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Experimental investigation on the time dependant behaviour of productivity of a stacked solar still

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ABSTRACT

In this experimental study, a conventional single slope solar still and an improved stacked solar still were designed, fabricated and tested. The experimental investigations were carried out to understand the effect of the various critical parameters influencing the time dependent behaviour of productivity of the solar still. The productivity of the stacked double basin solar still is evaluated and compared with the conventional single basin solar still of same base area of 0.5 m^2 under same meteorological conditions. The modified solar still contributes an improvement of 35.51% in the yield when compared to the conventional single basin solar still. With the provision of insulation materials such as Styrofoam, rubber and wood on the side of the basin, the daily yield of the solar still increased by 72.78%, 41.75% and 33.75% respectively. The production rate is increased by 32.66% with inclusion of wick material and 31.75% with addition of dye. The results obtained showed that the productivity of the still increases with decrease in water depth.

Keywords: Solar still; Transient analysis; Double basin; Stacked still; Distillation; Productivity of still

1. Introduction

Adequate supply of fresh water is one of the most essential substances for sustaining human life. Clean water ensures socio-economic development of a country. Consuming unsafe water leads to many diseases. Freshwater sources throughout the world are exploited by the increase in population. The discharge of toxic pollutants and effluents from the industries also leads to major exploitation of fresh water. Many conventional methods are used for conversion of impure water to potable water. The existing methods utilize either fossil fuel or fossil fuel educed electric energy which ensues atmospheric befoulment and global warming. Solar distillation process is a future promising technology. Solar distillation processes facilitate the arid areas where the availability of solar energy is plenty. It follows the natural hydrological cycle for the conversion of waste water into potable water.

A solar still device which uses inexhaustible solar energy can be utilized for the purification of impure water and conversion of the brackish water into potable water. The primary source of energy in this device is solar which is environmental friendly and inexhaustible. The solar still is primarily classified into two types as active solar still and passive solar still. The key difference between the passive and active solar still lies in the fact that an additional thermal energy is being contributed to the latter. In a solar still device, the brackish or impure water that has to be converted into potable form is kept in an enclosed area called as basin. The solar radiation enters through a transparent cover usually made of glass or plastic. The incoming radiation transfers its energy to the water in the basin thus making it to evaporate. The evaporated water

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in the form of pure vapour leaves behind the impurities and brackishness and gets condensed on the glass cover. The glass cover is usually inclined at an angle favouring the maximum incurrence of solar radiation. The sloping surface helps the condensate to trickle down and get collected through a separate channel. The converted water is free from impurities and is potable.

Many solar still devices were established throughout the world recently. Though the number of solar still devices installation has increased, it has faced many challenges in its implementation as a commercial water purification system [1,2]. Prakash et al. [3] conducted an experiment with aluminium, galvanized iron and glass as the basin material and the results shows that the productivity is high when aluminium is used as the basin material. It is observed that the cost of one liter of water from the aluminium solar still is twice that of galvanized iron solar still. Sharshir et al. [4] discussed the major factors that affect the productivity of the solar still and also reviewed the work of various researchers contributing to productivity enhancement in solar still.

