

Improving the Potable Water from Tubular Solar Still Using Eggshell Powder as an Natural Energy Storage Medium - An Experimental Approach

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Abstract

It seems like every hour, there is a greater need for fresh water. The demand for fresh water is rapidly growing as a consequence of the expanding population and the increased urbanization of the world's population. The tubular solar still offers much larger evaporative and condensing surface areas than normal single slope solar still. The scope of this study is to improve the performance of tubular solar still by employing eggshells as the bed material, which has good heat absorption properties. Results showed that the influence of eggshell powder as energy storage material in the basin improved the average water temperature by 10.8, 10.9, and 8.73% for the water thickness of 10, 15, and 20 mm respectively. The usage of eggshells as an energy store in the basin results in an increase of about 60.77 % potable water produced. The maximum observed distillate output from the solar still is 0.6 kg for solar stills with eggshell powder as energy storage material and 0.34 kg for solar stills without eggshell powder in the absorber of TSS at peak solar radiation and at the lowest water thickness of 10 mm. The hourly potable water generated from TSS using eggshell as an energy storage material increased by roughly 47% compared to the flat absorber without eggshell powder. TSS with eggshell powder as energy storage has a daily energy efficiency of 79.19, 75.49, and 44.18 % for water thicknesses of 10, 15, and 20 mm in the basin. Tubular solar still using eggshell as energy storage material and tubular solar still without any material produced 3.62 kg and 1.42 kg average yields at a water thickness of 10 mm. Water thickness of 10, 15, and 20 mm has performance improvement ratios of 2.54, 2.51, and 2.18 respectively.

1. Introduction

The need for fresh water is increasing by the hour. The demand for freshwater is quickly rising as a result of the increasing population and rapid urbanization. Besides serving as a source of drinking water, fresh water is essential in a wide range of industrial uses, including batteries, pharmaceutical manufacturing, and research facilities. Even though India has a population that accounts for 16 % of the world's total population, the nation possesses just 4 % of the world's freshwater resources. India is experiencing water scarcity as a result of shifting weather patterns and recurrent droughts (Sathyamurthy et al. (2017); Vaithilingam et al. (2021); Arani et al. (2021)). For ages, fetching water has been considered a woman's work in India, particularly in rural regions. Wells, ponds, and tanks are drying up as groundwater supplies are depleted owing to overuse and excessive usage. This has exacerbated the water situation, placing an even larger strain on women in terms of water availability. Water desalination with solar energy is the ideal option for developing water desalination systems in developing and developed nations because of the water shortage problem and the availability of solar energy is abundant, clean energy and available free of cost. Solar distillation has been utilized for thousands of years and is still in use today. A promising procedure and an alternate method of supplying potable water to tiny settlements on islands and in isolated places, solar distillation seems to be gaining traction (Chamkha et al. (2020); Madhu et al. (2017, 2019)).

Arunkumar et al. (2020) studied the influence of adding a sensible heat energy storage medium inside a traditional solar still to augment freshwater production. Different materials such as pebbles, clay balls, CuO nano-coated absorber, and PVA sponges were used in their study. Results showed that fresh water produced from the solar still using pebbles, clay balls, CuO nano-coated absorber, and PVA sponges were 2.8, 2.62, 2.9, and 1.9 L/m² respectively with their corresponding cost per liter for water produced as 0.0073, 0.008, 0.007, and 0.012 \$. The influence of higher thermal conductivity of clay balls with porosity improved the rate of water produced from the solar still. Also, it was observed that at a higher solar radiation period, the yield of all the solar still with sensible heat energy storage exhibited similar characteristics on potable water produced.

Kabeel et al. (2019) studied the effect of using composite heat storage medium on energy, exergy, and economic analysis of traditional solar still. Black gravels were added to the paraffin wax for improved thermophysical properties. The cumulative yield from the SS with PCM and composite PCM were found as 2.44 and 3.72 L/m² with an average energy efficiency of 48.22 and 66.87% respectively. Also, studies reported that the average exergy efficiency using composite PCM was higher while compared to SS with PCM. It was also reported that the cost per liter for composite PCM was varied from 0.0014 to 0.00163 \$ which is lesser than the solar still with PCM alone.

