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AUGMENTATION OF EVAPORATION RATE USING GLASS BASIN STEPPED SOLAR STILL*

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Abstract– This project mainly focuses on maximising the production of distillled water by emphasizing three important factors: decrease in depth of water, increase in exposure area and temperature of the saline water. In this work, to augment the evaporation and temperature of the still basin water, the basin is made by glass material because of its good absorption. The stepped type basin is composed of four trays. Each tray is detached into top and bottom trays. The depending water enters the top trays (evaporating zone) where evaporation takes place depending on depth provided by the glass strip. The overflow water driven to the bottom tray (heating zone) through the gap provided in the separation glass will be further heated and made to flow through the subsequent trays. Modifications such as sponges to increase the exposure area, sensible heat materials like sand, and metal scraps to increase the saline water temperature, glass cubes with dry salt, camphor, aluminum scraps and charcoal to increase both saline water temperature and exposure area showed subtle improvement in the production rate. Experimental results were compared with ordinary basin type still. Theoretical evaluation was also done and is closer to the experimental values.

Keywords– Solar desalination, stepped type still, solar still, renewable energy

1. INTRODUCTION

Desalination may occur naturally as part of the hydrologic cycle or as an engineered process. Engineering process is removal of salt content in the brackish water by using a suitable technology. Construction and operation of a single basin solar still is very simple. A black-painted basin contains brackish or sea water, which is enclosed in a completely air tight area formed by a transparent cover. Incident solar radiation passes through the transparent cover. The black basin absorbs the radiation. Consequently, water contained in the basin is heated and evaporates in the saturated conditions inside the still. Water vapors rise until they come in contact with the cooler inner surface of the cover. There they condense as pure water, run down along the cover bottom surface due to gravity and are collected using a container.

Badran [1] has studied the performance of a single slope solar still using different operational parameters experimentally. The study also showed that the daily production of still can be increased by reducing the depth of the water in the basin. Ayber et al.[2] have made an experimental study on an inclined solar water distillation system. Unlike solar systems, the feed water falls down on the solar absorber plate and the system produces fresh water and hot water simultaneously. The system was tested with three variants, bare plate, black-cloth wick and black –fleece wick. El-Sebaii et al.[3] improved the

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daily efficiency of the solar still in to 85.3%, by using phase change materials as storage medium. Kalidasa Murugavel et al. [4] designed a single basin double slope solar still and tested with a layer of water and different sensible heat storage materials like quartzite rock, red brick pieces, cement concrete pieces, washed stones and iron scraps. It was found that, the still with quartzite rock is an effective basin material. The variations in solar incidence angle and transmittance of the covers were also considered in the theoretical analyses.