One of the major challenges in commercializing the solar still is its low productivity per unit area [5]. Ahsan et al. [6] designed and tested an improved tubular solar still which is lightweight, economic and durable with an effective payback period of 0.03 y. A linear relation between the heat transfer coefficient and mass transfer coefficient was also formed. Arunkumar et al. [7] tested a hemispherical solar still with external cooling on the cover and achieved an improvement of 42% in efficiency. Ahsan et al. [8] developed a triangular solar still and analysed its performance at various water depth. It was observed that the productivity increases with decrease in water depth due to higher heat absorption capacity of water at lower depth. Arunkumar et al. [9] improved the performance of the hemispherical solar still by integrating it with concentrator and phase change material. Productivity increase of 26% was observed with addition of paraffin wax as phase change material. Panchal et al. [10] reported that fabricating the solar still basin using energy storage material improves the distillate during off sunshine hours. An experiment was conducted to analyse the effect of calcium stones, granite gravel and pebbles as basin material for the double basin solar still and found out that calcium stone which has the highest specific heat capacity among the three improves the distillate by 20.5% and 41.37% compared to granite gravel and pebbles respectively. Murugavel et al. [11] analysed the effect of various wick material such as cotton cloth, sponge sheet, coir mate and waste cotton pieces in double slope single basin solar still and found that light black cotton cloth was the most effective compared to other materials. Ahsan et al. [12] developed a numerical model to calculate the productivity of solar still and carried out a detailed comparison of several numerical models. The proposed model was found to be more reliable for tubular solar still productivity estimation. Kaimi Estahbanati et al. [13] investigated the effect of an internal reflector on the productivity of a single slope solar still and observed an increment of 22% in its efficiency. Feilizadeh et al. [14] analysed the effect of water cover distance and water depth on the productivity of solar still and found out that productivity of the still decreases with increase in water-cover distance and water depth. In this research, a double basin solar still of effective area 0.49 m^2 was fabricated and tested. The objective of this present work is to compare the productivity of the stacked solar still with a single basin solar still of same base area and improve the productivity of the stacked solar still. The stacked solar still yielded higher productivity for the same area and an increase of 35.51% is observed as shown in Fig. 3. Most of the researchers have used 2-napthylamine black azo dye which is a carcinogenic material and hazardous. The dye used in this research work is sulfonated cyanine black dye. The productivity of the double basin solar still was further enhanced with addition of dye, insulation on sides and wick material.

2. Experimental setup

A schematic representation of the conventional single basin and stacked solar still is shown in Fig. 1. Since the solar still requires large area for water distillation, an additional compartment is inducted at the top of the conventional solar still, thus creating a stacked solar still or double basin solar still. With this new design, the productivity can be increased for the same area.

Single slope, single basin and double basin solar still of base area 0.5 m^2 is fabricated using galvanized iron sheets of

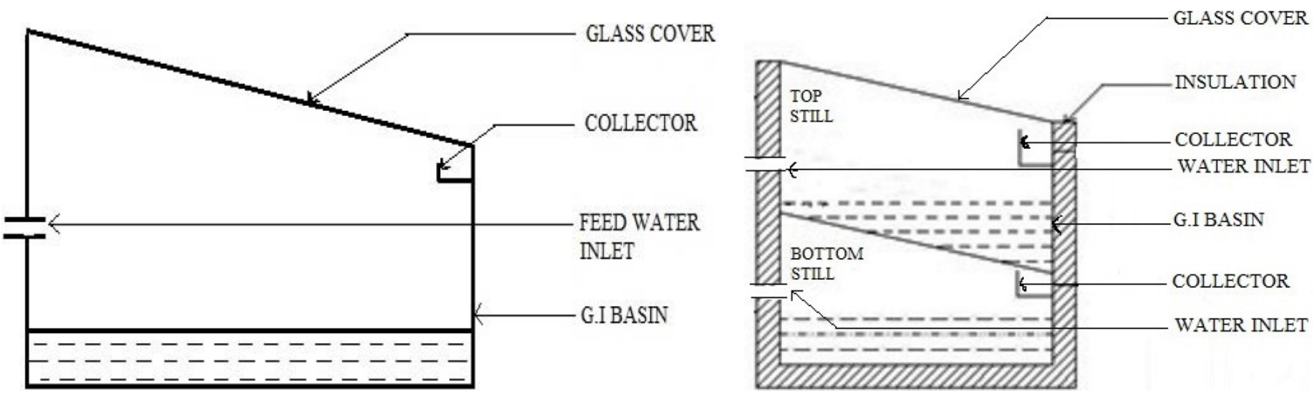

Fig. 1. Schematic representation of a solar still (a) Single basin solar still (b) Stacked solar still.

