Thermal Analysis of Single Slope Solar Still with Sensible Storage Material (Sand)

Abhilash Kumar Dahayat[1*], Aneesh Somwanshi[2]
[1*,2]Department of Mechanical Engineering, MATS University, Raipur, Chhattisgarh
Corresponding Author: Abhilash Kumar Dahayat[1*]
[1*]Department of Mechanical Engineering, MATS University, Raipur, Chhattisgarh

Abstract:

In this work authors utilized easily available and cheap sensible storage material (sand) in single basin solar still. The sensible storage material helps to enhance the distillate output from solar still during no sunshine hours. The mathematical model of the proposed solar still has been developed and experimentally validated. The numerical computation has been performed to analyse the effect of mass od sand placed beneath the basin plate. It is seen that with increase in mass of sand the overall daily distillate output decreases. When mass of sand increases from 15kg to 60 kg the daily distillate output decrease by 11.8%. The total daily distillate output produced by proposed still for a day in summer for Raipur is 5.32l/m^2 which is about 24.4% more than conventional single slope solar still. The total nocturnal production of pure water from the propped still for a day in summer in Raipur climate is 1.37l/m^2. The proposed solar still with sand storage is a good available cheap option to increase the overall productivity of conventional single slope solar still.

Keywords: *Single slope solar still, sensible storage, sand , daily distillate output, nocturnal production of pure water.*

1. Introduction

In many nations, there is an urgent demand for pure, clean drinking water. Frequently, water sources are unsafe for drinking because they are brackish or contain dangerous microorganisms. Additionally, there are numerous coastal areas with an abundance of seawater but no access to drinking water. Some companies, hospitals, and educational institutions also require pure water. One of the many methods that may be used to purify water is solar distillation. Where brackish or sea water evaporates and then condenses as pure water, solar radiation can be a source of heat energy.

The two main categories of solar stills are passive and active stills. Numerous strategies to increase the output of these stills have been the subject of extensive research [1–10]. Researchers focused on analysing some of the factors like wind velocity, basin water mass and solar intensity affecting the performance of solar still [11,12]. However, reducing the thickness of the basin's water causes a reduction in the still's nightly productivity [13]. Therefore, a baffle plate composed of mica was placed inside the water of the basin in order to increase still productivity even with thicker water layers (deep basins) [14]. The baffle plate has been proven to greatly improve the single basin solar still's performance year-round [15]. According to Tiwari et al. [16], the passive solar distillation method is a laborious one for cleaning brackish water. The nocturnal output of traditional active solar stills (ASS), however, is zero. Due to this, numerous attempts have been made to increase the efficiency of ASS by connecting these stills to flat plate collectors [17,18], shallow solar ponds [19,20], solar concentrators [21], etc. All of these techniques contribute to the cost and difficulty of running and maintaining an ASS. Utilizing sensible or latent heat storage systems is another way to increase the output of active and passive solar stills. In comparison to sensible heat storage systems, latent heat thermal energy storage systems have various benefits, such as a high energy storage capacity per unit space and nearly constant temperature during charging and discharging [22]. When using latent heat storage materials, issues like corrosion and leaking could arise. The use of phase change materials as storage media in solar stills has received little attention in the literature [23,24]. As far as the authors are aware, some research has been done on the integration of solar distillation systems with practical storage materials including pebble, coal, and sand [26], as well as black rubber and black gravel [25]. The goal was to increase the productivity of solar stills.

In this study authors examined the performance of an single-basin solar still (SBSS) that produces fresh water at night by integrating a thin layer of sensible storage material beneath the still's basin liner. Sand is utilized as a storing substance because it is affordable and readily available. The energy balance equations are created and solved analytically for the different components of the still as well as the storage material. The mathematical model of the proposed SBSS with sand storage has been developed and experimentally validated. Numerical computations have been performed for a day in summer months for the climate of Raipur to analyse the effect of varying the thickness of sand. Moreover, authors numerically compared the performance of proposed solar still with sand by conventional single slope solar still without sand. The use of sensible storage material (sand) beneath the basin plate helps to enhance the productivity during off sun shine hour. The distillate produces during night time by the proposed still has been compared with the output produced during night by conventional still.