Kalidasa Murugavel and Srithar [5] fabricated a double slope solar still with mild still plate tested with minimum mass of water and different wick materials in the basin. Still with aluminium rectangular fin arranged in different configurations and covered with different wicks was also tested. It was found that, the still with light black cotton cloth is the effective wick material. The still with rectangular Aluminium fin covered with cotton cloth and arranged in length wise direction was more effective. Theoretical values of water and glass temperatures using the proposed model were compared with theoretical values obtained by Dunkle model and actual experimental values. Moustafa and Brusewitz [6] have made experimental investigations on stepped solar still, wick type collector evaporator still and they found that the efficiency of solar desalination can be improved by controlling the radiation losses from the basin. Tarawneh [7] has studied the effect of water depth in the basin on the water productivity. The performance characteristics showed that the water productivity is closely related to the incident solar radiation intensity. Rahim [8] tried to store heat energy in horizontal solar desalination still by taking advantage of combining deep and shallow stills. The efficiency of recovering process, in the form of portable water produced at night, was found to be an average of 47.2% of the total amount of energy stored during the day. Selva Kumar et al. [9] presented a performance analysis of a “V” type solar still using a charcoal absorber and a boosting mirror. Velmurugan et al.[10] increased the productivity by about 20% more than conventional still, when black rubber was used and by about 19% when black gravel was used. Velmurugan et al. [11] increased the productivity rate of solar still by integrating fins and adding sponges and wick materials in the tray. They found that the productivity increased by 45.5%. Velmurugan et al. [12] have worked on stepped solar still and to improve the productivity, experiments were carried out by integrating small fins in basin plate and adding sponges in the trays. The average daily water production was found to be 80% higher than ordinary single basin solar still during the inclusion of fin and sponge in the stepped solar still. Abderachid and Abdenacer [13] made a simulation to analyse the effect of the orientations on the performance of a symmetric double slope solar still compared to those of an asymmetric solar still with a double effect. The obtained results show that10° is the optimum inclination angle that allows receiving a maximum solar radiation for both stills by increasing the evaporation condensation processes. Darzi et al. [14] provided a mathematical modelling of heat transfer enhancement during melting process in a square cavity through dispersion of nanoparticles. The nano-enhanced phase change material (NEPCM) is composed of a dilute suspension of copper particles in water (ice) and is melted from the left. Conduction heat transfer is taken in solid phase and convection in the case of liquid phase. Theoretical model was validated with experimental results. Predicated results illustrated that by suspending the nanoparticles in the fluid the thermal conductivity was enhanced, which in turn resulted in higher rates of heat release.

2. ORGIN AND OBJECTIVE OF THE WORK

The above literature study proved that the productivity of the still depends on exposure area, depth and temperature of the saline water. The design of the present work is such that all the above factors are accomplished. In this work the basin is made with four stepped type glass basin. Glass ensures better solar absorption. Each tray is divided as top (evaporating zone) and bottom (heating zone) portions. The top portion is exposed to solar radiation for direct evaporation (evaporation zone) and the bottom portion acts as a heating zone. Different depth can be maintained in the evaporating zone by means of glass strips insertion. Addition of sensible heat materials like sand and metal scraps in the trays shows better augmentation of evaporation rate. Further, sponges floated on the evaporating zone accelerate the productivity due to exposure area for evaporation by its capillary action. Small glass cubes are made to float in the trays. These glass cubes are filled with latent heat materials like dry salt and camphor and sensible heat materials like aluminium scraps and charcoal. This will ensure high saline water temperature due to its exposure area of the glass cubes as well as heat capacity of sensible and latent heat materials. Also, considerable quantity of night time productivity is observed during the usage of sensible and latent heat materials.

3. EXPERIMENTAL SETUP

a) Experimental process

This setup consists of a wooden box of size 1.07x1.07 m^2 and height of 0.61 m in one end and 0.40 m in another end making an inclination of 10^0. A glass fitted on the top admits the sun radiation inside a wooden box. A block coated basin tray of size 1.0x1.0x0.1m^3 is kept inside the wooden box. The designed stepped basin is placed over this tray. The stepped basin includes four trays as shown in Fig. 1. Individually, trays are partitioned into evaporating zone at the top followed by heating zone in the bottom. The inlet saline water fed from the saline storage tank enters the evaporating zone. The glass strips of various heights (0.5, 1, 1.5 and 2cm) are inserted between the strips holder in the evaporating zone to maintain the various water depth as shown in Fig. 2. Excess water from the evaporating zone is drained into bottom tray (heating zone) and this preheated water is directed to subsequent trays.