0.005 m thickness. The use of galvanized iron prevents the basin from getting rusted. The pictorial diagram of stacked solar still is shown in Fig. 2. Each basin of the stacked solar still is 0.5 m^2. The lower and upper basins are covered at the top using glass of 6 mm and 3 mm thickness respectively. The glass cover inclination angle is 13°. The inclination and direction of inclination depends upon the geographic location of the still [15,16]. Glass is the preferred material for cover, since it has higher solar transmittance for various angles of incidence and long service life [17], whereas a plastic can be used for short-term use. Though the heat transfer is efficient with reduction in thickness of the cover, the glass cover for the bottom still must be enhanced so as to withstand the weight of the water placed above. The experiment is conducted by varying the depth of water and the thickness of insulation of the stacked solar still. The effect of dye and wick materials on the productivity is also observed.

3. Results and discussion

3.1. Effect of double basin still

A single slope single basin solar still was fabricated and tested in the rooftop of Velammal engineering college (13.1497°N, 80.1919°E), Chennai, India during the months of March–May 2016. The readings were taken from 09.00 am to 09.00 am next day. The readings of the conventional solar still and stacked solar still were taken at the same time to compare it under same operating conditions. The productivity of the single basin solar still was measured to be 2.785 kg/m^2/d. It is observed from Fig. 3. that the productivity of the solar still increased to 3.774 kg/m^2/d with the modified stacked still. In the stacked solar still, the latent heat of condensation released by the condensing vapour is absorbed by the middle glass cover thus adding heat to the water in the upper basin. Thus with the development of a stacked solar still there is an increment of 35.51% in the productivity for the same base area. It is inferred from Fig. 3. that the productivity is maximum at sunset because of the maximum temperature difference between the water and the glass cover.

Fig. 2. Photographic view of Stacked solar still.

3.2. Effect of various water depth

The experiments were conducted by incrementing 10 mm of water depths in both the basin of the stacked solar still. The experiments were conducted in the range of 10 mm to 90 mm in the stacked solar still and the distillate output is calculated. The effect of water depth on the daily yield of the solar still is as shown in Fig. 4. It can be evident from Fig. 4 that with increase in water depth, the productivity of the solar still diminishes gradually. It is due to the fact that as the water depth increases, the heat capacity of the water also raises leading to lower evaporation rate. Moreover, when the water at the top layer evaporates, it absorbs the latent heat from below which results in decreasing the temperature of the water. It is therefore concluded that the productivity is maximum at minimum water depths.

3.3. Effect of insulation thickness

The experiments were conducted with three different insulating materials (Styrofoam, rubber and wood).

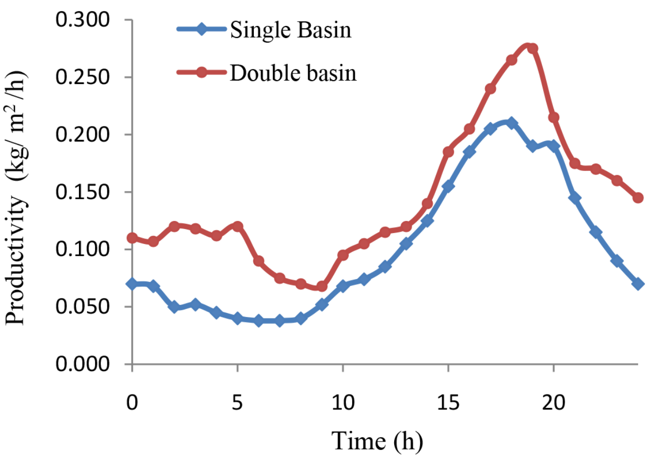

Fig. 3. Comparison of the productivity of single basin and stacked solar still.

