Thermal Performance of an Inverted Absorber Sand Bed Solar Still (IASBSS)

Ramendra Yadav*‡, Aneesh Somwanshi**, Raginee Pandey***

* Dep. of Mech Engg, MATS University Raipur CG, India

** Dep. of Physics, Government D.B. Girls PG College, Raipur, Chhattisgarh, India

(ramendra3883@gmail.com, aneeshsomwanshi@rediffmail.com, drraginee67@gmail.com)

‡ Corresponding Author- Ramendra Yadav, MATS University Raipur Chhattisgarh, India

ramendra3883@gmail.com, +919131112806

Received: 07.02.2024 Accepted: 14.03.2024

Abstract- Desalination holds promise as a sustainable solution to address the increasing need for water amidst the shortage of fresh water resources. But the high energy cost of traditional desalination techniques emphasizes the need to switch to more environmentally friendly technologies, particularly solar energy and other renewable sources. In this study, the authors proposed an inverted absorber sand bed solar still (IASBSS) layer of sand placed beneath basin water in an inverted absorber solar still (IASS). By using sand as a sensible storage material, the overall productivity of the conventional IASS increases. The developed mathematical model of the proposed IASBSS has been experimentally validated. For a day in Raipur, CG, India (21.251° N, 81.629° E). The daily performance of the proposed IASBSS is 14.9% higher than conventional IASS. The depth of water above the sand directly influences the amount of distillate produced by the still. When the depth of water increased from 1cm to 3 cm, the daily distillate output produced by the proposed method still decreased by 49%. The use of sand in IASS is found to be an economical option to improve the production output from solar still.

Keywords Inverted absorber sand bed solar still (IASBSS), sensible storage material, sand, distillate output.

1. Introduction

Despite water covering about three-quarters of the planet's surface, only a small fraction of the world's waterways is suitable for drinking. The water deficit crisis stands out as a major challenge confronting human society today due to heightened demand, irresponsible usage, and the impact of global warming, which is exerting pressure on numerous freshwater resources worldwide. Desalinating brackish or seawater is one of the sustainable ways to solve this issue. Desalination provides an additional and potentially sustainable source of freshwater.

Among the various desalination techniques available till date, the solar desalination system is found to be economical and climate friendly. Despite many advantages, the main problem with solar distillation systems is their low water producing capacity, which restricts the usage of solar distillation systems on a large scale. Ongoing research and development aim to advance the performance and affordability of solar desalination methods for broader and more effective implementation.

A solar still is a simple device employed for the solar desalination of water. Its simplicity makes it well-suited for areas with limited access to electricity or advanced infrastructure. These devices are commonly utilized in arid regions where obtaining clean water presents a substantial challenge. Although solar stills prove effective in purifying water, it's worth noting that they may have relatively lower production rates compared to other water purification methods. There are different designs and variations of solar stills, including the basin-type still, multiple-effect stills, and the aforementioned inverted absorber solar still. The choice of design depends on factors such as local climate, available materials, and the specific requirements of the water purification project. Temperature of basin water is an important factor which regulates the total distillate output produced by solar still the more temperature of basin water enhances the rate of water evaporation hence helps to increase the amount of distillate produced by solar still (SS Researchers have previously investigated a number of active and passive techniques to raise the basin water's temperature. Examples of active approaches include the utilization of external heat sources like flat plate collectors (FPC) or concentrative procedure such as parabolic dishes [1-3]. Additionally, employing reflectors has been identified as a passive method to augment basin water temperature in solar stills [4]. In a study by Sinha and Tiwari [5], a concentrator-assisted solar distillation system was introduced, highlighting that passive distillation systems exhibit higher efficiency compared to active systems. Moreover, it was observed that concentrator-assisted stills outperform collector-assisted stills in terms of efficiency [6].

