Glass	550	550
4	Supply tank	400	400
5	Collecting tank	600	600
6	Thermocol	250	250
7	Vacuum pump	–	2,100
8	Labor charges	500	500
9	Pebbles	–	500
10	Fins	–	500
11	Overhead charges	500	500
12	Total	Rs. 8,900	Rs. 12,000

The rate of energy lost from water surface by evaporation per m^2 is given by:

$$q_{\mathrm{ew}} = 0.0163\, h_{\mathrm{cw}}(P_{\mathrm{w}} - P_{\mathrm{g}}) \tag{4}$$

$$N_u = \frac{h_{\mathrm{cw}} d}{k} = C \cdot (Gr \cdot Pr)^n \tag{5}$$

The condensation rate is given by:

$$\frac{dm_{\mathrm{e}}}{dt} = \frac{h_{ew-g}}{L}(T_w - T_g) \tag{6}$$

The hourly distillate output per m^2 from distiller unit is given by:

$$m_{\mathrm{w}} = \frac{q_{\mathrm{ew}}}{L} \times 3,600 \tag{7}$$

$$m_{\mathrm{w}} = 0.0163(P_{\mathrm{w}} - P_{\mathrm{g}})\left(\frac{k}{d}\right)\left(\frac{3,600}{L}\right)C(Gr \cdot Pr)^n \tag{8}$$

$$\frac{m_{\mathrm{w}}}{R} = C(Gr \cdot Pr)^n \tag{9}$$

$$R = 0.0163(P_{\mathrm{w}} - P_{\mathrm{g}})\left(\frac{k}{d}\right)\left(\frac{3600}{L}\right) \tag{10}$$

where P_{w} = hourly saturated vapor pressures at saline water temperature and P_{g} = hourly saturated vapor pressures at inner glass temperature, h_{cw} = heat loss coefficient by convection from water surface to glass (W/m^2 K).

The absorptivity of the still basin α_{b} is taken as 0.95. The convective heat transfer between basin and water is taken as 135 W/m^2 K. The side loss coefficient from basin to ambient U_{b} is taken as 14 W/m^2 K. The mass of water in the still basin m_{w} is taken as 8 kg and the absorptivity of the water α_{w} is taken as 0.05. The mass of basin m_{b} without fin is taken as 1.5 kg. The absorptivity of the glass α_{g} is taken as 0.0475.

The exposure area of saline water A_{w} and basin A_{b} are taken as 0.27 m$^{2.}$ The area of the glass A_{g} is taken as 0.4 m^2. The specific heat of saline water C_{pw} can be calculated.

The still efficiency is defined as the ratio of heat energy used for vaporizing the water in the basin to the total solar intensity of radiation absorbed by the still. The daily efficiency (η_{d}) is obtained by summing up the hourly condensate production (m_{w}), multiplied by the latent heat of vaporization (L), and divided by the daily average solar radiation (I) over the still area (A_{s}).

The overall thermal efficiency of still (ηd) is given by:

$$\eta d = \frac{\sum m_{\mathrm{w}} \cdot L}{\sum A_{\mathrm{s}} \cdot I(t)} \tag{11}$$

where m_{w} = mass of distillate collected in kg/s, A = Area of the basin in m^2, $I(t)$ = solar radiation with respect to time W/m^2, and L = Latent heat of vaporization in kJ/kg.

3.9.2. Modifications in still

Simulation work is also extended for the following modifications in the still.

3.9.2.1. Still with pebbles. The theoretical results are compared with the experimental results and found that the theoretical results agreed well with the experimental ones. All the above equations are used for theoretical analysis except Eq. (1), in addition to the heat capacity of the basin ($m_w cp_w$), the heat capacity of the pebbles ($m_s cp_s$) is also added. The surface area of basin A_b is taken as 0.27 m^2 and the saline water surface A_w is taken as 0.22 m^2. The mass of the pebble taken for experimental analysis is 0.5 kg. The density and specific heat capacity of the pebble are taken as 2,500 kg/m^3 and 850 J/kgK, respectively.

3.9.2.2. Still with fins. In Eqs. (1)–(4), the area of the basin plate and the area of the free surface water are taken as 0.30 and 0.22 m^2, respectively. Now the mass of the basin plate (m_b) with fin is taken as 1.5 kg.

4. Conclusion

Two single-basin solar stills made up of copper sheet were designed and tested for still alone and still with modifications. The productivity and in turn the efficiency of the copper still is higher for the stills because copper has high thermal conductivity and the rate of heat transfer to water in the still is higher. The distillate yield increases with increase in intensity of solar radiation and ambient temperature. The copper solar still is modified with black paint coating, pebbles, fins, and finally with vacuum. Black paint coating, pebbles, and fins were used and the output of the still is increased significantly. The vacuum still efficiency is higher as the productivity is more due to vacuum in the morning and evening i.e. during low ambient temperature. The productivity is higher at noon because the ambient temperature is at its peak. The average daily output was found to be around 2.56 kg/d for the basin area of 0.27 m^2 based on data. The productivity is calculated as 150% higher when compared with stills used worldwide. It also shows an increase in the productivity for the minimum depths of water level. Moreover, the lower the salt concentrations the higher will be the productivity. This cost-effective design is expected to provide the rural communities an efficient way to convert the brackish water into potable water. Therefore, modified copper solar still coupled with vacuum pump is highly suitable and recommended for higher distilled water yield.

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