2. Description of the proposed still with sand layer

Fig.1 displays a schematic of the proposed solar still with sand serving as an integrated sensible storage medium. The still's basin measures 1 m^2 and is made of a 2 mm thick black coated galvanized iron sheet that has a gap under the horizontal part of the basin liner. Because it is inexpensive and widely available, sand has been employed as an appropriate storing medium. The basin's bottom and sides are insulated by a 3 cm layer of sawdust housed inside a 1 cm thick wooden frame. The still's cover is constructed of 3 mm thick glass at a 21.25° angle to the horizontal, which corresponds to latitude of Raipur (21.25°N). Fresh water is collected in a channel made of metal that is fixed to the bottom of the glass cover. The basin liner absorbs the solar radiation that passes through the glass cover and into the water in the basin, which raises the temperature of the liner. The sand layer in contact with the basin liner receives some of the part of thermal energy received by basin liner. The still continues to generate fresh water during the night because the sand acts as a heat source for the basin water after sunset. By means of radiation, convection, and evaporation, the basin water heats the interior of the glass cover. Heat is transferred to the surroundings by convection to ambient air and radiation to the sky after passing through the cover.

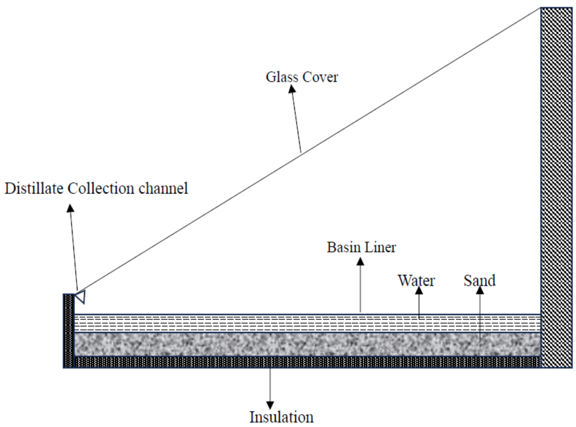

Figure 1 Schematic Diagram of the Proposed Still

3. Preparation of sand

Below the absorber plate, there is a layer of sand acting as a thermal energy storage medium. The sand is first of all filtered through a filter made of wire mesh to remove any impurity present and to collect sand of smaller size granular. The sand then is allowed to dry kept outside under sun for two to three hours to remove any moisture present in sand. The suitable sized dried sand is then used for further experimentations. The sand bed absorbs and stores the heat during the daytime when solar radiation is available in abundance. It acts as a thermal reservoir, maintaining high temperatures even during periods of low solar radiation

---

4. Mathematical analysis

Following assumptions have been made while writing the energy balance equations:

(i) Thermal capacities of basin plates and glass covers are negligible compared to those for basin water and storage material (sand).

(ii) The side losses are negligible

(iii) There is no temperature gradient across the thickness of the storage material the thickness of storage material considered is small

(iv) Plates area and area of glass cover is same.

(v) Quasi steady state operation has been considered.

SS with storage material

On the basis of the assumptions, the energy balance equations for various components of still are as follows:

Glass cover:

$$\alpha_g I + h_i(T_w - T_g) = h_o(T_g - T_a) \tag{1}$$

In Eq. 1 $h_o = h_{co} + h_{ro}$ is the total external heat transfer coefficient between glass cover and ambient here the convective h_{co} and radiative h_{ro} heat transfer coefficient between glass cover and ambient will be given by,

$$h_{co} = 2.8 + 3v_a \tag{2}$$

$$h_{ro} = \varepsilon_g \alpha \frac{[(T_g + 273)^4 - (T_a + 267)^4]}{(T_g - T_a)} \tag{3}$$

Water:

$$\tau_g \alpha_w I + h_p(T_p - T_w) = \frac{M_w c_w}{A_p}\frac{dT_w}{dt} + h_i(T_w - T_g) \tag{4}$$

In eq.4, h_p is the heat transfer coefficient between bottom plate and water. $h_i = h_r + h_c + h_e$ is the internal heat transfer coefficient between water and glass cover. The radiative h_r, convective h_c and evaporative h_e heat transfer coefficient between water and glass cover will be given by,

$$h_i = 0.884[(T_w - T_g) + \frac{(P_w - P_g)(T_w + 273)}{268.9 \times 10^3 - P_w}]^{1/3} \tag{5}$$

Saturated vapor pressure is given by,

$$P = \exp[25.317 - \frac{5144}{T + 273}] \tag{6}$$

$$h_r = \varepsilon_{eff}\sigma[(T_w + 273)^2 + (T_g + 273)^2](T_w + T_g + 546) \tag{7}$$

$$h_e = 16.273 \times 10^{-3} h_{ci} \frac{(P_w - P_g)}{(T_w - T_g)} \tag{8}$$

Absorber plate (P):

$$\tau_g \tau_w \alpha_p I = h_p (T_p - T_w) + K_n (T_p - T_s) \tag{9}$$

In Eq.9 $K_n = \frac{K_p}{y_p}$, K_p is thermal conductivity of plate material and y_p is the thickness of absorber plate

Storage material:

$$K_n (T_p - T_s) - U_b (T_s - T_a) = \frac{m_s c_s}{A_p} \frac{dT_s}{dt} \tag{10}$$