The Inverted Absorber Solar Still (IASS) represents an enhanced solar still design, combining elements from both a single slope solar still and a curved reflector positioned beneath its basin. In this innovative system, water is heated from both the top and bottom, leading to a more substantial increase in water temperature compared to a traditional single slope solar still. Consequently, this elevation in temperature contributes to a higher distillate output compared to conventional designs. Previous research on the Inverted Absorber Solar Still has been documented by Tiwari and Suneja [7-9]. They presented a thermal model of IASS having single, double, or multiple basins. They found the optimum water depth of 10cm with water flow over cover. Yadav and Yadav conducted a series of studies (references [10-12]) on a solar distillation system utilizing a compound parabolic reflector to assist the inverted absorber with an asymmetric line axis (CPC-IASS). Their investigation delved into the impact of factors such as water quantity, absorptivity, and concentration ratio on the system's output. Their findings revealed that reduced solar radiation resulted in lower temperatures for both the reflector and aperture cover. Additionally, an increase in the concentration ratio from 1 to 3 correlated with higher water temperatures and increased yield. In a related study, Dev et al. [13] explored an Inverted Absorber Solar Still (IASS) under varying water depths and total dissolved solid (TDS) conditions. In the specific climate of Muscat, they observed daily yields of 6.302, 5.576, and 4.299 kg/m^2-day at water depths of 0.01, 0.02, and 0.03 meters, respectively.

Using sensible storage material in solar still is one of the methods to enhance the production output of SS. Sensible storage material helps to store solar energy thus helps to increase the temperature of basin water. Among various sensible storage materials, the use of sand can be little inexpensive since sand is abundant and available in large scale. Sand can improve the basin's ability to absorb and store solar heat. This technique can be used as an easy, affordable way to enhance the solar distillation process. Previously the use of sand as thermal storage material has been employed in single slope passive and active solar stills. Sand was used by Omara and Kabeel [14] as a suitable storage material in SSSS. They looked at how the performance of the solar still was influenced by the height of the sand bed, the kind of sand (black, yellow), and the level of water above the sand. They discovered that a sand bed height of 0.01 meters and a water level of zero inches above the sand bed produced the most production. El- Sebaii et al. [15] investigate the performance of an active S B solar still with a sagacious storage medium (sand). Unlike [14] they suggested to use thin layer of sand beneath the basin liner of solar still. They concluded that the use of sand helps to enhance the nocturnal production of distilled water. They found that using 10 kg of sand, on a summer day, a value of daily productivity of 4.005 (kg/m^{2}day) with a daily efficiency of 37.8% was obtained; when the still is utilized without storage, the value drops to 2.852 (kg/m^{2}day) with a daily efficiency of 27%. When the still is operated with storage, its yearly average of daily productivity is determined to be 23.8% higher than when it is not.

In the present work, the authors proposed inverted absorber sand bed solar still [IASBSS], unlike previous research where sand was used as storage material in a separate compartment in indirect contact with basin water [14]. Here, the authors propose using sand as thermal storage material within the basin of SS beneath water inside the solar still. The use of sand as storage material will help to increase the overall production of water, thereby increasing the overall effectiveness of IASS. The mathematical model of the proposed IASS with sand has been developed and validated for Raipur, Chhattisgarh, India. The effect of parameters like the height of water above sand has been numerically computed in this work. Additionally, the authors performed an economic analysis to determine the cost of water produced by the proposed IASS with sand. The performance of the proposed IASS with sand has been compared with that of the IASS without sand.

2. Mathematical Analysis

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

(I) Compared to the heat capacities of the basin water and storage material, the heat capacities of the glass cover, insulating material, and basin liner are neglected;

(i) The side losses are negligible

(ii) Basin plate area and area of glass covers are same.

(iii) Area of aperture is equal to area of the absorber plates (P1 &P2) the concentration ratio is 1:1

(iv) Quasi steady state operation has been considered.

