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Research Article

Experimental and theoretical investigation of thermal efficiency and productivity of single slope basin type solar distillation system using honey-comb

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ABSTRACT

The aim of current research was to improve water quality by constructing a single slope basin type solar water distillation system with honeycomb, as well as to increase distilled water productivity. In this investigation, honeycomb structure of 2.25 cm and a diameter of 6 mm in a square section (100 cm ×100 cm) have been proposed to enhance the efficiency of the solar still. An experimental analysis was done to investigate the performance of the honeycomb structure. Thermal efficiency of the standard solar distillation system was obtained approximately 18.48%, while the thermal efficiency and productivity of the solar distillation system with honeycomb was obtained 25.45% and 749.58 ml/m^2 respectively. It was concluded that, the solar distillation system with honeycomb structure was more efficient that a simple conventional solar distillation system. The addition of honeycomb structure in simple solar desalination system increased the productivity and efficiency by 35.36% and 37.71% respectively.

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INTRODUCTION

Water is believed to be a basic ingredient of humanity, second only to oxygen. Approximately 1.2 billion people do not have access to safe drinking water, over 2.6 billion don't even have adequate sanitation, and 1.8 million children die every year avoidable water-borne infections. Fluoride contamination of water resources is another major issue caused by effluent from businesses such as glass, fertilizers, semiconductors, and metal processing. The most frequent and best technique for removing fluoride from water is a reverse osmosis (RO) filter system [1, 2]. Fluoride levels in water can be reduced by up to 92% with this method. Water travels through a semi permeable membrane, as well as an extra filter such as sealiment of filter media. Because it is

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This paper was recommended for publication in revised form by Regional Editor Jaap Hoffman Hoffman safe, cost-effective, and simple to maintain, RO is the most often utilized method [1]. The honeycomb has been used for water heating, air heating, and construction purposes. Honeycomb- panels are commercially adopted in Israel. Honeycomb's full potential has yet to be realised in nations such as India. Honeycomb can improve the efficiency of a solar cooker by absorbing solar energy efficiently throughout the day and maintaining heat until late afternoon and evening. Many methods have been devised, the most prevalent of which being precipitation, adsorption, and R O[2].

These procedures for water filtration are incredibly effective; however these processes are also quite expensive and out of reach for most people. Solar distillation is a simple process that does not require the use of any traditional energy sources. Solar still operates on the core premise of a miniature of the earth's hydrologic cycle. Water reserves cover 71% of the earth's surface, with 97.5% being saline water and 2.5% being fresh. Since these resources are brackish in nature. Also, it may contain hazardous microorganisms, Therefore it cannot be used directly [2, 3].

Renewable energy is a type of energy that can be used over and over again. Solar energy is the most readily available renewable resource on the planet's surface. The solar distillation method is based on a thermal energy technique that removes contaminants from water. Solar distillation is also one of the solar-powered technologies for obtaining potable water. Sun distilling is less expensive than other methods of distilling as RO system because it sun energy is available abundantly in nature. Solar distillation is a highly successful technology for purifying contaminated water in to potable water [3]. Ahmad and Ali [37] did a theoretical investigation to analyze the impact of the turning hollow cylinder. The turning hollow-cylinder within the solar still equipped with flat plate solar water collector on the output of distillate water and its thermal efficiency.

Solar still is one of the most cost-effective ways to produce pure water among solar distillation processes. Heat generated from sun radiations has been in use an input by solar. In comparison to a simple solar still, the suggested honey-comb solar still has a better efficiency. Solar radiation strikes the glass cover immediately, which the glass cover absorbs and converts into heat, and then used to evaporate water, which evaporate and condenses within the glass cover. The distilled water is gathered in a distilled jar. Water condenses at the glass cover du to the temperature difference between glass cover and flat plat, leaving all contaminants in the basin [3, 4]. There is a compelling need to improve the performance of the solar still and the yield of distilled water. The efficiency of solar stills can be improved by using a honeycomb structure basin to reduce reflectivity from waterways. The solar still's thermal efficiency is 19.11% compared to a solar still without a honeycomb construction [5]. Present work is associated with the production of potable water at minimum cost. Future scope of this work is to provide the fresh water to the house and industries.

Solar Desalination

Solar desalination is a closed-loop system where solar heat is utilised to evaporate the water. And the condensate is collected. This is the most basic method of treating brackish water. This is one of the most effective approaches for water filtration. It has been used to create water supply or water – for lead - acid, laboratory, hospital, and dealing production. The active and passive solar distillation systems are the two main types of solar distillation systems.

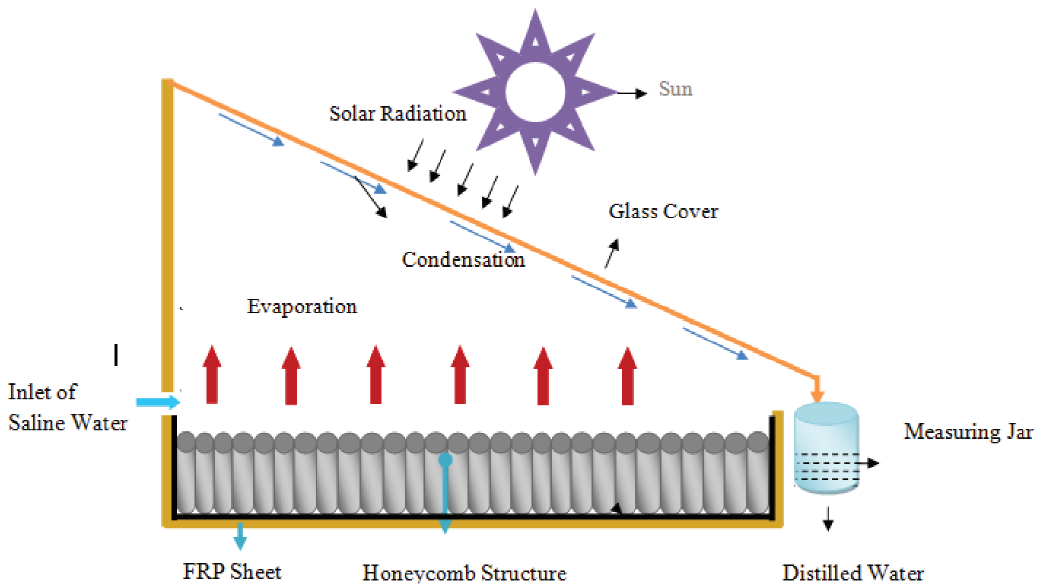

Figure 1. Schematic diagram of the single slope solar distillation system.