Kabeel et al. (2017) used a solar parabolic concentrator along with PCM to the bottom of the solar still in order to augment the potable water produced. Depth of water maintained inside the solar still was the only parameter that was analyzed in their study to assess the performance such as cumulative yield, energy, and exergy efficiency. The depth of water maintained in the basin was varied from 1, 2, 3, 4, 5, and 6 cm. Their study revealed that the potable water produced from the solar still under proposed

modification reduced as the depth of water inside the still was increased from 1-6 cm. The accumulated potable water produced from the solar still with dish type of concentrator and PCM were 4.2, 5.1, 5.5, 6.2, 6.8, and 7.2 L/m² for a water depth of 1, 2, 3, 4, 5, and 6 cm during summer condition. Similarly, the exergy efficiency was higher at the lowest water depth of 1 cm and on increasing the water depth the exergy efficiency reduced for both summer and winter conditions.

Pumice stones were used as an energy storage medium in a conventional type of solar still for augmenting the potable water produced which was experimentally investigated by Bilal et al. (2019). The mass of the storage medium was varied between 5 and 10 kg inside the basin. Results revealed that the use of energy storage inside the basin reduced the daytime productivity to about 10.38 and 17.02% for the mass of storage medium as 5 and 10 kg respectively on comparing the daytime yield of conventional solar still without any storage medium. This phenomenon was completely due to the change in internal heat energy storage by the material inside the basin. While comparing the distillate output during the overnight, there is a significant improvement of about 1.58 and 12.67% using 5 and 10 kg of pumice stones inside the absorber.

The effect of convex type of absorber with wicks (jute and cotton) spread in the absorber of TSS was experimentally studied by Essa et al. (2021). Along with the proposed modification, composite (graphene and TiO₂) were added to the basin water as a working fluid. The convex type of absorber increases the surface contact of water with the solar radiation for maximum evaporation which leads to increased thermal efficiency and potable water produced. The height of the convex absorber was varied between 5 and 20 cm and optimized to 15 cm as the contact angle of the solar radiation was maximum. The daily potable water produced from TSS using jute wick with convex absorber, jute wick with convex absorber and nanocomposite, cotton wick with convex absorber, and cotton wick with convex absorber and nanocomposite were found as 92, 114, 88, and 110% respectively. The increase in potable water produced from the TSS using wick material is due to the higher capillary effect while compared to that of cotton wick.

Dehmukh and Thombre (2017) used sand and servotherm oil as energy storage material and optimized the depth of SE material for improved thermal performance. In both cases, the depth of SE material was varied from 0.5 to 1.5 cm while the depth of water is constantly maintained at 0.6 cm. It was reported that in both cases, with increasing depth of SE material, the daylight productivity decreases, and the overnight productivity increases. The heat stored in the daytime is utilized by the water during night time which improved the rate of evaporation. Also, the optimized depth of SM oil and sand was limited to 0.5 cm as there was no significant improvement in increasing the depth of SE material beneath the basin. The daily yield from solar still using SM oil and sand at a water depth of 0.5 cm were found as 2525 L/m² and 2502 L/m² respectively.

The use of mushrooms and carbon black-based nanoparticles on mushrooms for improving the potable water produced from TSS was experimentally analyzed by Sharshir et al. (2021). Three different quantities of carbon black namely 25, 50, and 75 g/m² was coated on mushrooms and a comparison was made with mushrooms and without mushrooms on the basin. The mushrooms on the plate increase the capillary effect for effective evaporation from the water to get evaporated. The daily productivity of TSS with mushroom and mushroom with 25, 50, and 75 g/m² carbon black nanoparticles were found as 4.37, 5, 5.36, 5.46 kg/m² respectively, and which is higher than TSS without mushroom (3.41 kg/m²). On adding 25 g/m² of carbon black nanoparticle with 50 g/m², there is a meagre improvement in the potable water produced from the mushroom coating in the absorber of TSS. The average thermal efficiency from TSS with mushroom and mushroom with 25, 50, and 75 g/m² carbon black nanoparticles and TSS without mushroom were found as 54.3, 54.74, 49.61, 44.9, and 35.23 % respectively. The improvement in thermal performance was due to the effective increase in the thermal conductivity, pileus surface roughness, absorption of solar radiation for an effective increase in temperature further leading to an enhanced rate of evaporation. The thermal performance improvement of TSS using circular and hollow fins filled with phase change material was experimentally investigated by Abdelgaied et al. (2021). Results revealed that the use of square fins improved the daily potable water by 33% (5.52 L/m²) compared to TSS with a flat absorber (4.15 L/m²). On using hollow circular fins the heat exposure area was further improved which leads to an improvement in yield to about 47.12% than TSS with a flat absorber. Adding paraffin wax into the circular and square fins attached to the absorber further improves the potable water produced by 90.2% than the conventional case. The daily energy efficiency of TSS, TSS with hollow square fins, hollow circular fins, and circular fins with paraffin wax were found as 36.9, 49.1, 54.4, and 70.2% respectively. Similarly, from the economic point of view, the cost per liter of water for TSS with paraffin wax in the hollow circular fins was reduced to about 0.009 \$ whereas, in the case of TSS, TSS with square and circular fins were 0.015, 0.012, and 0.011 \$ respectively.