Energy balance equations for various components of still are as follows:

2.1 IASS with Sand

Glass cover (g_1)

$$\alpha_g A_{g1} I + h_i A_w (T_w - T_{g1}) = h_o A_{g1} (T_{g1} - T_a) \quad (1)$$

In Eq.1, $h_i = h_r + h_c + h_e$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 [6],

$$h_c = 0.884[(T_w - T_{g1}) + \frac{(P_w - P_{g1})(T_w + 273)}{268.9\times10^3 - P_w}]^{1/3} \quad (2)$$

Saturated vapor pressure is given by,

$$P = exp[25.317 - \frac{5144}{T+273}] \quad (3)$$

$$h_r = \varepsilon_{eff}\sigma[(T_w + 273)^2 + (T_{g1} + 273)^2](T_w + T_{g1} + 546) \quad (4)$$

$$h_e = 16.273 \times 10^{-3} h_c \frac{(P_w - P_{g1})}{(T_w - T_{g1})} \quad (5)$$

$h_o = h_{co} + h_{ro}$ 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 [6],

$$h_{co} = 2.8 + 3v_a \quad (6)$$

$$h_{ro} = \varepsilon_g \alpha \frac{[(T_{g1}+273)^4 - (T_a+267)^4]}{(T_{g1} - T_a)} \quad (7)$$

From Eq.1 temperature of glass cover g_1 will be given by,

$$T_{g1} = K_1 + K_2 T_w \quad (8)$$

Bottom plate (Basin liner)

$$\tau_{g2} r^N \alpha_p A_p I = h_s A_p (T_p - T_s) + h_b A_p (T_p - T_a) \quad (9)$$

In Eq.9 h_s and h_b are the convective heat transfer coefficient between sand and plate and plate and ambient

From Eq. 9 the temperature of plate will be given by,

$$T_p = K_3 + K_4 T_s \quad (10)$$

Storage Material

$$m_s c_s \frac{dT_s}{dt} = \tau_{g1}\tau_w \alpha_s A_s I + h_s A_p (T_p - T_s) - h_w A_s (T_s - T_w) \quad (11)$$

From Eq. 11 the temperature of storage material (sand) will be given by,

$$T_s = K_8 T_w + K_9 \quad (12)$$

Basin water

$$m_w c_w \frac{dT_w}{dt} = \tau_{g1}\alpha_w A_w I - h_s A_s (T_w - T_s) - h_i A_w (T_w - T_{g1}) \quad (13)$$

From Eqs. 8, 10, 12 and 13 we have

$$\frac{dT_w}{dt} + PT_w = Q \quad (14)$$

From Eq.14, the temperature of basin water after time "t" will be given by

$$T_{wt} = \frac{Q}{P}\{1 - exp(-Pt)\} + T_{w0}\, exp(-Pt) \quad (15)$$

In Eq. 15 T_{w0} is the initial temperature of basin water at time t=0

The average basin water temperature at time t will be given by,

$$\bar{T}_{wt} = \frac{1}{t}\int_0^t T_{wt}\, dt \quad (16)$$

From Eqs. 14 and 15, The average basin water temperature will be given by,

$$\bar{T}_{wt} = \frac{Q}{P}[1 - \frac{\{1-exp(-Pt)\}}{Pt}] + T_{w0}\frac{\{1-exp(-Pt)\}}{Pt} \quad (17)$$

From Eqs. 8,10, 12 & 17 the temperature of glass cover, sand and temperature of basin water can be determined. The hourly distillate output produced will be given by,

$$M_w = \frac{h_e A_w (\bar{T}_{wt} - T_g)}{L} \times 3600 Kg/m^2h \quad (18)$$

3. Description of the proposed design of IASS

The proposed design of IASS is a combination of an SSSS and a curved reflector with a radius of curvature of 1m attached under the basin of the SSSS. The SSSS is made of GI sheet of thickness 1.5mm. Above the basin of solar still sand bed (painted black by spray paint) of known thickness has been placed and filled with water at the required height. The proposed design is shown in Fig. 1. The basin area of SSSS is taken as 1m^2 and the glass cover at the top of SSSS has a thickness of 1.5mm. The sides of SSSS have been insulated by Styrofoam insulation material of thickness 1.5cm. The water in the basin of solar still receives solar radiation from the top as well as bottom through a reflector and sand helps to store the heat during sunshine hours.

Fig.1. Photograph of the proposed IASS with sand.