Solar energy is directly used to evaporate water in a passive solar distillation device. However, the system efficiency is modest. The evaporation of water in a passive solar distillation system requires an extra source of thermal energy in an active solar distillation system. Figure 1 shows the schematic of single slope solar distillation system with honeycomb structure [6, 7]. In this system solar radiation is incidence upon the glass cover. Water is evaporated and condensate another side of glass cover. This condensate is collected to the measuring jar.

Working

The solar distillation system purifies brackish or saltwater water and converts it to potable water. Solar radiation is emitted by the sun and reflected by the solar still's glass cover. The solar distillation system's honeycomb structure, which is connected to the water basin in the one slope solar distillation system, collected the solar energy through the cover glass. The honeycomb construction is constructed out of black plastic pipe with a length of 2.25 cm and a diameter of 6 mm in a square section (100 cm*100 cm), and it is filled with water. Solar radiation is focused on the glass cover and transmitted to the honeycomb structure. The honeycomb body is preheated at average exit temperature of water. The water that fills the honeycomb structure was also heated. Water condenses on the inside of the glass cover as it evaporates, and so this condense water is stored in the measurement jar. Because black pipe has a high absorptivity and has a low thermal conductivity, it is employed. The basin liner, a black painted surface, collects a huge percentage of the sun's light. However, there is some reflection loss at the cover glass, water, and basin liner as shown in Figure 1.

Literature Review

When compared to a simple traditional solar distillation system, the introduction of PCM in solar distillation systems increases desalinated water productivity by 35%-45% [8]. As the water temperature in the solar still was raised, the reflected loss of solar energy from the water surface was found to be strongly reduced. In an investigation, it is reported that the solar still performs well by reducing reflection losses by utilising the basin water structure of honey comb [9]. As per this, the effectiveness of a solar water desalination system using honeycomb is 24.37%, compared to 19.11% for a simple solar still. The solar distillation system's thermal efficiency was improved by using nanoparticles blended with black paint. The solar distillation system has a 38.09% increase in distilled water productivity and a 12.18% increase in thermal efficiency [10]. The quantity of desalinated water used is proportional to the solar still's efficiency. The productivity of distilled water is determined by the temperature of water and heat transfer characteristics. The productivity of distillation water increases as the water temperature rises [11]. Numerous studies have been conducted on various theoretically and experimentally topics under different atmospheric situations. It was discovered that the productivity of desalinated water reduces in the winter and increases in the summer. In the winter, the production of water from the humidification and dehumidification distillation solar still ranges from 2 to 3.5 kg/m^2, whereas in the summer, it ranges from 6 to 8 kg/m^2. The maximum distilled water productivity was reported to be 7.26 to 11 kg/m^2 in July and August The solar collector area boosts the active solar distillation system's distilled water productivity [12]. The still paired with the honeycomb covered solar collector generates more than the still alone on all typical working days year round [13, 14]. By evaluating immediate gain and loss efficiency at 0.01 and 0.04 m depth of water at a 15° inclination angle, the influence of depth of water on the performance of solar stills has been proven. It was discovered that a shallow water basin provides superior efficiency, which is in line with the findings of many other researchers [15, 16].The use of myristic acid as a PCM was used in a solar still experiment. This was done to see how the mass and basin water affect the distilled output productivity and solar still efficiency [17]. It was discovered that increasing the amount of PCM in the solar with a smaller mass of water increased the daily distilled output. The productivity of the distilled output decreases when the amount of PCM exceeds 20 kg [18, 19]. It has been discovered that the effect of water depth is the highly valuable factor in determining whether the solar distillation system's output increases or decreases [20]. The distilled output is higher, when the water depth is low vica versa. It also recognized that active solar stills have higher productivity than passive solar stills due to a greater difference in temperature between both the water and the inner glass temperature [21, 23].

In an experimental study fabricated model consisting of various device such as modified solar still and two condenser besides a double glass cover to prevent the heat loss of the solar still also the results of MSS with double glass with two condenser was more than that of conventional solar still by around 82.5% productivity and exergy efficiency was 31% [24]. In another investigation [25], the fabricated solar still was modified by using parabolic through collector in addition to those mentioned in experimental study [24]. In both the investigation, productivity and exergy efficiency were found to increase as compared to conventional solar still. In experimental analysis of drum solar still integrated with parabolic solar concentrator used of PCM with nanoparticles and also external condenser was also increased the rate of evaporation [26, 27, 35]. In this studied an experimental work had done for the enhancement of productivity of simple solar distillation unit at different density and have different thickness and different depth of water level in basin. A sponge of 16 Kg/m^3 density and 30 mm thickness with corresponds increase of 58.1 % and 55.3 % respectively [28, 29].

Experimental Setup

Figure 2 displays the solar distillation system with honeycomb structure and the honeycomb structure is fitted in the water basin. The experiment was done on a solar distillation without honeycomb structure for the purpose of the comparison. Base area of the solar still was 100 cm×100 cm. The glass was fitted on the solar distillation system at an angle of 26.3^0 which is the latitude of the Sultanpur. The experiments were performed during the month of (28 April -2019 to 30 April -2019) without honeycomb structure and also with honeycomb structure experiments were performed during the month of May from (1 to 4 may-2019) at the top floor of the department of mechanical engineering KNIT Sultanpur (Uttar Pradesh), India (latitude $26^0$15'N, longitude $82^0$4'E). All experiment s were done from 8 AM to 7 PM. Figure 3 shows the honeycomb structure having height 2.25 cm and 6 mm diameter with very thin plastic pipes. The material of black plastic pipe is poly propylene which has low thermal conductivity. Hence the materials have less thermal conductivity which absorbs high heat. This honeycomb structure is installed in the water basin. The usage of a honeycomb structure minimises the solar distillation system's reflection losses, resulting in a greater distilled output.