From Eq. 1

$$T_g = K_1 + K_2 T_w \tag{11}$$

From Eq. 4 and Eq.11

$$\frac{dT_w}{dt} + K_3 T_w = K_4 + K_5 T_p \tag{12}$$

Eq. 12 can be solved to get the transient water temperature at time t

$$T_w = \frac{K_4 + K_5 T_{p2}}{K_3} (1 - e^{-K_3 t}) + T_{w0} e^{-K_3 t} \tag{13}$$

Average water temperature will be given by,

$$\bar{T}_w = \frac{1}{t} \int_0^t T_w dt \tag{14}$$

$$\bar{T}_w = \frac{K_4 + K_5 T_{p2}}{K_3} [1 - \frac{(1 - e^{-K_3 t})}{K_3 t}] + T_{w0} \frac{(1 - e^{-K_3 t})}{K_3 t} \tag{15}$$

In Eq. 14 and 15, T_{w0} is the initial water temperature at time *t=0*

Eq. 15 can be written as

$$\bar{T}_w = X_2 + X_3 T_p \tag{16}$$

From Eq. 19 and 9

$$T_p = K_6 + K_7 T_s \tag{17}$$

From eq. 10 and 17

$$\frac{dT_s}{dt} + A T_s = f(t) \tag{18}$$

From Eq. 22 the temperature of storage (sand) will be given by

$$T_s(t) = \frac{f(t)}{A}(1-e^{-At}) + T_{s0}e^{-At} \tag{19}$$

In Eq.19, T_{s0} is the initial temperature of storage material sand at time *t=0* From Eq. 19 the temperature of sand can be found, putting the value of T_s in eq. 17 the temperature of plate can be found out. The average temperature of water and glass cover can be found out by eq. 16 and 11.

The hourly distillate output produced by proposed solar still will be given by,

$$m_{ew} = \frac{h_{ew}(\bar{T}_w - T_g)}{L} 3600 kg/m^2h \tag{20}$$

The values of various constants are as follows

$$K_1 = \frac{\alpha_g I + h_o T_a}{h_i + h_o}$$

$$K_2 = \frac{h_i}{h_i + h_o}$$

$$K_3 = \frac{A_p(h_i + h_p - h_i K_2)}{M_w c_w}$$

$$K_4 = \frac{A_p(\tau_g \alpha_w I + h_i K_1)}{M_w c_w}$$

$$K_5 = \frac{h_p A_p}{M_w c_w}$$

$$X_1 = 1 - \frac{(1-e^{-K_3 t})}{K_3 t}$$

$$X_2 = \frac{K_5}{K_3} X_1 + T_{w0}(1 - X_1)$$

$$X_3 = \frac{K_5}{K_3} X_1$$

$$K_6 = \frac{\tau_g \tau_w \alpha_p I + h_p X_2}{h_p - h_{p3} + K_n}$$

$$K_7 = \frac{K_n}{h_p - h_p X_3 + K_n}$$

5. Experimental validation

Experiment was performed on 10/04/2023 on college premises in Raipur, Chattisgarh, India. Photograph of experimental setup is shown in Fig.2. Before starting experiment the basin of solar still was filled with 10L of potable water up to height 1cm. Below the basin plate, prepared sand layer of 1 cm thickness is spread. To measure the temperature of water in basin, temperature of glass cover and sand temperature RTD sensors of accuracy 0.1^0C has been placed at different points in basin and into the glass cover and in sand. The solar radiation incident on glass cover has been measured by pyranometer of accuracy 1W/m^2. The velocity of wind incident over the glass cover is measured by a hot wire anemometer of accuracy 0.1m/s.

Before starting the experiment, the initial temperature of basin water and glass cover has been recorded. The temperature of basin water, glass cover and the distillate output produced by the proposed setup is recorded at 1 hour interval from morning 7AM to evening 7AM. The experimental reading is compared with the theoretical reading which is obtained by using Eqs. 14, 19 and 20. The various design parameters used for computations has been given in table 1. The recorded initial temperature of basin water and glass cover was 31.2ºC and 28.1ºC, respectively. The wind velocity during experiment was between 2m/s to 3m/s for computations we considered the average value as 2.5m/s.

Figure 2 Photograph of experimental setup

Table 4.1 Various parameters used for computations

$A_p=A_g=1m^2$	$\alpha_g=\alpha_w=0.05$	$\alpha_p=0.90$
$h_p=200$	$\varepsilon_w=0.9$	$\varepsilon_g=0.9$
$\varepsilon_{eff}=0.82$	$h_b=10$	$\tau_w=\tau_g=0.95$
M_w=10kg	Cw=4190	$\sigma=5.66x10^{-8}$
K_p=45W/mk	y_p=0.003m	m_s=15kg, 30kg, 45kg
c_s=800J/kgK		

To validate mathematical model the experimental values of water temperature, glass cover temperature and the hourly yield of distillate output produced by the solar still with sand has been compared with the theoretical values computed by using the mathematical model given above. The hourly averages of ambient temperature and solar radiation during the experiment is given in Fig.3. The mass of water in basin is taken as 10Kg and the mass of sand storage is taken as 15Kg (1cm depth). The experimental theoretical temp of basin water, has been determined and shown in figures 3,4,5,7,8. It is seen that the experimental readings are close to the theoretical reading.