4. Experimental Validation of the Proposed Model

Various parameters used for determining theoretical yield from IASS has been given in Table 1. The schematic of the proposed IASS with sand has been given in Fig.2. Experiment was performed in Raipur, Chhattisgarh, India (21.251° N, 81.629° E). Experiment was performed in a summer day (18/03/2023). Before starting experiment initial water temperature, temperature of glass covers and the temperature of sand (basin) has been recorded. Hourly water temperature,

temperature of glass cover and temperature of basin (sand) has been recorded by using RTD sensor placed at different points. Theoretical water temperature of glass cover and sand temperature has been computed by solving Eq. 1-10 by using MATLAB software. To validate the proposed model the theoretical and experimental readings have been compared and to determine the closeness of the theoretical and experimental readings, the correlation of coefficient "r" and root mean square of percentage deviation "e" has been determined

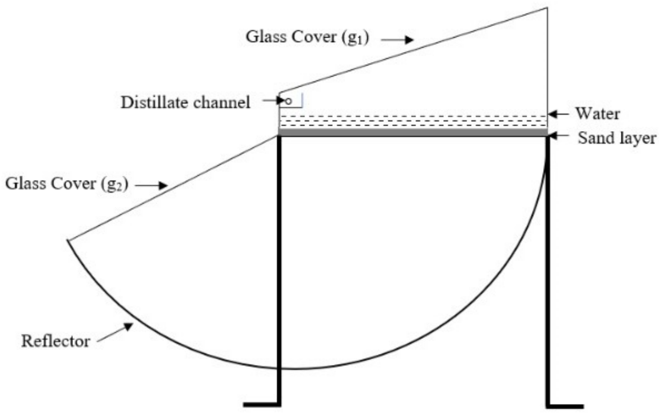

Fig. 2. Schematic view of the proposed IASS with sand.

Table 1. Various parameters for computation

$m_s = 10kg$	$m_w = 10kg, 20kg, 30kg$	$\tau_g = 0.95$	$\tau_w = 0.95$
$\alpha_g = 0.05$	$\alpha_w = 0.05$	$\varepsilon_{eff} = 0.90$	$r = 0.9$
$\alpha_{b/s} = 0.90$	$\varepsilon_g = 0.88$	$c_s = 1640J/kgK$	$h_b = 9$
$N = 2.5$	$c_w = 4200J/kgK$	$\sigma = 5.67x10^{-8}W/m^2K^4$	$A_{g1} = A_{g2} = A_s = 1$

5. Experimental Determination of Specific Heat Capacity of Saturated Sand

When sand is saturated with water the overall specific heat capacity of the mixture (sand & water) will be given by,

$$c_s(mixture) = \frac{m_s c_{ds} + m_w c_w}{m_s + m_w}$$

In above equation, $m_s$and $m_w$are the mass of sand and mass of water in mixture and c_{ds} (700 J/kg °C)and c_w (4180J/kg °C) are the specific heat capacities of dry sand and water. The mass of sand and water in mixture depends on the porosity of the given sample of sand. The sample of sand is dried in oven and the porosity has been determined experimentally in the laboratory. It is seen that the specific heat capacity of saturated sand (73% sand and 37% water) is 1640J/kg K.

Hourly ambient temperature and solar radiation during experiment for a summer day is shown in Fig. 3. The temperature of water and glass cover has been experimentally recorded and numerically computed by the proposed model. It is seen that the experimental and theoretical readings are close to each other. The maximum water temperature reached is 76.1ºC at 12.00 in afternoon. Maximum temperature of glass cover is 60.6ºC at 12.00noon. The hourly experimental and theoretical temperature of water and cover is shown in Fig. 4a & Fig 4b. The maximum theoretical temperature of sand is 81.3ºC at 12.00 noon. Fig 5 & Fig 6 has shown the experimental and theoretical temperature of sand bed & experimental and theoretical distillate output.