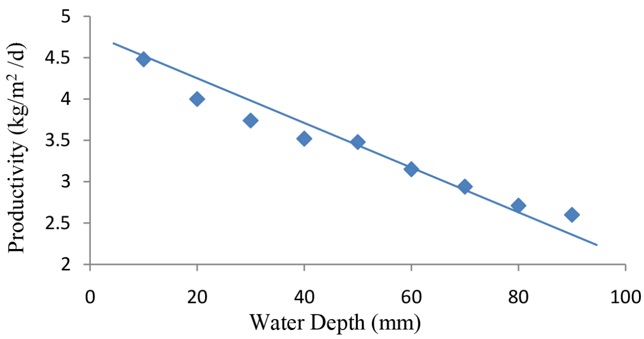

Fig. 4. Effect of water depth on the productivity of stacked solar still.

The insulation materials were fixed on the side walls of the basin. The thermal conductivities of the materials are 0.033 W/m-K, 0.13 W/m-K and 0.12 W/m-K respectively.

Fig. 5 compares the performance of the solar still with no insulation and with various insulation materials. It can be observed that the yield of the solar still increases with an inclusion of insulation materials. The daily yield of the solar still without any insulation is 2.74 kg/m^2/d. With an inclusion of the various insulating materials such as Styrofoam, wood and rubber the daily yield of the solar still increased to 4.748 kg/m^2/d, 3.784 kg/m^2/d and 3.555 kg/m^2/d respectively. Fig. 6 shows that the productivity of the solar still increases proportionally with increase in insulation thickness up to a certain thickness. It is observed that the increase in the productivity of the solar still with the inclusion of insulating material is due to increase in the nocturnal productivity. Beyond this thickness the productivity enhancement is minimal with addition of more thickness. This critical thickness depends upon the type of the insulation material used. It can be observed that the optimum thickness decreases with the material's conductivity.