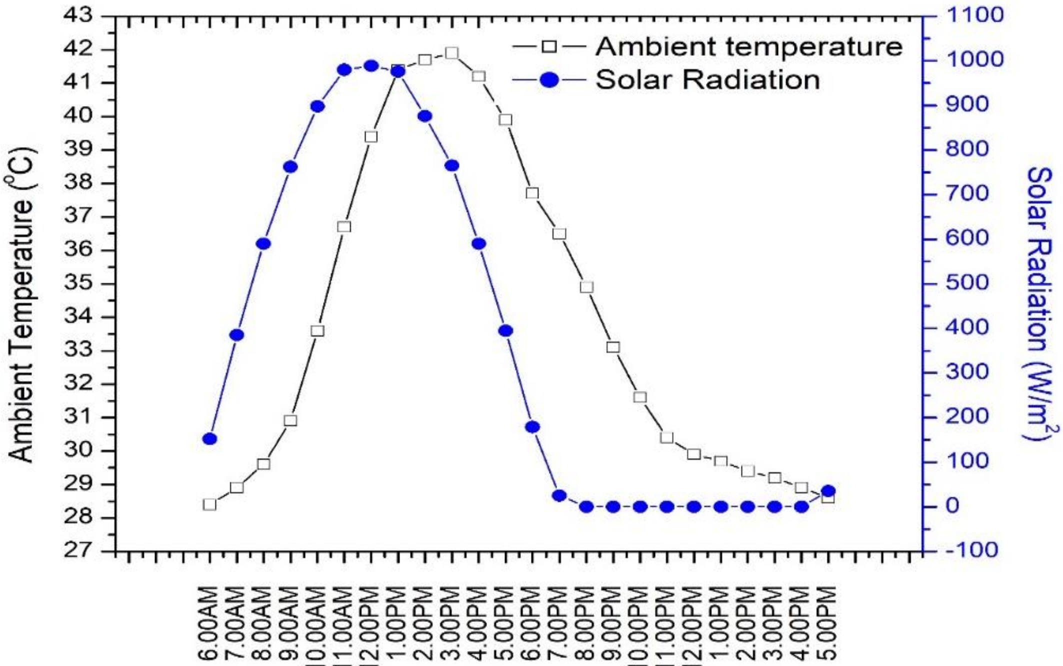

Figure 3 Ambient temperature and solar radiation during experiment

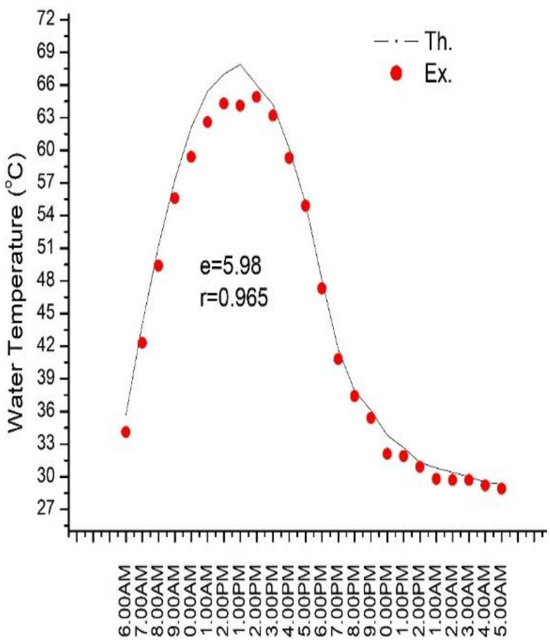

Figure 4 Experimental and theoretical water temperature

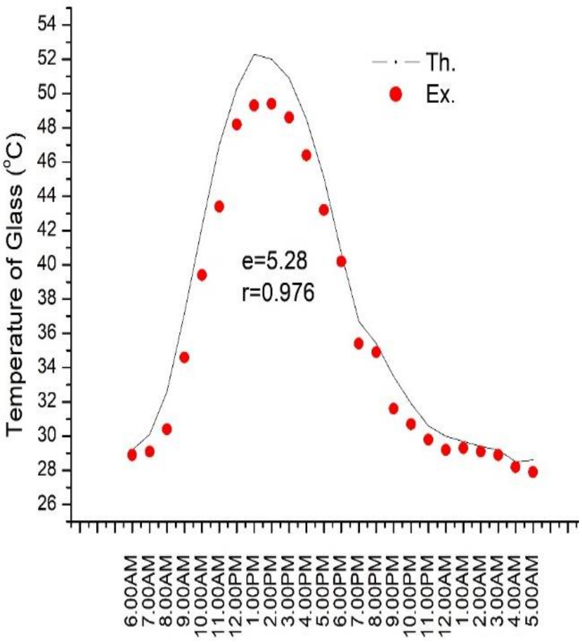

Figure 5 Experimental and theoretical glass cover temperature

---

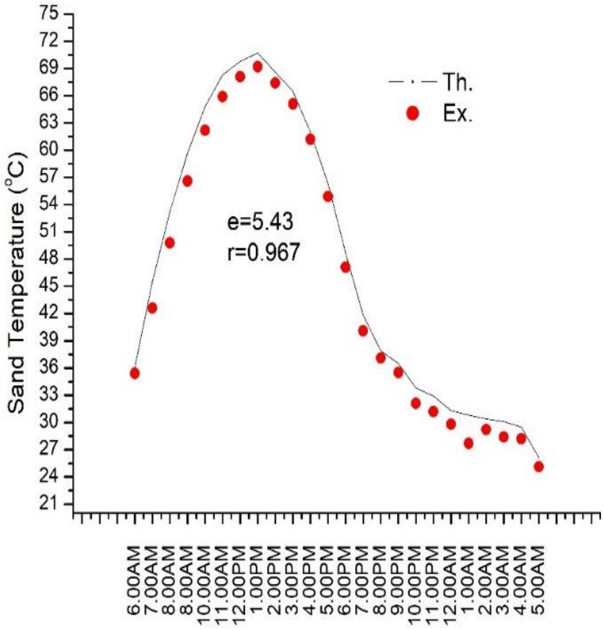

Figure .6 Experimental and theoretical sand temperature

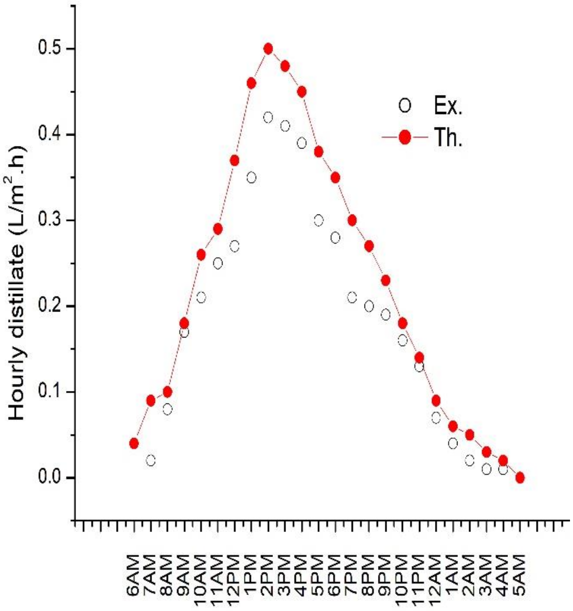

Figure 7 Experimental and theoretical distillate output

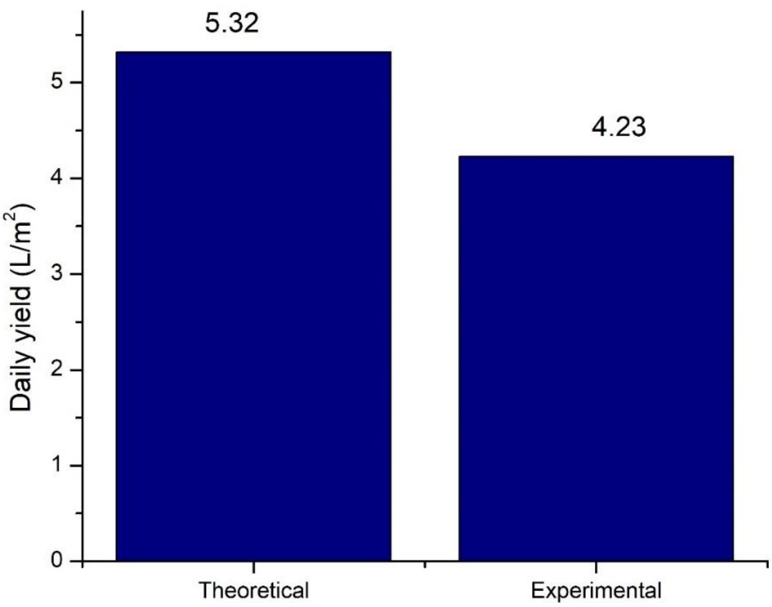

Figure. 8 Experimental and theoretical daily distillate output

6. Numerical computations

6.1 Effect of increasing depth (mass) of sand

Numerical computations have been performed to analyse the effect of changing depth of sand bed (mass of sand beneath basin plate). Daily distillate output of the proposed solar still has been computed for a summer day by varying the mass of sand viz. 15kg (1cm depth), 30kg (2cm depth), 45kg (3cm depth) and 60kg (4cm depth). Various parameters for