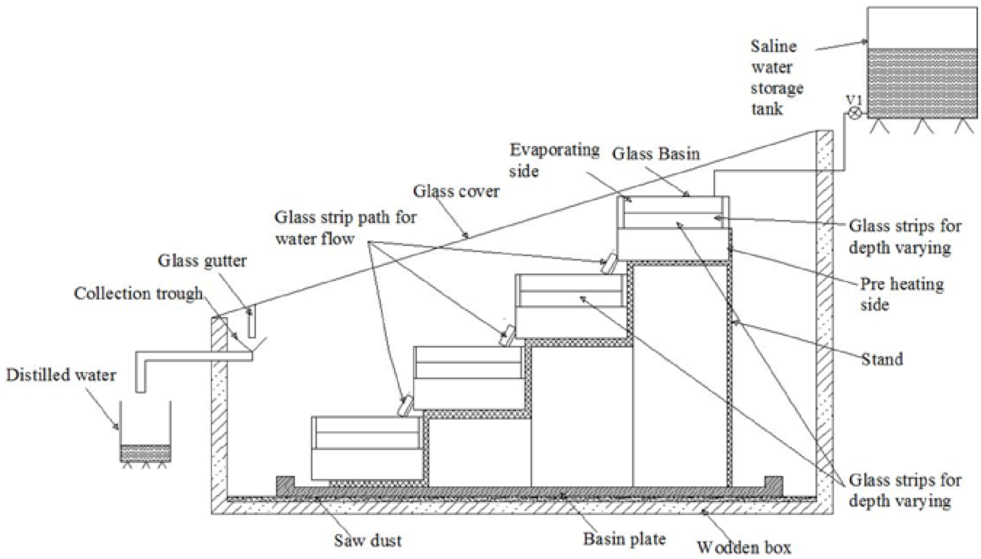

Fig. 1. Schematic diagram of stepped solar still

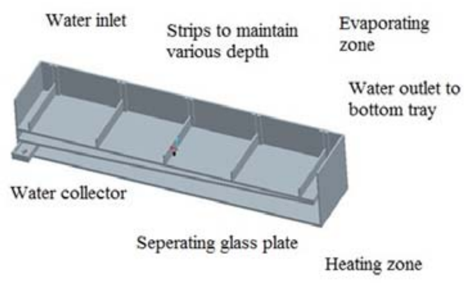

Fig. 2. Sectional 3D view of basin tray

b) Modifications in stepped solar still

In order to increase the productivity of the solar still the following modifications are made:

- Maintain various depths at evaporating zone using glass strips.
- Placing sensible heat materials like sand (800g/tray) and metal scraps (350g of metal scraps) in the heating zone.
- Floating sponges on the evaporating zone and heating zone. In this experiment, 30 sponges/tray size $25 \times 25 \times 25$ mm^3 are used.
- Floating the small glass cubes filled with latent heat materials like camphor and dry salt and sensible heat materials like aluminium scraps and charcoal in the evaporating zone. Totally, 24 cubes are put inside the still.

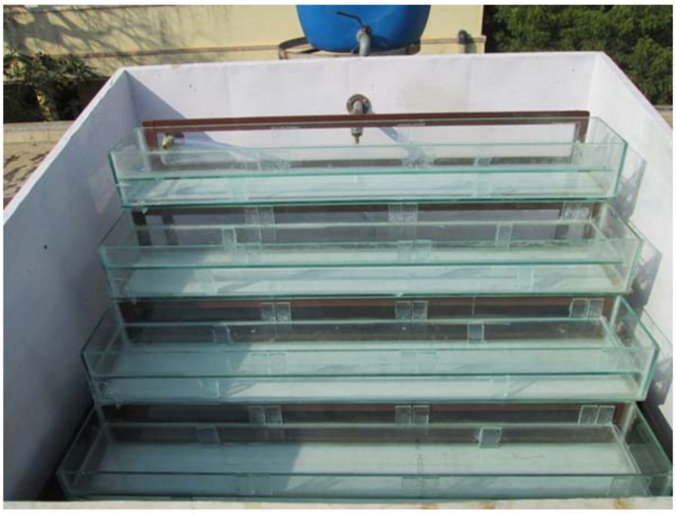

Fig. 3. Photographic view of stepped solar still

c) Experimental procedure

Saline water from storage tank is allowed to enter the evaporating zone of the first tray. Different depth can be maintained in the top tray depending on the glass strips height. The excess water flows down the bottom tray and enters the subsequent trays. After all the trays are filled by saline water the supply is closed using the valve V_1. Temperatures variations in the basin and water are measured using Copper-Constantan thermocouple integrated with selector switch and digital temperature indicator. The evaporation rate was measured by the use of beaker. Solar intensity and wind velocity were measured with the help of anemometer and Kipp - Zonan Solarimeter. The water collected was measured at the end of every hour. The experiment was carried out from 9 am to 5 pm every day. The same procedure was repeated for other modifications also.