Figure 4 depicts the honeycomb - like structure installed in the solar distillation system's basin. The honeycomb construction lowers the solar distillation system's reflection losses. Figure 5 shows how a Pyranometer is used to measure irradiance from all directions. The quantity of radiant energy (electromagnetic radiation from the sun) on a flat surface is referred to as global irradiance. The department of mechanical engineering at KNIT Sultanpur has a Pyranometer on the top floor. This pyranometer's reading is done automatically at the Solar Radiation Resources Assessment (SRRA) in Chennai.

Figure 2. Experimental setup of solar distillation system.

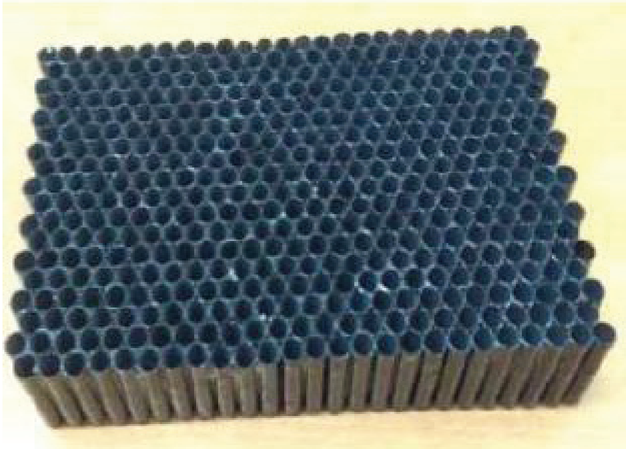

Figure 3. Honeycomb structure.

Figure 4. Solar distillation system with honeycomb structure.

Table 1. Specification and properties of araldite 3112 resin/ hardener 3112 [30].

Properties	Araldite 3112	Hardener 3112
Colour	Water clear liquid	Light yellow liquid
Specific gravity	1.17	1.12
Viscosity at 25°C	(8000-15000) Ns/m^2	(10000-17000) N.s/m^2
Pot life minutes (3.0 gram at 25°C)		5.30-6.20
Hardness		70
Thermal conductivity	0.22 W/m.K	0.22 W/m.K

Specification and properties of araldite 3112 resin/hardener 3112

Araldite 3112 resin and hardener 3112 harden quickly. Epoxy adhesive contains two components and a handy 1:1 resin to hardener mix ratio. In a short amount of time, the product forms strong bindings on a wide range of substrates. Araldite is a high-strength, high-toughness, two-component, room-temperature curing paste adhesive. It can be used to connect a wide range of metals, ceramics, glass, rubber, stiff plastic, and most other common materials. It's versatile glue that may be used for both crafts and industrial purposes. Table 1 lists these characteristics. It is believed that the amount of araldite added to the honeycomb is small, and that the araldite's melting point is lower than that of the honeycomb material.

Mathematical Equation of Solar Distillation System

An energy balance equation based on the heat and mass transfer connection was used to determine the operation of the solar distillation system. The energy balance on the glass cover and water in the basin liner are used to characterise the transient behaviour of a single slope basin type solar distillation system. The unit area of the water basin is used to calculate all heat amounts. Figure 5 depicts the energy transfer that takes place in the still and has a direct impact on the output [7, 36]. In order to write the energy balance equation, the following assumptions are made. (1) The water level in the basin is assumed to be constant. (2) Condensation happens at the film type of glass. (3) The glass cover insulation material and absorption material have little heat capacity. (4) The solar desalination system has no vapour leakage. (5) There is no temperature difference in the water depth or the glass cover. (6) The insulator's heat capacity is insignificant.

The energy balance equation for the water can be expressed as;

$$I_1 + Q_b + C_w \frac{dT_W}{dt} = Q_{cw} + Q_{rw} + Q_{ew} + I_2 + m_w \cdot C_w \frac{dT_W}{dt} \quad (1)$$

Where Q_b represents convective heat transfer from the basin to the water, C_w represents the basin's heat capacity, and T_W represents the basin's water temperature. The evaporative heat transfer from water to the glass is known as Q_{EW}. The radioactive heat transfer from water to glass isQ_{rw}, while the convective heat transfer from water to glass is Q_{cw}. I_1 is the amount of radiation that reaches the water's surface after passing through glass. Glass cover energy balance equation expressed as;

$$Q_{rg} + Q_{cg} + I_1 = I + Q_{ew} + Q_{rw} + Q_{cw} \quad (2)$$

Where Q_{cg} represents convective heat transfer from glass to atmosphere, I represents solar radiation falling on the distillation system, and Q_{rg} represents radioactive heat transfer from glass to atmosphere.

The rate of evaporated heat dissipation is calculated as follows:

$$Q_{ew} = h_{ewg} \cdot (T_w - T_g) \quad (3)$$

Where, the convective heat transfer coefficient is given by Dunkle [31].