computations are same as mentioned in Table 1. The daily distillate output produced at various depths of sand has been computed and shown in Fig.9. It is seen that the output decreases with increase in sand depth. When the depth of sand increased from 1cm to 4cm the decrease in the output is about 13.53%. The reason is due to increase in the thermal capacity with increase in mass of sand as higher depth the temperature rise is less in comparison to sand at lower depth. However, the nocturnal production of distillate is higher depth due to more heat energy stored at higher death but the overall production of water decreases at higher depth of sand.

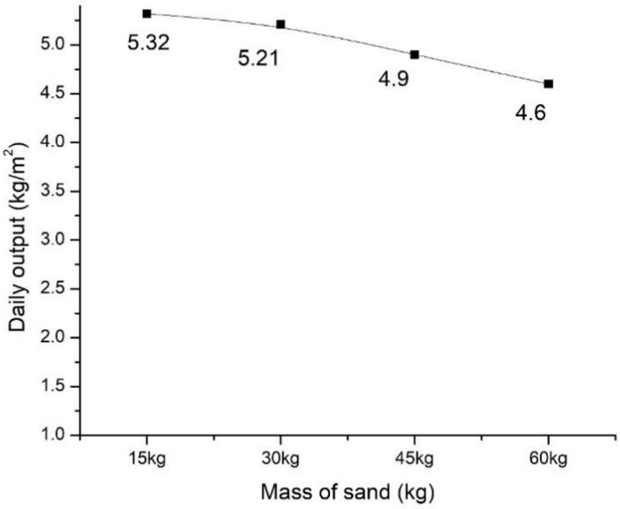

Figure 9 Effect of increasing depth (mass) of sand

6.2 Comparing the proposes solar still with sand with the conventional solar still without sand

To compare the performance of the proposed solar still with sand with the conventional single basin solar still without sand numerical computation has been performed. The daily distillate of both stills with sand and without sand has been computed for a summer day in the climate of Raipur, Chhattisgarh, India. It is seen that the proposed still performs better in comparison to the conventional solar still (Fig.10). The daily distillate output produced by the proposed still is 5.32l/m^2 and the daily distillate output produced by conventional still is 4.02l/m^2 (Fig.11). The daily distillate output produced by proposed still is 24.43% more than the conventional still without sand.

6.3 Nocturnal production of water

As sensible storage (sand) placed beneath basin plate it is expected that the output during no-sunshine hours must enhance. As the sand stores heat during sunshine hours the sane heat is released during no sunshine hours. The same is reflected in Figs. 10 and 12. The proposed still performs better during night time however during day time the conventional still performs good. The total nocturnal production of water from the proposed still is 1.37L/m^2 for the conventional still the nocturnal production of water is negligible.