4. THEORETICAL ANALYSIS

In this, energy balance equation is applied to basin, water and glass separately. By considering the basin, the energy absorbed by the basin by solar radiation is used to increase the sensible heat of the basin and some part of the energy is reflected to water as convective heat and remaining energies are lost.
The transient energy balance equation for the basin is given by references [1,2,7,11,13],

$$m_b C_{p,b} \left(\frac{dT_b}{dt}\right) = I(t) A_b \alpha_b - Q_{c,b-w} - Q_{loss} \tag{1}$$

The absorptivity of the still α_b was taken as 0.95.

The convective heat transfer between basin and water was taken from references [1, 2, 7, 11, 13],

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

The convective heat transfer coefficient between basin and water was taken from reference [13, 15],

$$h_{c,b-w} = Nu \frac{k_w}{L_w} = \frac{k_w}{L_w} [Gr.\Pr]^{\frac{1}{4}} \tag{3}$$

The heat loss from basin to ambient was taken from references [1,2,7,11,13],

$$Q_{loss} = U_b A_b (T_b - T_a) \tag{4}$$

where

$$U_b = \frac{k_b}{x_b} \tag{5}$$

The transient energy balance equation for water using the references [1, 2, 7, 11, 13],

$$m_w C_{p,w} \left(\frac{dT_w}{dt}\right) = I(t)\alpha_w A_w + Q_{c,b-w} - Q_{c,w-g} - Q_{r,w-g} - Q_{e,w-g} \tag{6}$$

The absorptivity of the still α_w was taken as 0.05 using references [4, 7, 11]

The convective heat transfer between water and glass was taken as from the references [1, 2, 7, 11, 13],

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

where

$$h_{c,w-g} = 0.884[(T_w - T_g) + \frac{(p_w - p_g)(T_w + 273.15)}{269800 - p_w}]^{\frac{1}{3}} \tag{8}$$

The evaporative heat transfer from the basin water to glass was taken from the references [1, 2, 7, 11, 13],

$$Q_{e,w-g} = h_{e,w-g} A_w (T_w - T_g) \tag{9}$$

where

$$h_{e,w-g} = 0.0162 h_{c,w-g} \frac{(p_w - p_g)}{T_w - T_g} \tag{10}$$

The radiative heat transfer from the basin to glass cover was taken from the references [1, 2, 7, 11, 13],

$$Q_{r,w-g} = \sigma \varepsilon_{w-g} A_g [(T_w + 273.15)^4 - (T_g + 273.15)^4] \tag{11}$$

The latent heat of evaporation of water in J/kg at a given basin water temperature (°C) is given by the following correlation, using references [4, 7, 11]

$$h_{fg} = (25033 - 2.398 \times T) \times 1000 \tag{12}$$

The partial pressure of water vapour in air in $\frac{N}{m^2}$ is estimated for a given temperature (°C) by using references [4, 7, 11],

$$p = 7235 - 431.43\ T + 10.76\ T^2 \tag{13}$$

The specific heat capacity of the air inside the still is in J/kg K, calculated using the following correlation [ref: 4, 7, 11] in terms of average temperature (T_{av} in °C) between glass and basin water

$$C_{p,a} = 999.2 + (0.14339 \times T_{av}) + (0.0001101 \times T_{av}^2) - (0.0000000675\ 81 \times T_{av}^3) \tag{14}$$

The transient energy balance equation for glass using references [1, 2, 7, 11, 13] is:

$$m_g C_{p,g}\left(\frac{dT_g}{dt}\right) = I(t)\alpha_g A_g + Q_{c,w-g} + Q_{r,w-g} + Q_{e,w-g} - Q_{r,g-sky} \tag{15}$$