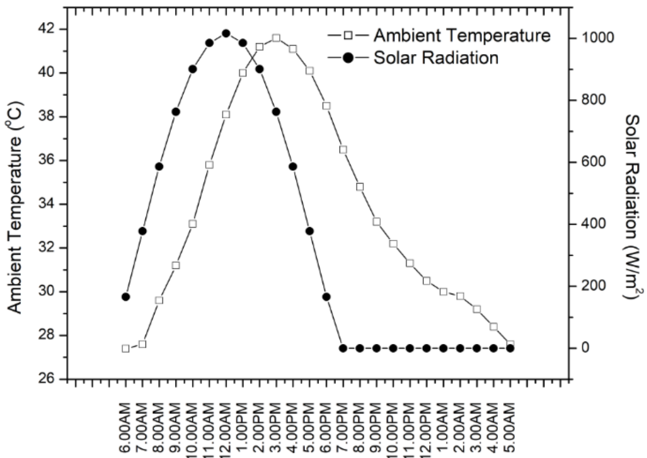

Fig. 3. Ambient temperature and solar radiation during experiment.

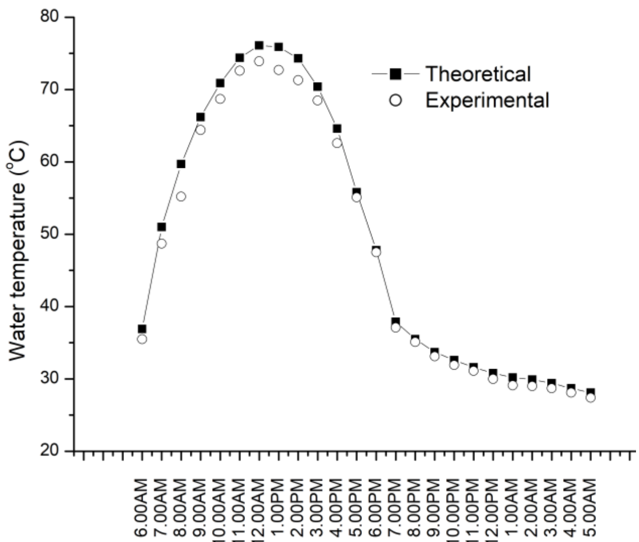

Fig. 4a. Experimental and theoretical water temperature.

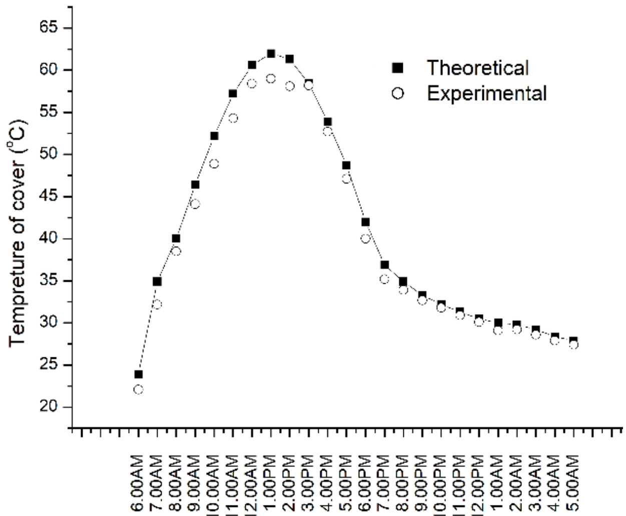

Fig. 4b. Experimental and theoretical cover temperature.

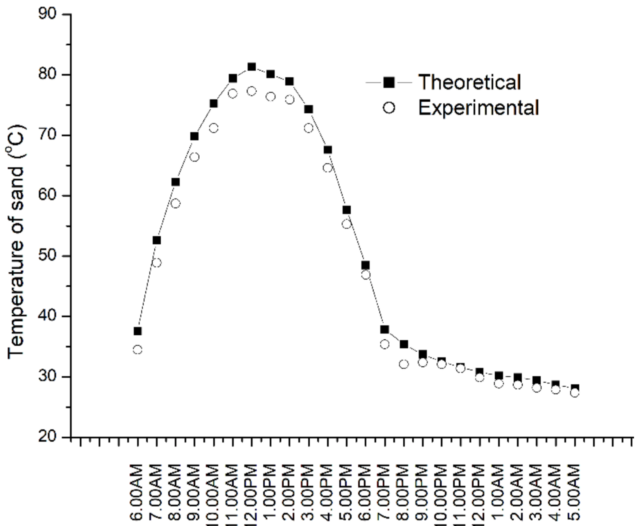

Fig. 5. Experimental and theoretical temperature of sand bed.