Kabeel et al. (2020) used parabolic concentrators on TSS to augment the performance of TSS by optimizing the thickness of water in the absorber. It was observed that the varied thickness of water in the semicircular trough the fresh water produced was improved by 87.9, 90.8, 81.9, and 68.1% for the thickness of water as 1, 2, 3, and 4 cm respectively while compared to rectangular absorber in TSS without parabolic concentrator. The improvement in the yield of fresh water from the proposed modification was that the entire heat from the solar radiation is focused on the lower circumference of the absorber which leads to increased temperature while compared to the rectangular flat absorber.

Kabeel et al. (2021) increased the surface area of exposure to solar radiation with the water placed in the TSS using corrugated absorber and wick material. Thermal modeling analysis was carried out to assess the performance of the proposed modification in TSS. Results showed that the corrugated fins on the absorber increased the potable water produced by 44.82% than conventional TSS. The daily potable water produced from the corrugated absorber TSS and flat absorber TSS was found to be 6.01 and 4.15 L/m² respectively. According to the experimental and numerical results, the largest variances were found to be within the limits (2.5 %). Also, there is a significant improvement of about 46.86% in the daily efficiency was observed using corrugated absorber and wick material in TSS.

Abdelaziz et al. (2021) proposed five different configurations on TSS to augment the potable water produced. SS with modifications such as corrugated absorber, corrugated absorber with wick material, corrugated absorber with wick material, and carbon black nanoparticles in working fluid and corrugated absorber with wick material, NePCM (carbon black nanoparticles in PCM), and carbon black nanoparticles were proposed. Results show that the use of wick material in corrugated absorber improves the potable water produced by 30.3% and 16.2 % than the use of flat absorber and corrugated absorber without wick material. Furthermore, the influence of using carbon black nanoparticles in PCM and nanofluids as working fluid in corrugated absorber solar still, the potable water produced was improved to about 88.84% than the conventional TSS. Economical aspects revealed that the CPL was reduced to about 22.47% using corrugated absorber, CB nanofluids, NePCM and wick material in the basin as compared to TSS with the flat absorber.

The effect of thickness of water in the conventional solar still using sensible energy storage was experimentally investigated by Kabeel et al. (2018). Along with the sensible heat storage material, jute cloth was knitted to augment fresh water production. It was reported that the production of fresh water is fully dependent on characteristics like sensible energy mass and basin depth. With the use of jute cloth woven in the sensible heat energy storage, the augmentation of fresh water production was found as 25% than solar still without jute cloth on energy storage at the lowest water thickness of 0.02 m. The cumulative yield from solar still without any energy storage was recorded as 2.5 kg/m² while the solar still equipped with energy storage and energy storage with jute cloth were 5.5 and 5.9 kg/m² respectively. The increase in the freshwater was completely due to the higher capillary effect exhibited by the jute cloth on the energy storage material placed in the basin. Employing low-cost heat storage materials, Samuel et al. (2016) were able to augment the performance of basin solar still productivity by 22.73 %. Their findings also revealed that the potable water produced from basin-type solar still was improved from 2.2 to 2.7 L/m² (a 21.7 % increase). The properties of various sensible heat energy storage materials are compared and presented in Table. 1.

It is relatively simple to add sensible or latent heat energy storage material in conventional solar still as the basin area is higher, but it is difficult to place energy storage material in tubular solar still. The area of condensing cover is closer to the exposure area of the basin. In this study, the effect of waste eggshells was used as an energy storage material in the basin of TSS to improve the potable water produced. Three different water layer thicknesses were chosen namely 10, 15, and 20 mm to assess the performance of solar still. Furthermore, the effect of energy storage material on energy efficiency was analyzed in comparison to TSS without energy storage.