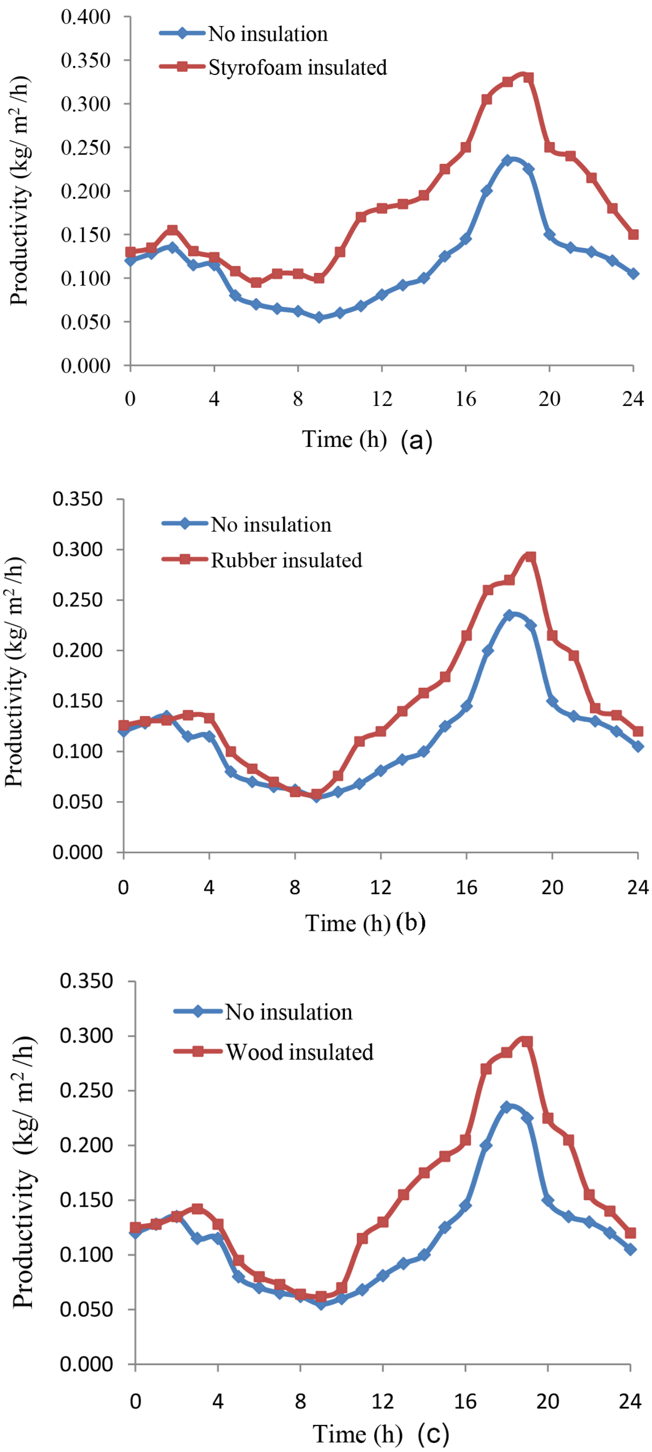

Fig. 5. Comparison of productivity of the solar still with insulation and without insulation.

3.4. Effect of dye

The incident solar radiation is mostly absorbed by the basin material rather than the water in a conventional solar still. Heat is transferred in all directions through convection and conduction from the basin material thus leading to heat losses. With the inclusion of dye, most of the incident solar radiation is absorbed by the basin water thus leading to increased water temperature and also low heat loss from the basin material. The experiments were conducted by injecting sulfonated cyanine black dye of 200 ppm concentration into the lower basin of water depth 0.1 m and the readings are plotted as shown in Fig. 7. The effect of dye is significant when the mass of water is higher [18]. It can be seen that the addition of dye increases the productivity of the solar still from 4.47 kg/m^2/d to 5.89 kg/m^2/d.

3.5. Effect of wick material

Fig. 9. depicts the effect of wick material on the productivity of the solar still. The wick material is usually selected based on its porosity, capillary effect, absorption capacity and heat transfer coefficient. The wick material maintains uniform water depth through capillary effect.

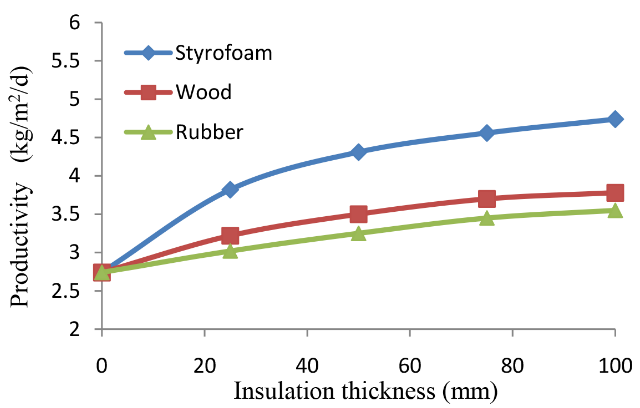

Fig. 6. Effect of insulation thickness on the productivity of the solar still.

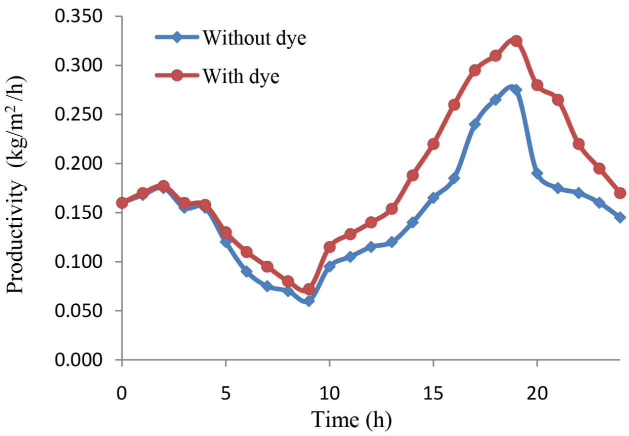

Fig. 7. Effect of dye on the productivity of the solar still.