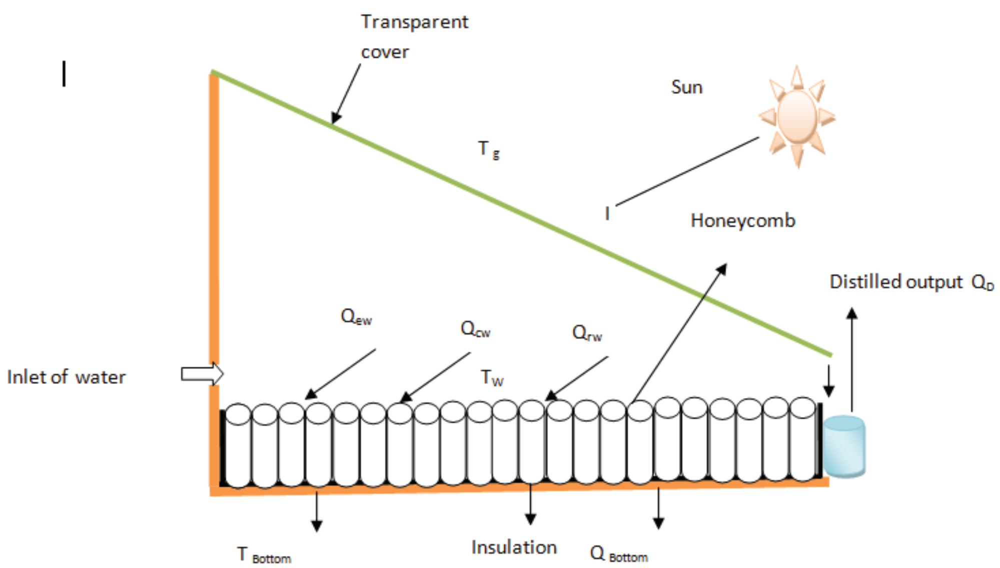

Figure 5. Heat transfer analogy of the system.

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$$h_{cwg} = 0.884 \cdot \left[(t_w - t_g) + \left\{ \frac{(p_w - p_g)(t_w + 273)}{268900 - p_w} \right\} \right]^{1/3} \quad (4)$$

Where the evaporative heat loss coefficient between water and glass cover was expressed as[32];

$$h_{ewg} = \frac{(0.01628 \cdot h_{cwg} \cdot (p_w - p_g))}{(t_w - t_g)} \quad (5)$$

And the relation yields the hourly distillation output every unit area of the basin can be shown as;

$$M_w = h_{ewg} \cdot (T_w - T_g) \cdot \left(\frac{3600}{L_{ev}} \right) \quad (6)$$

Daily distilled per unit area is given as;

$$M'_w = \sum_{i=1}^{24} M_w \quad (7)$$

The efficiency of the solar still is given for the relation;

$$\eta = \frac{M'_w \cdot L_{ev}}{(A_b \cdot \sum I(t) \cdot \Delta t)} \quad (8)$$

Internal heat transfer process can be written as;

$$Q_{cwg} = h_{ewg} \cdot (T_w - T_g) \quad (9)$$

The radioactive and convective losses from the glass cover to the ambient environment can be represented as [10] in order to establish the minimum thickness of the glass cover for obtaining a consistent temperature on it.

$$Q_{tga} = Q_{rga} + Q_{cga} \quad (10)$$

$$P_w = \exp\,[25.317\text{-}(5144/T_w + 273)] \quad (11)$$

$$P_g = \exp\,[25.317\text{-}(5144/T_g + 273)] \quad (12)$$

The heat transfer coefficient was examined, and the mean temperature of the water and glass cover temperature were utilised to calculate the solar distillation system's thermal efficiency. The solar distillation system's efficiencies are computed as [4].

$$\eta_{Thermal} = \frac{\alpha w \cdot T_g \cdot h_{ewg}}{h_{ewg} + h_{cwg}} \quad (13)$$

RESULTS AND DISCUSSION

Results of Solar Distillation System without Honeycomb Structure

Table 2 shows the result of the solar distillation system without honeycomb structure. In this table, the water temperature data are shown for different days. It is seen that the water temperature as well as distilled output were maximum at 2.00 PM.

Results of Solar Distillation System without Honeycomb Structure

Table 3 shows the result of the solar distillation system with honeycomb structure. In this table, the water temperature data was shown for different days. The water temperature and distilled output were maximum at 2.00 PM is 720 ml. Figure 6 depicts the relationship between solar radiation and cumulative distillation output in the solar still without honeycomb structure. The maximum 928 W/m^2 of solar radiation was obtained at 12.00 PM after this it decreased

Table 2. Results of solar distillation system without honeycomb structure for different days

Time (Hour)	Water temperature (°C) (28/04/2019)	Water temperature (°C) (29/04/2019)	Water temperature (°C) (30/04/2019)
8:00 AM	34.8	35.4	35.2
9:00 AM	41.5	42.2	42.6
10:00 AM	48.2	48.9	49.2
11:00 AM	55.4	54.1	54.3
12:00 PM	59.6	58.6	58.6
1:00 PM	61.9	62.1	62.9
2:00 PM	57.1	63.2	65.1
3:00 PM	60.6	60.2	60.5
4:00 PM	58.4	55.4	58.3
5:00 PM	48.9	49.0	49.1
6:00 PM	45.6	44.6	45.7
7:00 PM	40.6	40.4	40.6

Table 3. Results of solar distillation system with honeycomb for different days

Time (Hour)	Water temperature (°C) (01/05/2019)	Water temperature (°C) (02/05/2019)	Water temperature (°C) (03/05/2019)	Water temperature (°C) (04/05/2019)
8:00 AM	35.8	37.6	35.2	35.1
9:00 AM	47.5	42.8	42.1	42.0
10:00 AM	53.0	50.7	48.9	49.1
11:00 AM	60.2	55.8	54.2	54.1
12:00 PM	64.6	60.1	58.6	58.5
1:00 PM	68.2	63.9	62.1	62.4
2:00 PM	69.3	65.5	62.6	63.3
3:00 PM	68.4	64.6	60.3	60.4
4:00 PM	65.3	61.1	55.6	58.2
5:00 PM	58.7	56.3	49.1	49.1
6:00 PM	52.5	50.9	44.7	44.1
7:00 PM	47.1	46.2	40.4	40.3

continuously. While distilled water was obtained as 700 ml at this solar radiation. The distilled water production increased continuously with the time as shown in Figure 6.