Table 1
Properties of sensible heat energy storing material

Property	Material								
	Pebbles (Kedida et al. (2019))	Gravel	Graphite (Kabeel et al. (2018))	Marbles (Čáchová et al. (2016))	Mild steel scraps (Murugavel et al. (2010))	Cement (Murugavel et al. (2010))	Red bricks (Murugavel et al. (2010))	Sand (El-Sebaili et al. (2009))	Aluminium (Murugavel & Srithar (2011))
Thermal conductivity (W/m K)	2.5	0.9 [#]	190	2.995	50 [#]	0.3 [#]	0.77 [#]	-	205 [#]
Specific heat capacity (J/kg K)	880	-	706.9 [#]	609 [#]	465 [#]	780	840	798	850
Density (kg/m ³)	2700	1680 [#]	2260 [#]	2750 [#]	7850 [#]	1440 [#]	1500 [#]	1500 [#]	2710 [#]
# Experimental value measured for the present work									

2. Experimental Setup And Procedure

2.1. Preparation of eggshell powder and thermal properties

Eggshell waste was collected from domestic households and restaurants it is cleaned to remove the outer thin layer of the skin. The cleaned eggshell is then crushed into a fine powder using a planetary ball mill. The collected powdered eggshell is made into a thick layer as a bed inside the absorber for effective absorptivity of solar radiation. The eggshell is composed mostly of calcium carbonate, which has a heat conductivity of around 2.348 W/m²K. The thermal conductivity of the eggshell powder is determined using TEMPOS thermal analyzer. The detailed properties of the eggshell powder are provided in Table. 2. The deviation between the experimental value and literature was between 1-1.5% and within the limit.

Table 2
Properties of eggshell

Property	Literature	Experimental value
Thermal conductivity (W/m K)	2.25 (Denys et al. (2004))	2.348
Density (kg/m ³)	2300 (Denys et al. (2005))	2352
Specific heat capacity (J/ kg K)	888 (Denys et al. (2004))	895

2.2. Experimental setup

The experimental test rigs shown here were developed based on two different experimental setups namely TSS without eggshell and with eggshell as bed material for energy storage. The eggshell powder was employed as a bed material for energy storage medium for improved thermal performance of a tubular still. Fig. 1 represents the base case of the tubular solar still with a flat absorber. In both cases, the dimensions of the cover and the basin are the same. The material used to fabricate the solar still was mild steel with 2 mm thickness. The absorber plate is made with a dimension of 27 cm in length and 50 cm in length with an effective area of the basin as 0.135 m². The transparent tube is made using acrylic material whose diameter and length are 29 cm and 53 cm respectively with a tube thickness of 4 mm. The height of the rectangular tray was fixed as 50 mm. A storage tank with a capacity of 50 liters is used to store the water and it is constantly supplied to the basin in order to maintain a constant level of water. A calibrated steel ruler is fixed to the basin to see the level of water available in the basin. Fig. 2 shows the dimensions of the tray and Fig. 3 represents the mechanism and photograph of the experimental setup.

The experimental data such as solar radiation, temperature, wind velocity, and distillate output were recorded on an hourly basis. Thermocouples were used to monitor the absorber, water, cover, eggshell bed, and the surrounding environment temperature. In order to determine the quantity of condensed water vapor collected via the flexible hoses of the distillate water storage tank, a scaled vessel was employed to gather data. The solar power meter was used to record the amount of solar energy received throughout the testing period. A vane-type anemometer was used to measure the wind velocity to study the effect of condensation while the air interacts with the external cover surface. Table. 3 shows the range and uncertainty of the measuring instruments that were used in this study to gather data. The entire experiments were carried out in the outdoor roof top facility available in KPR institute of Engineering and Technology, Coimbatore, Tamil Nadu, India between 9:00 Hrs and 19:00 Hrs. The egg shell in powder form is added to the basin of tubular solar still with a thickness of 3 cm in the basin.

Table 3
Instrument, purpose, range, accuracy, and uncertainty

Instrument	Purpose	Range	Accuracy	Uncertainty (%)
PT100 type RTD thermocouple	To measure the temperature of water, absorber, cover and ambient	-300 to 1500 °C	± 0.1 °C	1.5
TES 133R Solar power meter	To measure the solar radiation	0-3500 W/m ²	± 10 W/m ²	3.2
Anemometer	To measure the wind velocity	0-50 m/s	± 0.1 m/s	1.5
Graduated flask	To measure the amount of water collected	0-1000 ml	± 3 ml	1.9

3. Results And Discussion

Ambient temperature, solar radiation, wind velocity, temperature records in the still, water-holding capacity of materials, and fresh water production are all measured during the experimental portion of this study which is discussed in detail in this section.

3.1. Performance of conventional tubular solar still

The temperatures of the different elements such as absorber, water, cover, and ambient temperature increase steadily and reach the maximum value as the solar radiation reaches a maximum value in both cases. It is observed from Fig. that the solar radiation and temperature follow a similar trend while the wind velocity is intermittent.