The radiative heat transfer between glass and sky was taken by using references [1, 2, 7, 11, 13],

$$Q_{r,g-sky} = h_{r,g-sky} A_g (T_g - T_{sky}) \tag{16}$$

where

$$h_{r,g-sky} = \varepsilon\sigma \frac{[(T_g + 273)^4 - (T_{sky} + 273)^4]}{T_g - T_{sky}} \tag{17}$$

The instantaneous water production was given by using references [4, 7, 11],

$$m_e = \frac{Q_{e,w-g}}{h_{fg}} \tag{18}$$

The overall production of the still is = $\Sigma\ m_e\ (t)\ \Delta t$ (19)

Initially, the time interval was 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), (6) and (15), 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 parameters are redefined as

$$T_b = T_b + dT_b,\ T_w = T_w + dT_w, \text{ and } T_g = T_g + dT_g.$$

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

The simulation was carried out by finite difference method using the Mat-lab software.

5. RESULTS AND DISCUSSION

Experiments were carried out in two types of experimental set up namely, conventional still and stepped solar still, and performance comparisons are discussed in this section.

a) Effect of depth on productivity

Figure 4 reveals the productivity of still with respect to the water glass temperature changes. It shows that the increase in water glass temperature difference increases the productivity of the solar still. The stepped basin solar still is made by glass to increase the absorption of solar intensity. Using the modified stepped solar still the output is increased by 19% compared with conventional still. Maximum output was obtained at 0.5cm water depth and has the maximum water temperature difference. As the depth decreases the mass of water in the basin, the decreases, which in turn reduces the heat capacity (m C_p) of the liquid. This increases the water temperature (Eq. (4)).

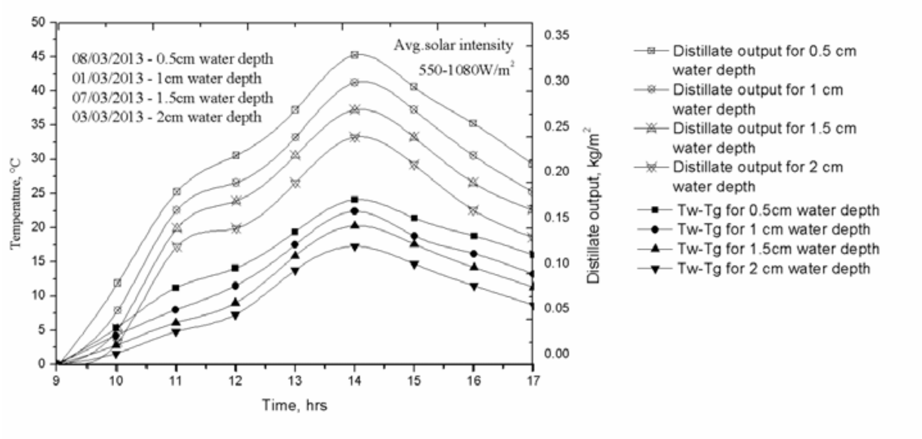

Fig. 4. Productivity variation for various basin depths

b) Effect of productivity on sensible heat materials

The sensible heat storage materials like sand and metal scraps are used to increase the productivity of the solar still. Experiments were carried out for constant water depth of 0.5 cm in the evaporating zone. Figure 5 shows that the theoretical and experimental output for modified stepped still using sand and metal scraps. The output for sand is increased by 24% compared with conventional still. And for metal scraps it is increased by 30%. Addition of sand or metal scraps increases the heat capacity (m_b $C_{p,b}$) of basin. This increases the saline temperature which in turn increases the evaporation rate.