Figure 7 depicts the fluctuation of solar radiation and cumulative distillation production with the honeycomb structure. The maximum solar irradiation was obtained at 12.00 PM having values of 946 W/m^2, then decreases. The maximum distilled was found at 2:00 PM having value of 955 ml. after which the solar radiation decreased continuously as shown in Figure 7. This observation has been taken at the different date. It can be observed that in comparison with Figure 6, Distillation water was more accumulated that without honey comb structure as can be compare with Figure 6 and Figure 7.

Variation of the water temperature in the different parts (water, glass inner, glass outer and basin) of the solar still desalination system without and with honey comb structure can be seen in the Figures 8 and Figure 9 respectively. The maximum basin and water temperature was found at maximum at 2.00 PM. While maximum inner and outer temperature of glass was found at 1.00 PM. Because of higher solar radiation is available at mid-noon. The maximum temperature of water, glass inner, glass outer and basin were found as 60.02°C, 55.3°C, 49.87°C and 50°C respectively at 2PM without honey comb structure. While these corresponding values with honey comb structure were found as 61.02°C, 56.43°C, 50.87°C and 51.2°C respectively at 1PM. It can be seen that temperature increased continuously with time and maximum value is found at 1.00 PM. The solar irradiation increases with the time, it leads to the increase in these temperatures also.

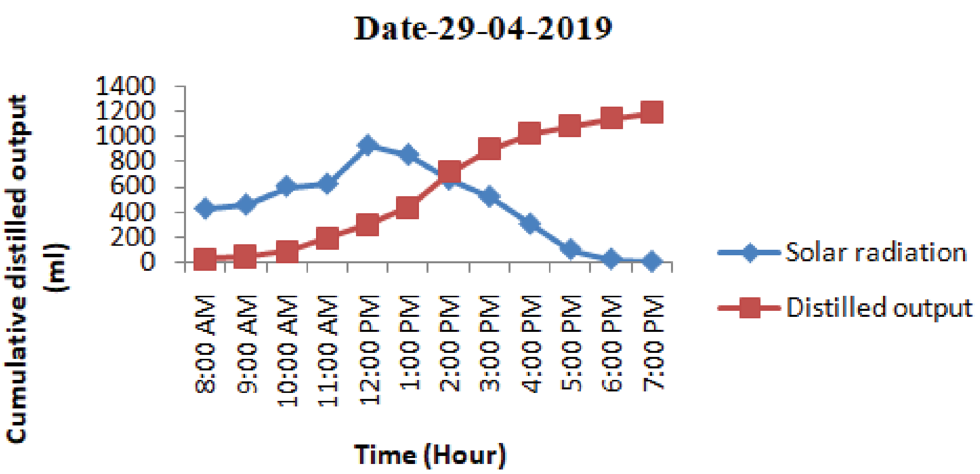

Figure 6. Variation of solar radiation and cumulative distilled output without honeycomb structure at Sultanpur, India.

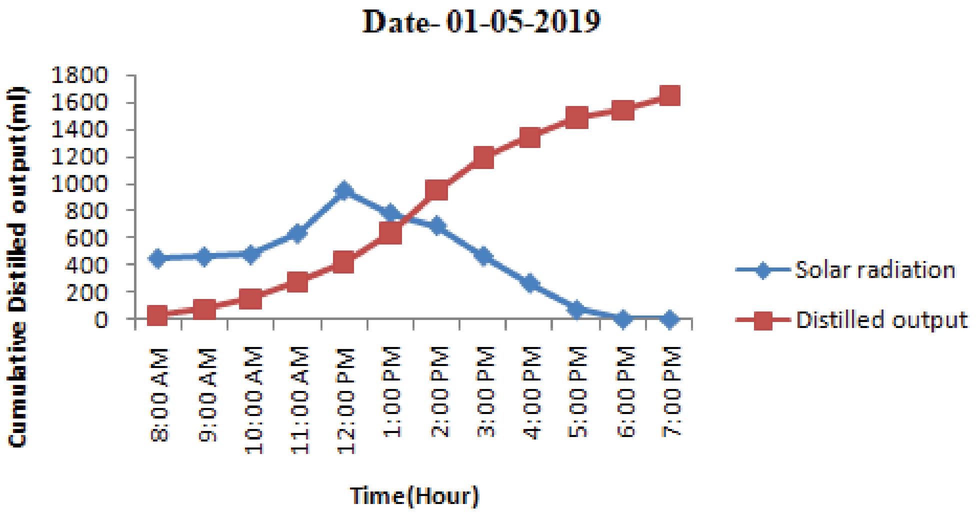

Figure 7. Variation of solar radiation and cumulative distilled output with honeycomb structure in solar still Sultanpur, India.

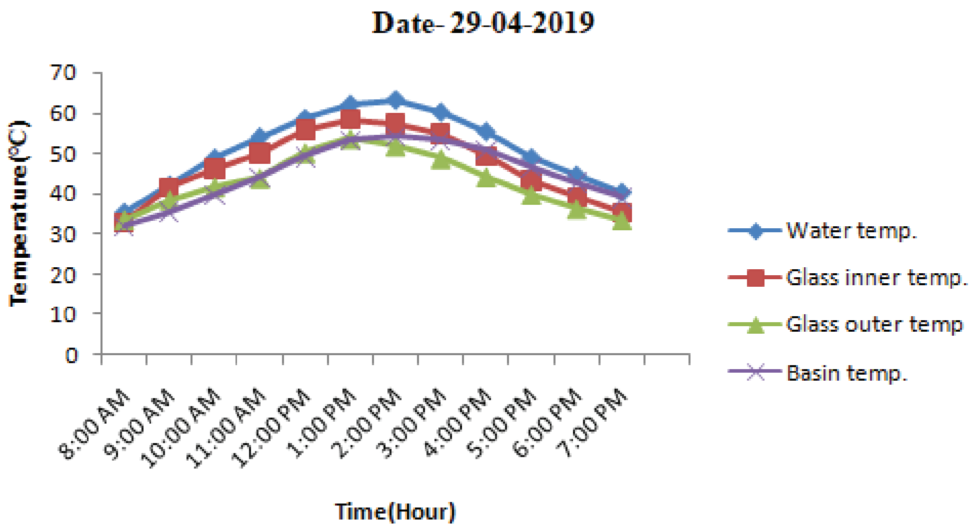

Figure 8. Hourly variations of temperatures without honeycomb structure.