Variations on wind velocity, solar radiation, ambient, absorber, water, and the cover temperature of TSS without energy storage for water thicknesses of 10, 15, and 20 mm are plotted in Fig. 4 (a-c). It can be seen that on maximum recorded temperature of water in the case of TSS without energy storage for the thickness of water as 10, 15, and 20 mm were found as 54, 53, and 51 °C respectively. For an increase in the thickness of water, the temperature is reduced as the energy is stored in the form of sensible heat during the period of solar radiation. Similarly, the maximum temperature of cover is recorded as 47, 46, and 45 °C for the tubular solar still without energy storage for the thickness of water as 10, 15, and 20 mm respectively. The experimental findings clearly illustrate that water depth influences enhanced production. The rate of potable water produced from the solar still is influenced by the temperature of water for effective evaporation and the temperature of cover for enhanced condensation. The peak cover temperature for water thicknesses of 10, 15, and 20 mm was recorded as 47, 46, and 45 °C respectively. The average difference between the water and cover during the decline of solar radiation is found to be 5.1, 5.3, and 5.8 °C for water thicknesses of 10, 15, and 20 mm respectively. This clearly indicates that the difference in temperature between water and cover is increasing for increased water thickness for the increase in the potable water produced during the decline of solar intensity. The difference in water and cover temperature is higher during the peak intensity ($I(t)=840 \text{ W/m}^2$) and it is found as 10, 7, and 5 °C for water thickness of 10, 15, and 20 mm respectively for the solar still without any heat-storing material.

3.2. Performance of tubular solar still with eggshell powder as energy storage material

Fig. 5 (a-c) depicts the variations on wind velocity, solar radiation, ambient, absorber, water, and the cover temperature of TSS without energy storage for water thickness of 10, 15, and 20 mm. It is observed from Fig. 5 (a-c) that the water and absorber temperature of solar still at lower water thickness is higher while compared to the SS with eggshell powder as energy storing material in the absorber it is lower with increased water thickness from 10 mm to 20 mm. Similarly, it is observed that the temperature of the absorber, water, and cover temperature during the increase in solar intensity is found to be lower than the TSS without any energy storing material in the absorber. It is obvious that the eggshell powder in the absorber acts as an energy storing material and the energy is excess heat from the water is stored by the material for efficient heat transfer. For the peak solar intensity of 840 W/m², the recorded water temperature for 10, 15, and 20 mm water thickness are found as 55, 54, and 53 °C respectively. The average water temperature during the lower intensity period from the TSS with eggshell powder as energy storage is found as 44.1, 44.5, and 44.8 °C for water thickness of 10, 15, and 20 mm respectively and while comparing the average temperature of solar still without energy storing material it is found as 39.8, 40.1 and 41.2 °C. With the influence of high thermal conductive energy storage material in the absorber, the average temperature of the water is improved by 10.8, 10.9, and 8.73 % for water thickness of 10, 15, and 20 mm respectively. Cover temperature is also a critical parameter for effective condensation. The maximum recorded cover temperature from the solar still using eggshell as energy storing material is found as 41, 39, and 38 °C for water thickness of 10, 15, and 20 mm respectively. The average difference in temperature of the water and cover for 10, 15, and 20 mm water thickness during the afternoon session is calculated as 11.3, 10.2, and 9.15 °C with the use of eggshell powder as energy storage material in the absorber respectively. The potable water from the SS is higher with a higher temperature difference. The difference in water and cover temperature is higher during the peak intensity ($I(t)=840 \text{ W/m}^2$) and it is found as 14, 12, and 9 °C for water thickness of 10, 15, and 20 mm respectively for the solar still without any heat-storing material. The average temperature difference of water and cover from the SS with eggshell as energy storing material is improved by about 54.3, 47.7, and 36.2 % for water thickness of 10, 15, and 20 mm respectively.