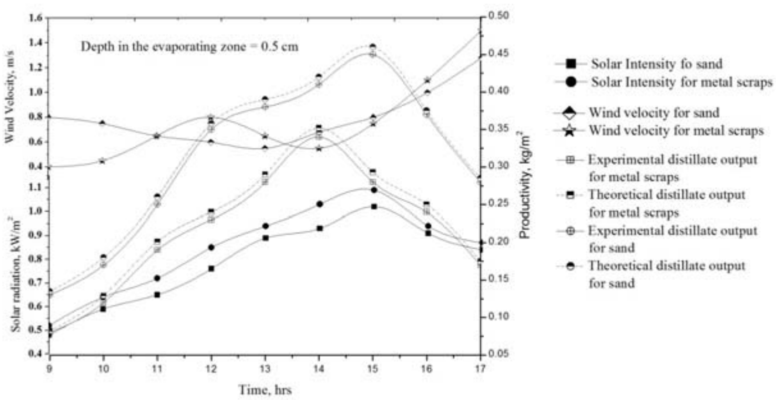

Fig. 5. Effect of productivity on sensible heat materials

c) Comparison of cumulative distillate output for sensible and latent heat materials

Figure 6 shows the cumulative distillate output for sensible and latent heat materials for conventional and modified still. These materials are filled in the glass cubes and made to flow over the basin. It shows that by using the sensible heat materials like Aluminium scraps the productivity is increased about 29%. Then by using the latent heat materials like camphor the productivity of the still is increased by 40% compared to conventional still. Results show that for the same meteorological conditions stepped solar still yields more than conventional solar still and compared to adding sensible heat materials adding latent heat materials in the glass tubes gave the higher evaporation rate.

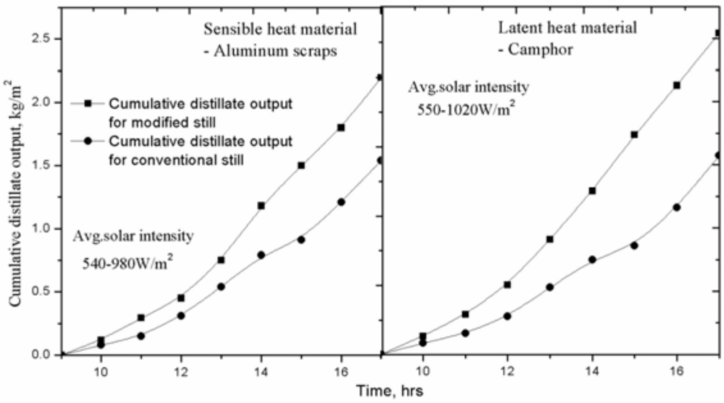

Fig. 6. Comparison of cumulative distillate output for sensible and latent heat materials

d) Effect of using sponges on distillate production

To augment the productivity of the still, sponge cubes are used. Sponges of size 2.5 cm are used in the solar still. The average increase in productivity is 28% of still production. More water will rise to the top of the sponge surface by capillary force. As the exposure area increases, evaporation rate increases. The experimental performance agrees well with the theoretical performance with a maximum deviation of 8.2%. This effect is depicted in Fig. 7.

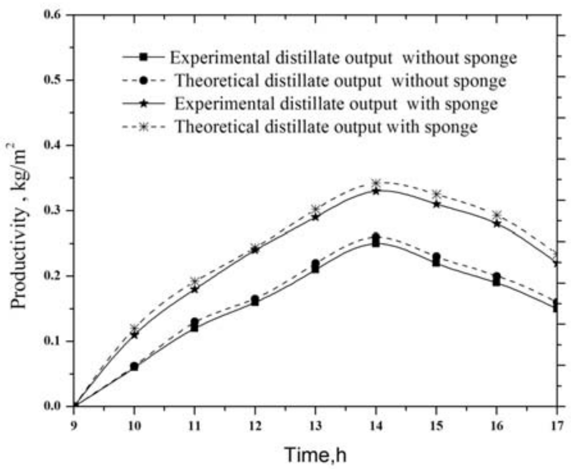

Fig. 7. Experimental and theoretical comparisons

e) Comparison of day and night water collections

Experiments were carried out by adding sensible heat materials like aluminum scraps, charcoal and latent heat materials like camphor and dry salt filled in the glass cubes. These glass cubes were made to float in the water basin. Experiments were carried out for a period of 24 h duration. Figure 8 shows the day and night water collections for the stepped solar still with such modifications. The day and night productivity increases by 25-30%, the basin of the stills is added with charcoal and aluminum scraps. It is found that, the day and night productivity increases by 35-40% when camphor and dry salt are used in the stills.