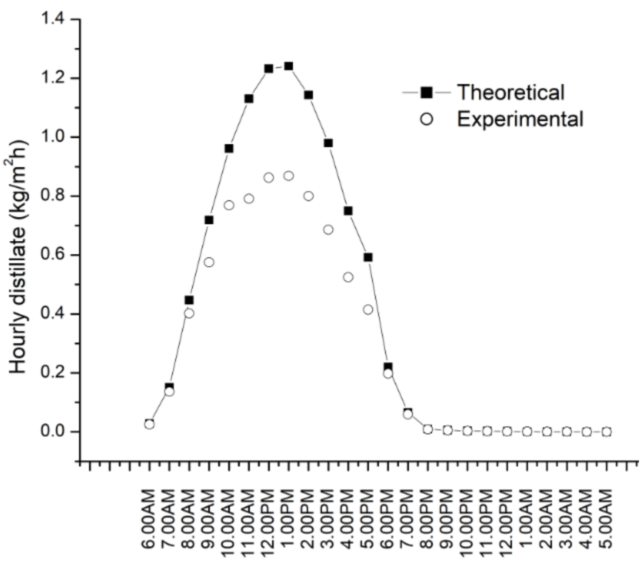

Fig. 6. Experimental and theoretical distillate output.

6. Numerical Computations

To analyse the effect of water depth on the output produced by the proposed sand bed solar still, numerical computations have been performed at different water depths, i.e., 1 cm, 2 cm, and 3 cm. The depth of sand (the mass of sand) has been kept constant. Hourly distillate output has been computed for a day (18/3/23) considering the weather conditions given in Fig. 3. The result is as expected: with an increase in water depth, the daily and hourly distillate output decreases (Fig. 7a & Fig. 7b).

When the depth of water increses from 1 cm to 2 cm the decreese in daily distillate output is 33.3% with futher decrease in depth of water from 2 cm to 3 cm the output decresee by 24.1%. With increase in water depth the thermal capacity incersees the heating of water is less at higher heat capacity of water therby the daily and hourly output deceseses.

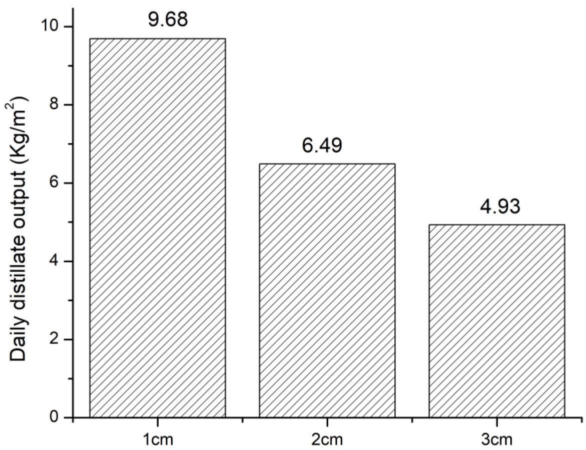

Fig.7a. The daily distillate output of IASBSS at different water depth.

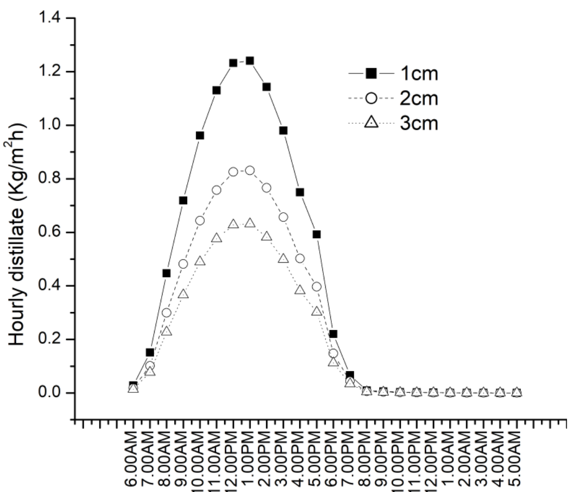

Fig.7b. The hourly distillate output of IASBSS at different water depth.