3.3 Comparison of potable water produced from tubular solar still with eggshell as energy storage and without energy storage

Because of the higher amount of solar radiation available at 13:00 Hrs all the stills achieved their highest hourly potable water produced at that time. The potable water produced continues and rises in the morning session and reaches its peak in the afternoon session, after which it begins to decline as a result of the decreased levels of solar radiation. The critical parameter in the performance of solar still is its amount of potable water produced. On an hourly basis, the potable water produced from the tubular solar still without energy storage and tubular solar still with eggshell as energy storage is plotted in Fig. 6 (a, b). The peak recorded yield from the solar still under the maximum solar intensity of 840 W/m² is found as 0.6 and 0.34 kg for solar still with eggshell powder as energy storage material and without eggshell powder in the absorber of TSS respectively at a constant thickness of water 10 mm maintained inside the basin. On daylight hours, the variations on the potable water produced at increased water thickness are decreasing and the same is reversed under the lower solar radiation period (evening hours) which simultaneously denote that the reported yield is more stable. With decreased water thickness inside the basin, in the evening hours the potable water produced is lower than increased water thickness. In the flat absorber tubular solar still, the effect of eggshell powder as a bed material for energy storage is found to be more effective solar intensity increases (during sunlight hours), however, the yield during off-shine hours is found to be poor. The hourly potable water produced from TSS with eggshell as energy storage material increased by about 47% than the flat absorber without eggshell powder as sensible heat-storing material. This is found when comparing both the yields from solar stills. During the absence of solar radiation, the potable water produced is increased to about 40.34, 45.32, and 6.98% for 10, 15, and 20 mm water thickness respectively with the use of eggshell powder as energy storage. Similarly, there is a decrease of about 88.21, 85.92, and 79.60 % in the potable water produced for water thickness of 10, 15, and 20 mm respectively. The decrease in the potable water produced was due to the loading of eggshell powder as bed material which resulted in reduced temperature of water, cover, and absorber during morning hours.

3.4 Comparison of daily yield and daily energy efficiency of tubular solar still with and without material

The daily thermal efficiency of the system is mathematically expressed as,

$$\eta_{\text{average thermal efficiency}} = \left(\frac{\sum m_e \times h_{fg}}{\sum I(t) \times 3600} \right) \times 100 \% \quad (1)$$

For calculating the daily thermal efficiency of the solar still, Equation (1) is utilized as the basis. The daily efficiency and daily potable water produced from TSS with eggshell powder as energy storage material and without energy storage for different water thicknesses is tabulated in Table. 4. From the table, it is observed that the energy efficiency of TSS decreases as the thickness of water increases. The daily energy efficiency of TSS without energy storage for water thickness of 10, 15, and 20 mm in the basin is calculated as 33.56, 30.05, and 20.82 % respectively while the daily energy efficiency of TSS with the use of eggshell powder as energy storage material in the basin of the absorber is calculated as 79.19, 75.49 and 44.18 % respectively. The performance enhancement ratio of potable water produced is the ratio of potable water produced from the solar still with eggshell as energy storage (Y_{est}) and potable water produced from SS without energy storage material. It is observed that the performance enhancement ratio of SS for water thickness of 10, 15, and 20 mm is calculated as 2.54, 2.51, and 2.18 respectively.

Table 4
Variations on daily energy efficiency and potable water produced from TSS using eggshell as energy storage at different water thickness

Water thickness (mm)	Daily energy efficiency (%)		Potable water produced (kg)		Performance enhancement ratio of potable water produced (Y_{est}/Y)
	TSS	TSS with eggshell as energy storage	TSS (Y)	TSS with eggshell as energy storage (Y_{est})	
10	33.56	79.19	1.42	3.62	2.54
15	30.05	75.49	1.34	3.37	2.51
20	20.82	44.18	0.95	2.08	2.18

4. Conclusions

The following are the primary conclusions reached as a consequence of the experimental work:

- Using eggshell powder as an energy storage medium, it was found that the mean water temperature during the lower intensity phase from the TSS using eggshell powder as energy storage was 44.1, 44.5, and 44.8 °C for water thicknesses of 10, 15, and 20 mm, respectively.
- When using a high thermal conductivity energy storage material in the absorber, the average temperature of the water is enhanced by 10.8, 10.9, and 8.73 % for water thicknesses of 10, 15, and 20 mm, respectively, under the impact of eggshell powder as energy storage material.
- There is an improvement in potable water of about 60.77% with the use of eggshells as energy storage in the basin.
- At a constant thickness of water 10 mm maintained inside the basin, the peak recorded yield from the solar still is found to be 0.6 and 0.34 kg for solar stills with eggshell powder as energy storage material and without eggshell powder in the absorber of TSS, respectively.
- Compared to the flat absorber without eggshell powder as a sensible heat-storing material, the hourly potable water produced from TSS with eggshell as an energy storage material increased by around 47 %.
- For water thicknesses of 10, 15, and 20 mm in the basin, the daily energy efficiency of TSS with eggshell powder as energy storage is calculated as 79.19, 75.49, and 44.18 %, respectively.
- The average yield from the tubular solar still with eggshell as energy storage material and tubular solar still without any material at the lowest water thickness of 10 mm is found as 3.62 and 1.42 kg respectively.
- The performance improvement ratio of SS is computed as 2.54, 2.51, and 2.18 for water thicknesses of 10, 15, and 20 mm, respectively.