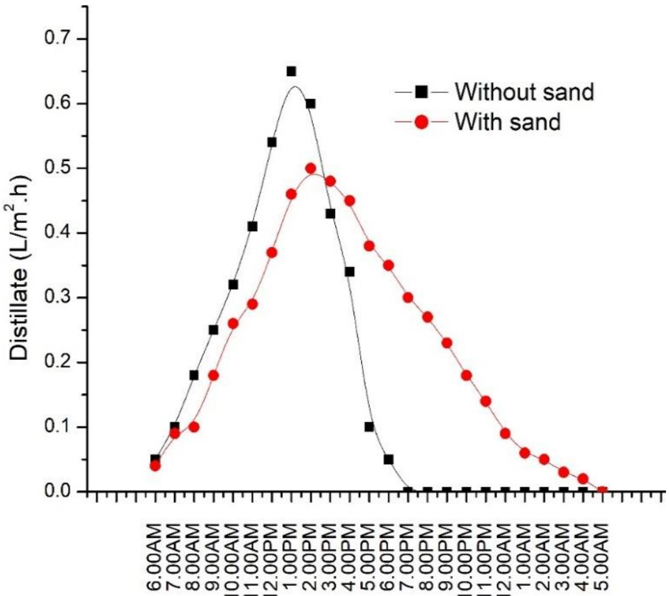

Figure. 10 Comparison of proposed still with conventional still

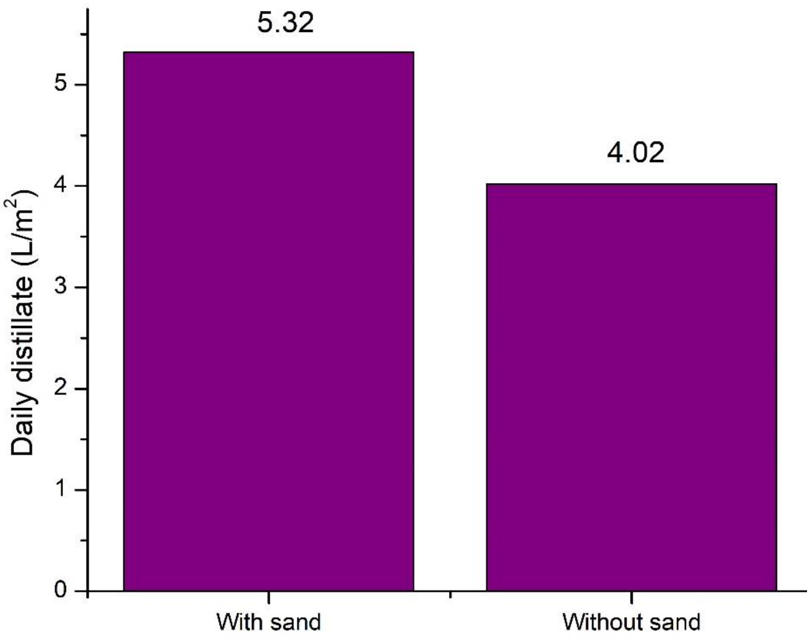

Figure. 11 Daily distillate output produced by proposed still and conventional still

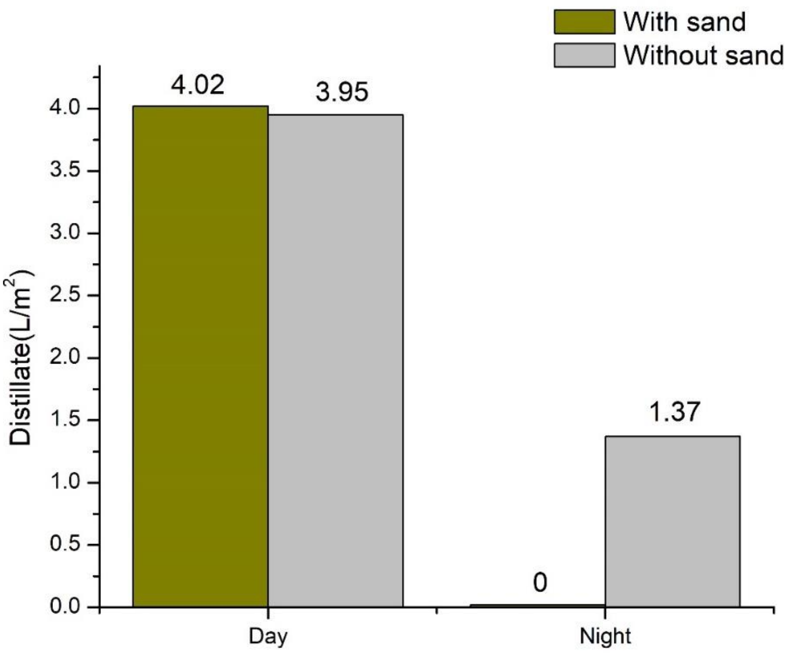

Figure 12 The production of distillate day and night time

7. Conclusions

The use of sand beneath basin plate helps to enhance the nocturnal production of pure water. Moreover, it helps to increase the overall production of pure water from solar still. In this work authors proposed single basin solar still (SBSS) with sensible storage material (sand). The conclusion drawn from the study are as follows:

1. The proposed mathematical model will help to determine the thermals performance of solar still with sensible storage material.

2. With increase in depth of sand (mass of sand) beneath basin plate the overall daily distillate output decreases. The depth of sand increases from 1cm to 4cm the decrease in daily distillate output is 13.5%.

3. For a summer day in Raipur the daily distillate output from the proposed still with sand is 5.32l/m^2 which is about 24.4% more than the conventional single basin solar still.

4. The nocturnal production of water from the proposed still is 1.37l/m^2, and from the conventional still the nocturnal production of water is negligible.