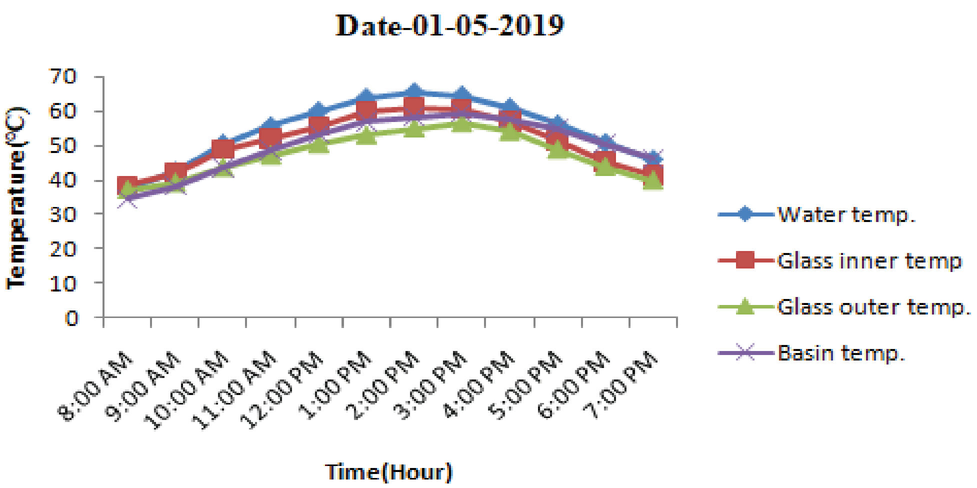

Figure 9. Hourly variations of temperatures with honeycomb structure.

Distilled water output variation at different days and time and without and with honeycomb structure were observed in Figures 10 1nd 11 respectively. The distilled water production was increased with the time in different days. This is because of respective variation in the solar irradiation and water temperature with time as discussed earlier section. The Figure 11 shows the variation in distilled output with honeycomb structure in different days. The high distilled was found on 1st May 2019 due to the higher intensity of the solar radiation is available in this day as compared to the other days. It was also observed that higher the solar radiation intensity higher the water temperature.

The hourly variations of temperature in different sections without and with honey comb structure were also observed in this experiment. It was seen that all components have their maximum temperature at almost 1PM and be seen in Figures 12 and 13. Figure 13 displayed higher values as compared to the Figure 12. This means temperature of the components with honeycomb are higher are higher than the without components. This bell pattern is obtained due to same variation of the solar intensity in whole day. Temperature with honey structure is higher 2-3°C higher than that of without honey comb structure.

The variation of basin temperature, water surface temperature, glass inlet temperature, glass outlet temperature, south wall temperature, north wall temperature, east wall temperature and west wall temperature with honeycomb structure are given in Figure 14. The temperature of the water surface, the glass inner surface temperature, and the glass outer surface temperature all were increasing with time, peaking at 2 PM. The fluctuation of solar radiation

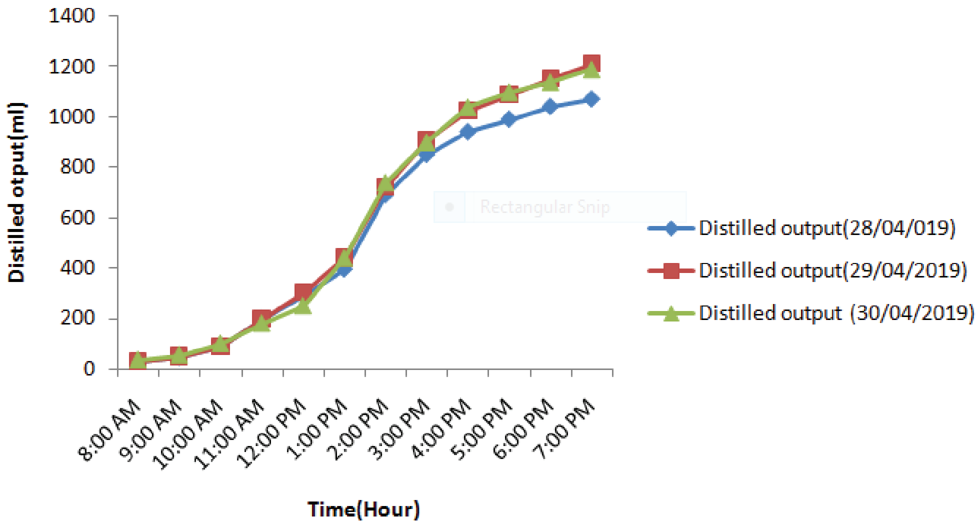

Figure 10. Variation in distilled output without honeycomb structure on respective days.

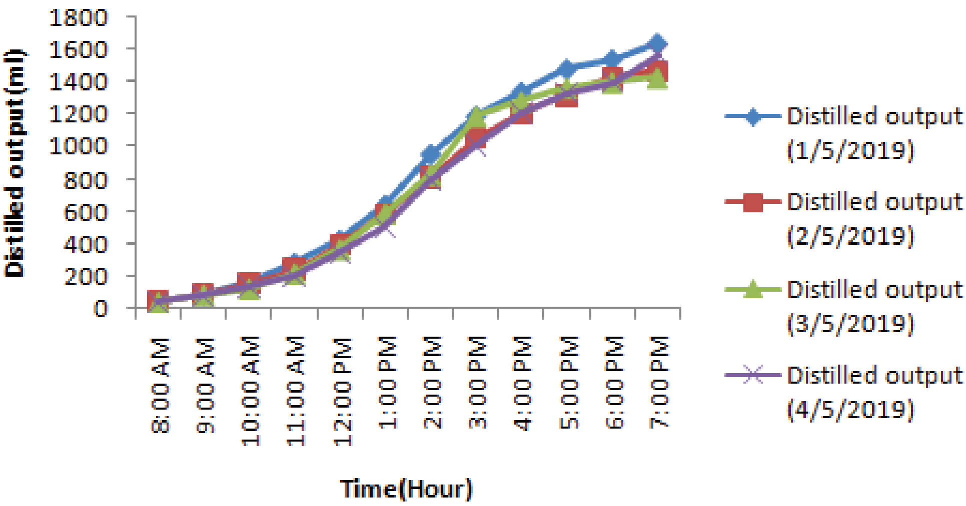

Figure 11. Variation in distilled output with honeycomb structure on respective days.