Abbreviations

hfg Latent heat of condensation (J/kgK)

I(t) Solar radiation (W/m²)

TSS Tubular solar still

EM Energy material

SM Servotherm

m_e Mass of distillate collected (kg)

Declarations

Contributions

Amrit Kumar Thakur - Conceptualization, methodology, software, Software, investigation, validation.

Ravishankar Sathyamurthy - Conceptualization, methodology, software, Software, investigation, validation, Writing – reviewing; formal analysis, project administration, supervision.

Ethical approval

Not applicable.

Consent to participate

Not applicable.

Consent to publish

Not applicable.

Competing interests

The authors declare no competing interests.

Availability of data and materials

Not applicable.

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Figures

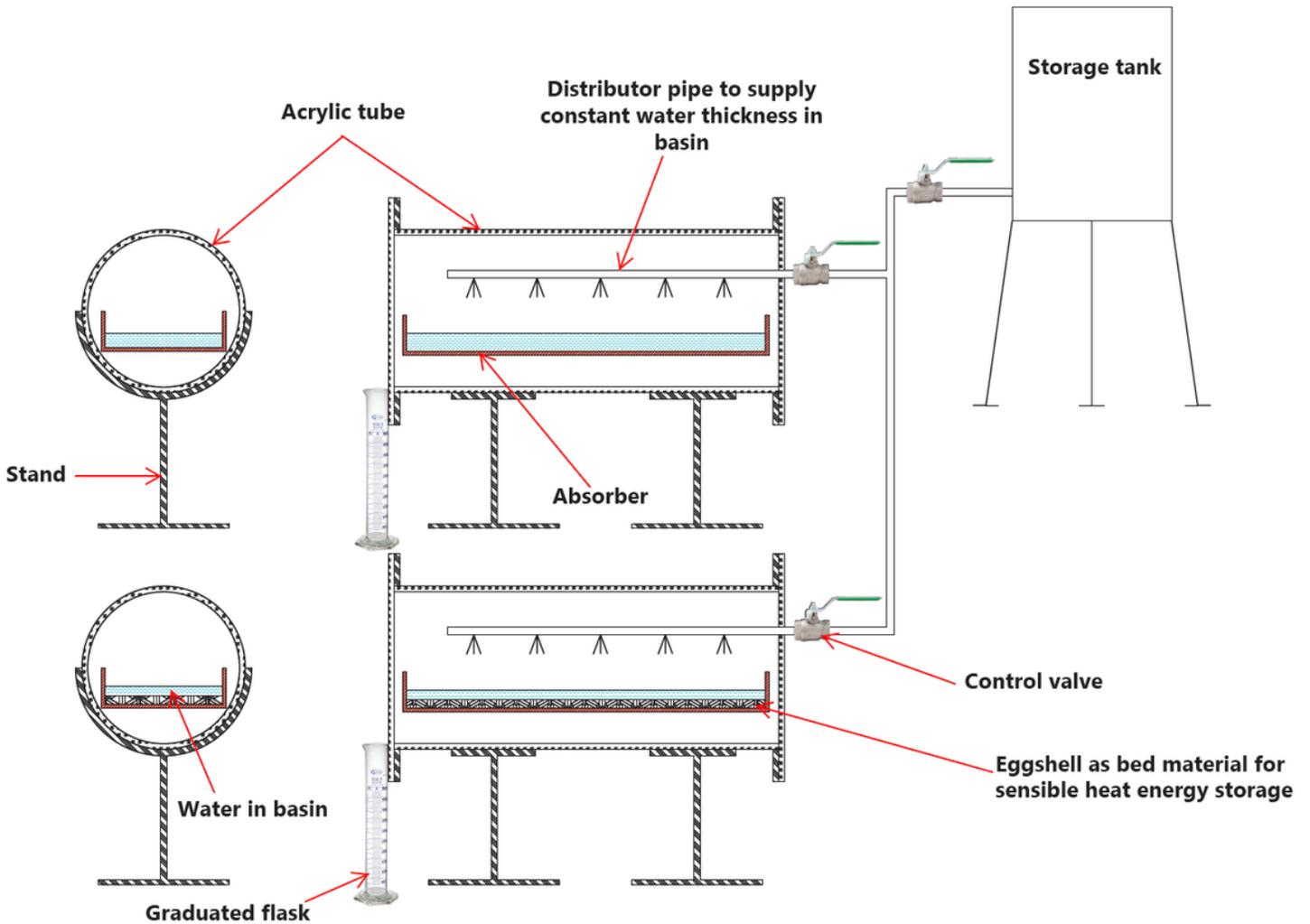
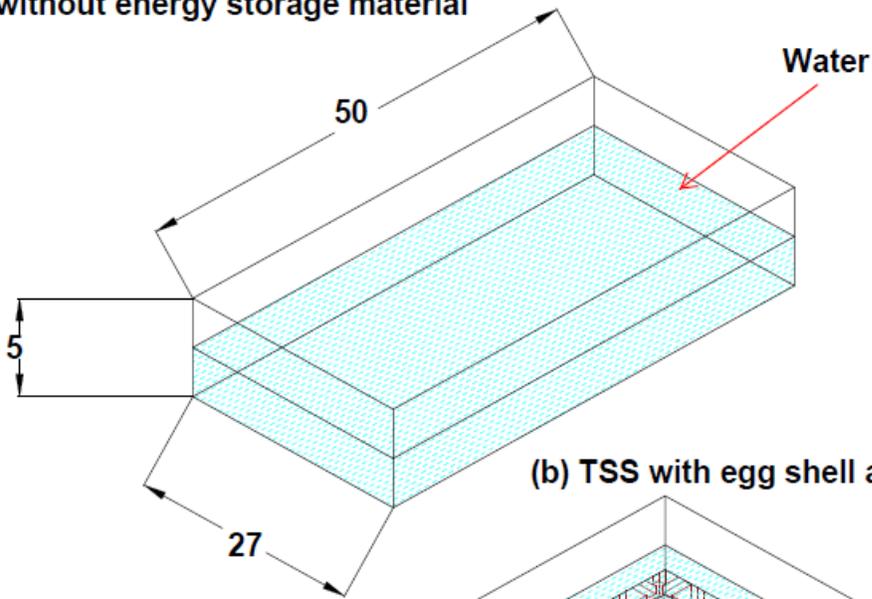