References

1. M.A. Samee, U.K. Mirza, T. Majeed, N. Ahmed, Design and performance of a simple single basin solar still, Renew. Sustain. Energy. Rev. 11 (2007) 543–549.
2. H.S. Aybar, F. Egelioglu, U. Atikol, An experimental study on an inclined solar water distillation system, Desalination 180 (2005) 285–289.
3. I. Al-Hayek, O.O. Badran, the effect of using different designs of solar stills on water distillation, Desalination 169 (2004) 121–127.
4. K. Murase, H. Tobata, M. Ishikawa, S. Toyama, Experimental and numerical analysis of a tube-type network solar still for desert technology, Desalination 190 (2006) 137–146.
5. S.B. Sadineni, R.Hurt, C.K.Halford, R.F. Boehm, Theory and experimental investigation of a wire-type inclined solar still, Energy 33 (2008) 71–80.
6. A.N. Minasian, A.A. Al-Karaghouli, An improved solar still: the wick-basin type, Energy Convers. Manag. 36 (1995) 213–217.

7. P. Namprakai, J. Hirunlabh, Theoretical and experimental studies of an ethanol basin solar still, Energy 32 (2007) 2376–2384.
8. Tanaka Hiroshi, Nakatake Yasuhito, Effect of inclination of external flat plate reflector of basin type still in winter, Sol. Energy 81 (2007) 1035–1042.
9. G.N. Tiwari, A. Kupfermann, S. Aggarwal, A new design of a double-condensing chamber solar still, Desalination 114 (1997) 153–164.
10. A. Yousif, F. Ahmed, Theoretical and experimental investigation of a novel multistage evacuated solar still, J. Sol. Energy. Eng. 127 (2005) 381–385.
11. A. Safwat, M. Abdelkader, A. Abdelmotalip, A.A. Mabrouk, Parameters affecting solar still productivity, Energy Convers. Manag. 41 (2000) 1791–1809.
12. A.A. El-Sebaii, Effect of wind speed on active and passive solar stills, Energy Convers. Manag. 45 (2004) 1187–1204.
13. S. Aboul-Enein, A.A. El-Sebaii, E. El-Bialy, Investigation of a single-basin solar still with deep basins, Renew. Energy 14 (1998) 299–305.
14. A.A. El-Sebaii, S. Aboul-Enein, M.R.I. Ramadan, E. El-Bialy, Single basin solar still with baffle suspended absorber, Energy Convers. Manag. 41 (2000) 661–675.
15. A.A. El-Sebaii, S. Aboul-Enein, M.R.I. Ramadan, E. El-Bialy, Year-round performance of a modified single-basin solar still with mica plate as a suspended absorber, Energy 25 (2000) 35–49.
16. G.N. Tiwari, S.K. Shukla, I.P. Singh, Computer modeling of passive/active solar stills by using inner glass temperature, Desalination 154 (2003) 171–185.
17. S.N. Rai, G.N. Tiwari, Single basin solar still coupled with flat plate collector, Energy Convers. Manag. 23 (1983) 145–149.
18. A.A. Badran, A.A. Al-hallaq, I.A. Eyal Salman, M.Z. Odat, A solar still augmented with a flat-plate collector, Desalination 172 (2005) 227–234.
19. A.A El-Sebaii, M.R.I. Ramadan, S. Aboul-Enein, N. Salem. Thermal performance of a single basin solar still integrated with a shallow solar pond. Energy Convers. Manag., (Accepted for publication).
20. V. Velmurugan, K. Srithar, Solar still integrated with a mini solar pond—analytical simulation and experimental validation, Desalination 216 (2007) 232–241.
21. Z.S. Abdel-Rehim, A. Lasheen, Experimental and theoretical study of a solar desalination system located in Cairo, Egypt, Desalination 217 (2007) 52–64.
22. H.E.S. Fath, Solar thermal energy storage technologies: technical note, Renew. Energy 14 (1998) 35–40.
23. A.M. Radhwan, Transient performance of a steeped solar still with built-in latent heat thermal energy storage, Desalination 171 (2004) 61–71.
24. N.M. Naim, M.A. Abd El Kawi, Non-conventional solar stills part 2, non-conventional solar stills with energy storage element, Desalination 153 (2002) 71–80.
25. A.S. Nafey, M. Abdelkader, A. Abdelmotalip, A.A. Mabrouk, Solar still productivity enhancement, Energy Convers. Manag. 42 (2001) 1401–1408.
26. V. Velmurugan, C.K. Deenadayalan, H. Vinod, K. Srithar, Desalination of effluent using fin type solar still, Energy 33 (2008) 1719–1727.
27. R.V. Dunkle, International development in heat transfer, ASME Proceedings. Inter. Heat Transfer, Part V, University of Colorado, 1961, p. 895.
28. H.Y. Wong, Handbook of Essential Formula and Data on Heat Transfer for Engineers, Longman, London, 1977.
29. V.B. Sharma, S.C. Mullick, Estimation of heat transfer coefficients, the upward heat flow and evaporation in solar still, Sol. Energy Eng. 113 (1991) 36–41.
30. J.A. Duffie, W.A. Beckman, Solar Engineering of Thermal Processes, Wiley, New York, 1991.