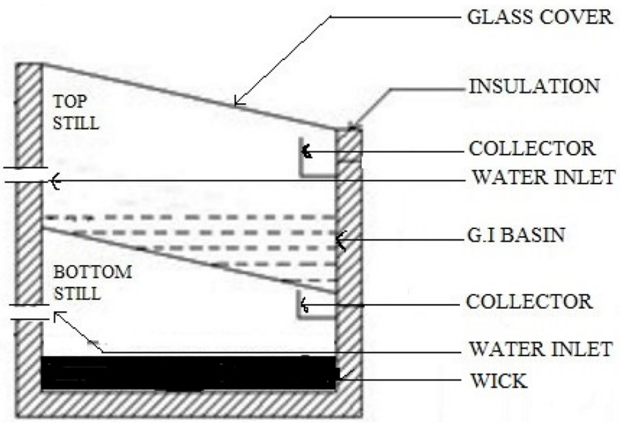

Fig. 8. Schematic diagram of solar still with wick material.

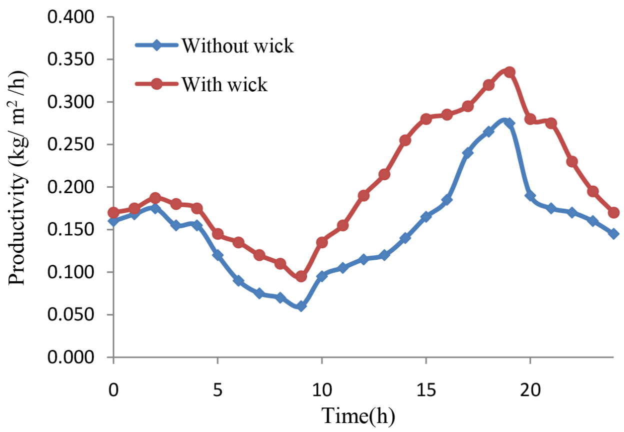

Fig. 9. Effect of wick material on the productivity of solar still.

In this research work, black jute cloth was selected as the wick material. The density of the jute cloth is given as 1080 kg/m^3, heat capacity 1.25 J/kg-K and thermal conductivity 0.11 W/m-K. The wick material is placed in the bottom basin since addition of wick material in the upper basin leads to blockage of the solar radiation to the bottom still as shown in Fig. 8. The increase in productivity is achieved by increasing the evaporative surface area of the water with the help of wick materials. The yield of the stacked solar still increased from 4.47 kg/m^2/d to 5.93 kg/m^2/d.

4. Theoretical analysis

The theoretical yield of the solar still can be calculated using Eqs. (1)–(9). The amount of distillate water output from the double basin solar still on hourly basis can be calculated by

$$m_w = \frac{q_{e,w-g}}{L} \times 3600 \tag{1}$$

The evaporative heat transfer rate for double basin solar still from water to glass, $q_{e,w-g}$ is given by

$$q_{e,w-g} = q_{e,w-g,l} + q_{e,w-g,u} \tag{2}$$

where $q_{e,w-g,l} = h_{e,w-g,l}\left(T_w - T_g\right)_l$, and (3)

$$q_{e,w-g,u} = h_{e,w-g,u}\left(T_w - T_g\right)_u, \tag{4}$$

The relation between convective (h_{cw}) and evaporative (h_{ew}) heat transfer coefficient in a solar distillation unit is given by Dunkle as

$$h_{ew} = 0.0163\, h_{cw} \frac{p_w - p_{ci}}{T_w - T_{ci}} \tag{5}$$

The convective heat transfer coefficient is determined using the Nusselt number relation. It is given as

$$Nu = \frac{h_{cw}}{\left(\frac{k}{d}\right)} = C\left(Gr \cdot \mathrm{Pr}\right)^n \tag{6}$$

where *Gr* and *Pr* are Grashoff and Prandtl number respectively and are given by

$$Gr = \frac{\beta g d^3 \rho^2 \Delta T}{\mu^2} \tag{7}$$

$$Pr = \frac{\mu C_p}{k} \tag{8}$$

The Grashoff number and Prandtl number can be calculated from the various physical properties of the vapour as shown in Table 1. The values of the constants *C* and *n* depends on the geometry of the surface and the flow regime, which is characterized by the range of Rayleigh number. The water temperature (T_w) and the condensing cover temperature (T_{ci}) can be measured using thermocouple The cumulative production is found to be 4.55 kg/m^2 d for the double basin solar still without any addition of performance enhancement parameters such as dye, insulation and wick. Deviation of 15.26% is observed with experimental values because in theoretical analysis it is assumed that the condensation rate is equal to the evaporation rate which is not possible.