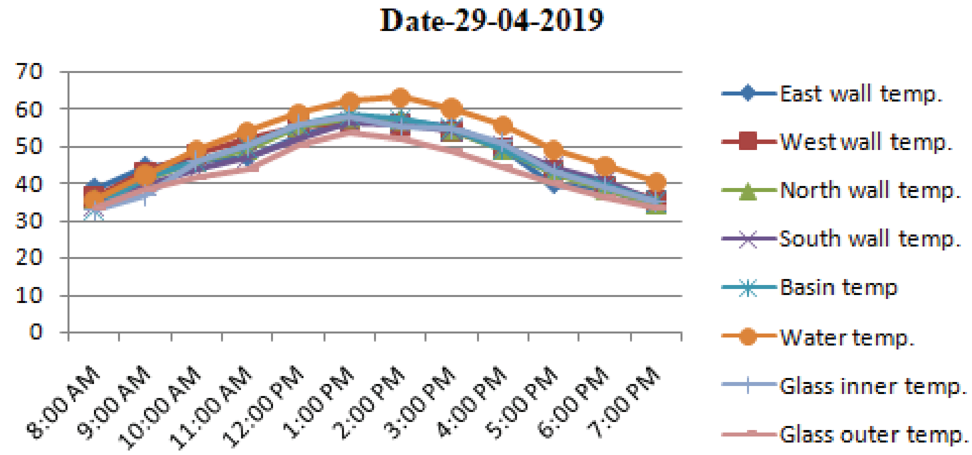

Figure 12. Hourly variations of temperatures without honeycomb structure.

are seen in the Figures 7 and 8, which increased over time and peaks at midday, and the total distillation output with

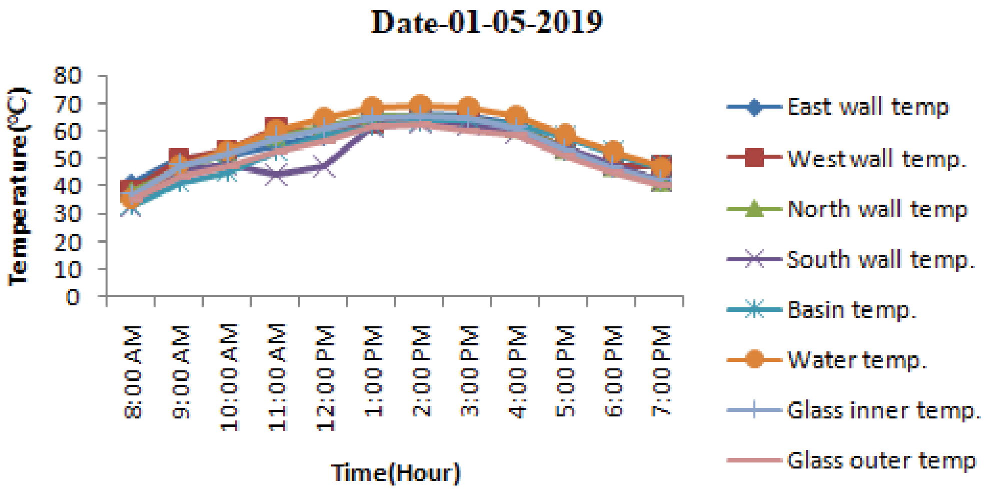

Figure 13. Hourly variations of temperatures with honeycomb structure.

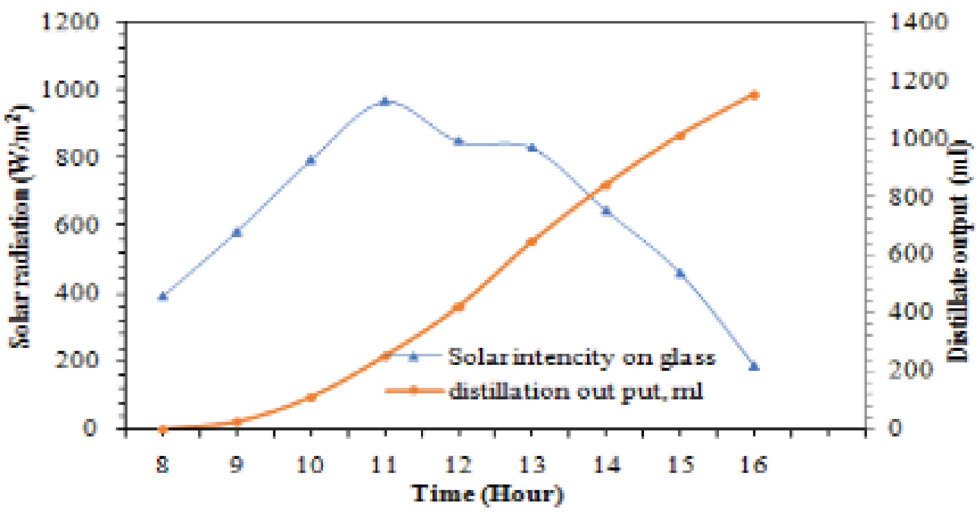

Figure 14. Variation cumulative distilled output and solar irradiation [33].

the honeycomb structure was higher than the total distilled output without the honeycomb structure. Figures 8 and Figure 9 demonstrate the variation in water surface temperature, basin temperature, glass inner surface temperature, and glass outer surface temperature without and with honeycomb structure. The cumulative distillation output with and without honeycomb construction is shown in Figure 10 and Figure 11. Solar radiation was increasing with the passing of time, peaking around 2 PM. Figure 14 depicts temperature changes over time. The temperature of the water surface, the glass inner temperature, and the glass outer temperature all rise with time, peaking around 1 PM [3]. Figure 9 shows less volatility in water temperature than Figure 14, with the highest temperature around 2 PM. After that, the temperature drops.