7. Comparison of Proposed IASBSS with IASS without Sand

Numerical computations have been perormed to comapre the proposed IASBSS with inverted absorber solar still without sand. The hourly yield for a day has been computed considering 1cm water depth for convetional IASS and proposed sand bed solar still. Various numerical parameters for computations are considerd same as given in Table-1. It is seen from Fig. 8 that the output produced by the proposed still with sand is more than the output produced by inverted absorber solar still without sand. For a day in the climate of Raipur, Chhatisgarh the daily distillate output produced by the proposed IASBSS is 14.87% more than the daily output produced by IASS.

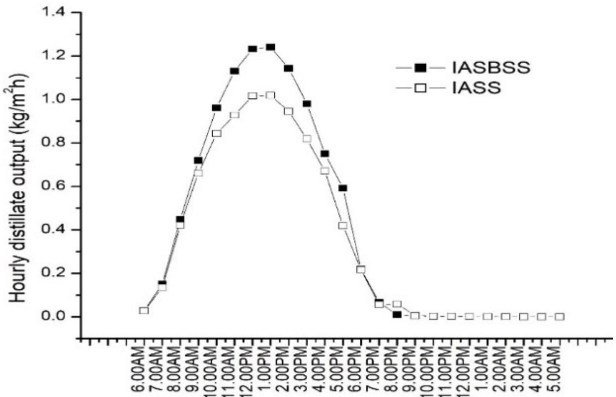

Fig 8. Hourly distillate output from IASBSS and IASS.

8. Conclusions

In this work, the authors proposed an inverted absorber sand bed solar still (IASBSS). The layer of sand placed below water in the basin of the inverted absorber solar still. The use of sand as a sensible storage material helps to enhance the overall productivity of conventional inverted absorber solar still. The mathematical model of IASBSS has been created and experimentally validated. It is seen that the overall daily productivity of the proposed IASBSS is 14.9% higher than that of the conventional IASS. Moreover, the depth of water above the sand affects the performance of the proposed still. At higher water depths, the output from still decreases. When the depth of water in the basin is increased from 1cm to 3 cm, the decrease in the daily output of the proposed solar still is 49%.Sand in a basin appears to be a simple and affordable way to raise IASS performance. To address the potable water requirement in a semi-arid environment, the suggested IASBSS can be utilized.

Acknowledgements

Authors sincerely thank Department of Mechanical Engg., MATS university Raipur CG India for the support in conducting experiments and completion of this study.

Author Contributions

Ramendra Yadav was responsible for the conceptualization, planning the experiment, research methodology, and data analysis Aneesh Somwanshi and Raginee Pandey. jointly contributed to the methodology, data collection, investigation, original draft preparation, review and editing. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest

The author(s) hereby declare that there are no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

References

[1] A. Badran, A. Ahmad, E. S. Imad, and O. Mohammad, “A solar still augmented with a flat plate collector,” Desalination, vol. 172, pp. 227–234, 2005.

[2] S. N. Rai and G. N. Tiwari, “Single basin solar still coupled with flat plate collector,” Energy Conversion and Management, vol. 23, pp. 145–149, 1983.

[3] G. N. Tiwari and A. K. Tiwari, Solar Distillation Practice for Water Desalination, 1st ed., New Delhi: Anamaya Publishers, 2008.

[4] Z. M. Omara, A. E. Kabeel, and A. S. Abdullah, “A review of solar still performance with reflectors,” Renewable and Sustainable Energy Reviews, vol. 68, pp. 638–649, 2017.

[5] S. Sinha and G. N. Tiwari, “Thermal evaluation of concentrator-assisted solar distillation system,” Heat Recovery Systems and CHP, vol. 12, pp. 483–488, 1992.