5. Economic analysis

With the inclusion of additional basin, the material and fabrication cost of the double basin solar still is higher compared to the single basin solar still. The higher investment cost of the stacked solar still is justified by its increased productivity. The material cost of both the basin is shown in Table 2. The maintenance cost is assumed to be Rs. 1000/y for stacked solar still and Rs. 700 for single basin solar still. Assuming the lifetime of solar still is 10 y for both. Total cost incurred for 10 y is Rs. 16500 for double basin and Rs. 14200 for single basin solar still. The total amount of potable water produced in 10 years in double basin and single basin solar still are 7335 kg and 4875 kg respectively. Thus the cost of water per liter is Rs.2.24 for double basin and Rs.2.91 for single basin solar still.

Table 1
Various properties of vapour used for theoretical analysis

S. No	Properties
1	Difference in surface and bulk temperature 'ΔT' (°C)
2	Coefficient of thermal expansion 'β' (K^{-1})
3	Specific heat 'C_p' (J/kg °C)
4	Density 'ρ' (kg/m^3)
5	Thermal conductivity 'k' (W/m K)
6	Viscosity 'μ' (kg/m-s)
7	Latent heat of vaporization 'L' (J/kg)
8	Saturation vapour pressure 'p_w' at T_{ci} (N/m^2)
9	Saturation vapour pressure 'p_{ci}' at T_w (N/m^2)

Table 2
Cost details for making double basin and single basin solar stills

S.No	Component	Double basin solar still cost (Rs.)	Single basin solar still cost (Rs.)
1	GI sheet	2500	1700
2	Glass cover	900	300
3	Insulation	200	150
4	Black paint	400	250
5	Labour charge	2500	1800
Total cost (Rs.)		6500	4200

6. Conclusions

The following conclusions are inferred from the experimental investigation of the modified stacked solar still,

- The productivity of the stacked solar still is 35.51% higher than that of the single basin solar still as shown in Fig. 3. The productivity of various researches on double basin solar still is compared in Table 3.
- The productivity of the solar still is inversely proportional to the depth of water as it can be inferred from Fig. 4. that the productivity of the still decreases by 44.44% with an increase of 80 mm water depth.
- With the provision of insulation materials on the side of the basin, the daily yield of the solar still can be improved. An increase of 72.78%, 41.75% and 33.75% in the productivity of the solar still is observed with the addition of Styrofoam, wood and rubber as insulating materials respectively.
- The productivity of the solar still records an increment of 31.76% and 32.66% with the presence of black dye and wick material respectively. The productivity is found to be high during sunshine hours and low in the off sun shine hours.

Table 3
Comparison of productivity of various researches on double basin solar stills

S. No	Author (s)	Base area (m^2)	Modification	Productivity ($kg/m^2/d$)
1	Al-Karaghouli et al. [19]	0.45	Double basin still	3.13
			Double basin still with insulation	3.91
2	Rajaseenivasan et al. [20]	0.72	Double basin double slope still	5.68
3	Gnanaraj et al. [21]	1.40	Double basin still	4.33
			Double basin still with reflectors	5.65
			Double basin still with reflectors, flat plate collector and mini solar pond	6.24
4	Panchal et al. [22]	0.53	Double basin still with vacuum tube	11.06
5	Pandey [23]	0.72	Double basin still	5.06
			Double basin still with black dye	5.33
			Double basin still with methylene blue	2.41
6	Present work	0.50	Double basin still	3.77
			Double basin still with Styrofoam insulation	4.78
			Double basin still with black dye	5.89
			Double basin still with jute wick	5.93

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