For analysis of different systems, data are chosen from various days of experiments which are having an average solar intensity of 620 W/m^2 and average wind velocity of 1.1 m/s.

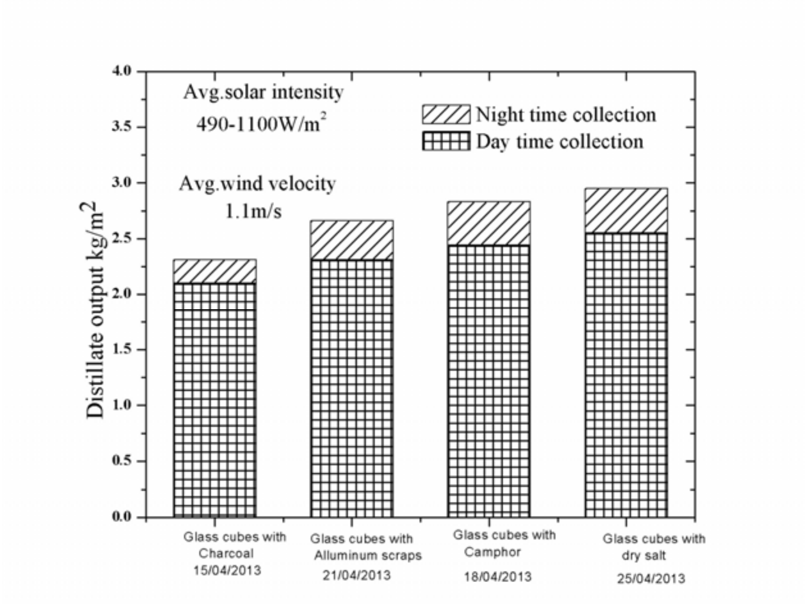

Fig. 8. Comparison of day and night water collections of various materials

f) Percentage of gain in distilled water yield for various modifications

Figure 9 illustrates the percentage gain obtained for each absorbing material used. It is clear that compared to sensible heat materials, the latent heat material produce the maximum gain percentage. Energy required for phase changes highly contributed for accelerated evaporation rate.

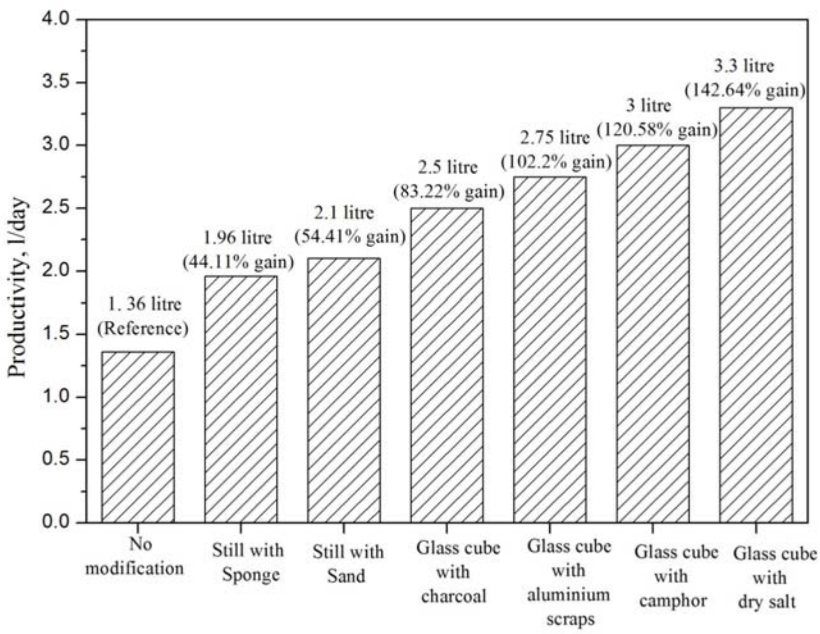

Fig. 9. Comparison of gain percentage of various materials

6. ECONOMIC ANALYSIS

The payback period of the experimental setup depends on the following factors.