Validation of Fabricated Solar Still

Figure 14 and 15 show the variation of solar radiation and cumulative distilled output without honeycomb. It was observed that from both Figures the distilled output is increasing with time and reaches at maximum at mid noon about 2 PM on the 01-05-2019. The distilled output increases with increases in solar radiation.

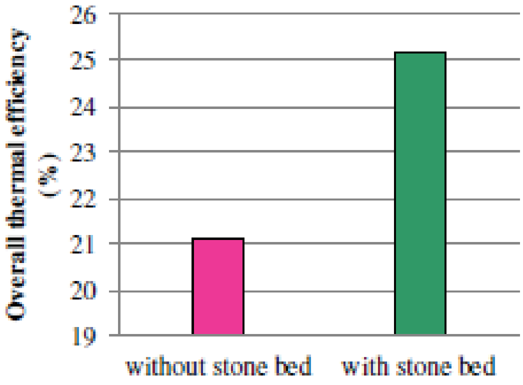

Figure 16. Overall thermal efficiency of solar still without stone bed and with stone bed [34].

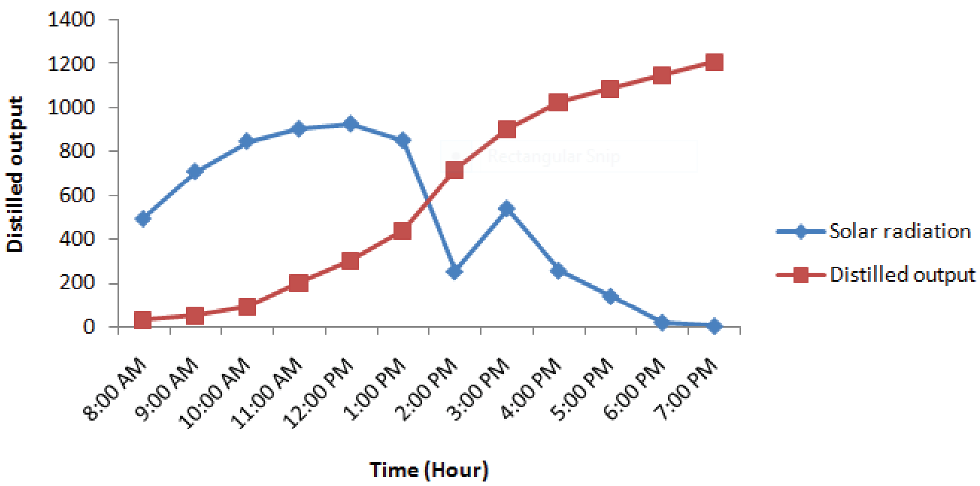

Figure 15. Variation of cumulative distilled output and solar radiation without honeycomb.

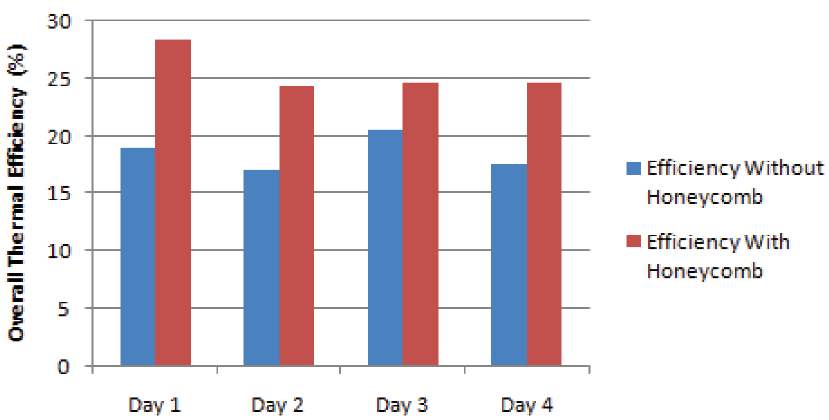

Figure 17. Comparison of the thermal efficiency of solar still with and without honeycomb structure.

The solar still with Omani rock bed has 25% efficiency, while the solar still without Omani rock bed has 21% efficiency as shown in Figure 16. The use of Omani rock bed in the water basin in the solar still improves the effectiveness of the traditional solar still [34]. Figure 17 depicts the solar still's overall thermal efficiency without honeycomb. The thermal efficiency of the solar still varies due to variations in solar radiation intensity and water temperature, and the efficiency of the solar still has been shown as 18.61%, 16.70%, and 20.12% on different days.

CONCLUSIONS

- Solar still with honeycomb was fabricated for the better performance of solar still desalination system.
- The honeycomb decreases the solar distillation system's reflection losses and at the same time, it was assisting in increasing the solar distillation system's productivity.
- The solar distillation system without the honeycomb structure has a thermal efficiency of 18.48% and distilled output productivity of 553.74 ml/m^2.
- Thermal efficiency and productivity of the solar desalination system with honey structure were obtained as 25.45% and a productivity of 749.58 ml/m^2 respectively.
- Solar distillation system with honeycomb has a 35.36% increase in the productivity in distilled output over the solar desalination system without honeycomb.
- The increase in the global thermal efficiency of solar distillation by honeycomb was 37.71% as compared to that without honeycomb structure.
- Double glass with two condensers was more efficient than that of conventional solar still by 82.50% productivity wise and exergy efficiency wise by 31%.

DATA AVAILABILITY STATEMENT

No data associated with this study

CONFLICT OF INTEREST

Author declares no conflict of interest.

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