[6] G. N. Tiwari, Solar Energy Fundamentals, Design Modelling and Applications, New Delhi: Narosa Publishing House, 2002.

[7] S. Suneja and G. N. Tiwari, “Effect of water depth on the performance of an inverted absorber double basin solar still,” Energy Conversion and Management, vol. 40, no. 7, pp. 1885–1897, 1999.

[8] S. Suneja and G. N. Tiwari, “Optimization of number of effects for higher yield from an inverted absorber solar still using the Runge-Kutta method,” Desalination, vol. 120, no. 3, pp. 197–209, 1998.

[9] G. N. Tiwari and S. Suneja, “Performance evaluation of an inverted absorber solar still,” Energy Conversion and Management, vol. 39, no. 3, pp. 173–180, 1998.

[10] Y. P. Yadav and S. K. Yadav, “Parametric studies on the transient performance of a high-temperature solar distillation system,” Desalination, vol. 170, no. 3, pp. 251–262, 2004.

[11] Y. P. Yadav and B. P. Yadav, “Transient analytical solution of a solar still integrated with a tubular solar energy collector,” Energy Conversion and Management, vol. 39, no. 9, pp. 927–930, 1998.

[12] Y. P. Yadav, A. K. Yadav, N. Anwar, P. C. Eames, and B. Norton, “An asymmetric line-axis compound parabolic concentrating single basin solar still,” Renewable Energy, vol. 9, no. 1–4, pp. 737–740, 1996.

[13] R. Dev and G. N. Tiwari, “Characteristic equation of the inverted absorber solar still,” Desalination, vol. 269, no. 1–3, pp. 67–77, 2011.

[14] Z. M. Omara and A. E. Kabeel, “The performance of different sand beds solar stills,” International Journal of Green Energy, vol. 11, no. 3, pp. 240–254, 2014.

[15] A. A. El-Sebaii, S. J. Yaghmour, F. S. Al-Hazmi, F. S. Faidah, F. M. Al-Marzouki, and A. A. Al-Ghamdi, “Active single basin solar still with a sensible storage medium,” Desalination, vol. 249, no. 2, pp. 699–706, 2009.

Nomenclature

A_{g1}	Area of glass cover	m^2
A_w	Area of water surface	m^2
A_p	Area of basin plate	m^2
A_s	Area of sand	m^2
c_w	Specific heat of water	j / kgK
c_s	Specific heat of saturated sand	j / kgK
h_i	Total internal heat transfer coefficient between water and glass cover	$W / m^{2o}C$
h_o	Total outer heat transfer coefficient between glass cover and ambient	$W / m^{2o}C$
h_e	Evaporative heat transfer coefficient between water and glass cover	$W / m^{2o}C$
h_r	Radiative heat transfer coefficient between water and glass cover	$W / m^{2o}C$
h_c	Convective heat transfer coefficient between water and glass cover	$W / m^{2o}C$
h_{co}	Convective heat transfer coefficient between glass cover and ambient	$W / m^{2o}C$
h_{ro}	Radiative heat transfer coefficient between glass cover and ambient	$W / m^{2o}C$
h_b	Convective heat transfer coefficient between plate and ambient	$W / m^{2o}C$
I	Solar radiation	W / m^2
m_s	Mass of sand	kg
M_w	Hourly distillate output produced	$kg / m^2 h$
T_a	Ambient temperature	^oC
T_p	Plate temperature	^oC
T_s	Sand temperature	^oC
T_g	Temperature of glass	^oC
T_w	Temperature of basin water	^oC
T_{wt}	Basin water temperature at time t	^oC
r	Reflectivity of glass	
N	Number of reflections	
σ	Stefan Boltzmann constant	$W / m^2 K^4$
τ_g	Transmissivity of glass	
τ_w	Transmissivity of water	
α_g	Absorptivity of glass	
α_s	Absorptivity of sand	

Abbreviations

SSSS	Single slope solar still
IASS	Inverted absorber solar still
IASBSS	Inverted absorber sand bed solar still