- Cost of land
- Overall cost of fabrication
- Maintenance cost

Cost of land was not considered for the economic analysis, as the space occupied was negligible. The average pay back period comes around 2 years as shown in Table 1.

Table 1. Economic analyse

Types of analysis	Solar still – without any modifications	Solar still with sponge	Solar still with sand	Glass cube with charcoal	Glass cube with Aluminum scraps	Glass cube with Camphor	Glass cube with Dry salt
Overall cost to be considered	Rs. 20000 (320 $)	Rs. 20000 (320 $)	Rs. 20000 (320 $)	Rs. 20000 (320 $)	Rs. 20000 (320 $)	Rs. 20000 (320 $)	Rs. 20000 (320 $)
Productivity of the distilled water (kg/m^2)	1.36	1.96	2.1	2.5	2.75	3	3.3
Cost of water produced per litre	Rs.15 (0.24 $)	Rs.15 (0.24 $)	Rs.15 (0.24 $)	Rs.15 (0.24 $)	Rs.15 (0.24 $)	Rs.15 (0.24 $)	Rs.15 (0.24 $)
Maintenance cost	Rs. 2/day (0.032 $)	Rs. 2/day (0.032 $)	Rs. 2/day (0.032 $)	Rs. 2/day (0.032 $)	Rs. 2/day (0.032 $)	Rs. 2/day (0.032 $)	Rs. 2/day (0.032 $)
Payback period (days)	981	680	635	534	485	445	404

7. CONCLUSION

Based on the experiments conducted on the stepped basin type solar still, it is observed that the productivity is increased compared to that of the conventional still in all modifications. The stepped basin type consists of stepped tray with glass materials. Due to higher absorptions to solar intensity, using glass as basin materials yields higher productivity. Provisions of two compartments: heating and evaporating zones augment the evaporation rate due to increase in temperature of the saline water. Sponge flows over the basin accelerate the evaporation rate due to its capillary action. Sensible heat materials like sand and metal scraps placed on the heating zone further speed up the productivity rate. Also, it ensures the increase in production rate in night time also. Glass cubes floating on the evaporating zone acts as a fin which is the reason for higher evaporation rate compared to all modifications. Sensible heat materials like aluminium scraps and charcoal and latent heat materials like Camphor and dry salt filled in the glass cubes are proved a better method to increase the productivity of the still. Also, the high heat release capacity of nanoparticles diluted with water [14] will be a focus for future research options in solar desalination using saline water diluted with nanoparticles.

NOMENCLATURE

English letters

A area (m^2)
C_p specific heat (J/kg K)
L_w characteristics length (Area/perimeter of the saline surface) (m)
I(t) solar flux on an inclined collector (W/m^2)
P partial pressure (N/m^2)
Q heat transfer (W)
T temperature (ºC)

dt	time interval (s)
h	heat transfer coefficient (W/m² K)
h_{fg}	enthalpy of evaporation at Tw (J/kg)
m_c	condensate (kg/m²)
m	mass (kg)
U	side heat loss coefficient from basin to ambient (W/m² K)
x	thickness of the basin (m)

Greeks

e	emissivity
a	absorptivity
s	Stefan–Boltzmann constant (W/m^2 K^4)

Subscripts

a	ambient
av	average
b	basin
c	convective
e	evaporative
g	glass
r	radiative
w	water
eff	equivalent
loss	side loss

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