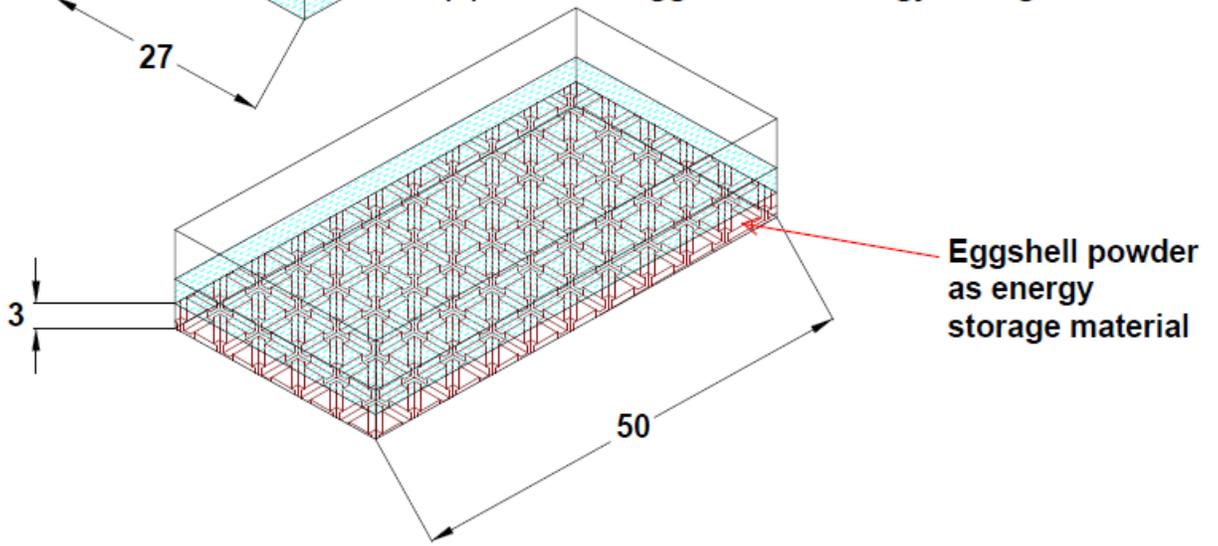
Figure 1

Schematic of the experimental setup

(a) TSS without energy storage material



(b) TSS with egg shell as energy storage material



All dimensions are in cm

Figure 2

Dimensions of absorber plate of tubular solar still (a) without energy storage (b) with eggshell as energy storage

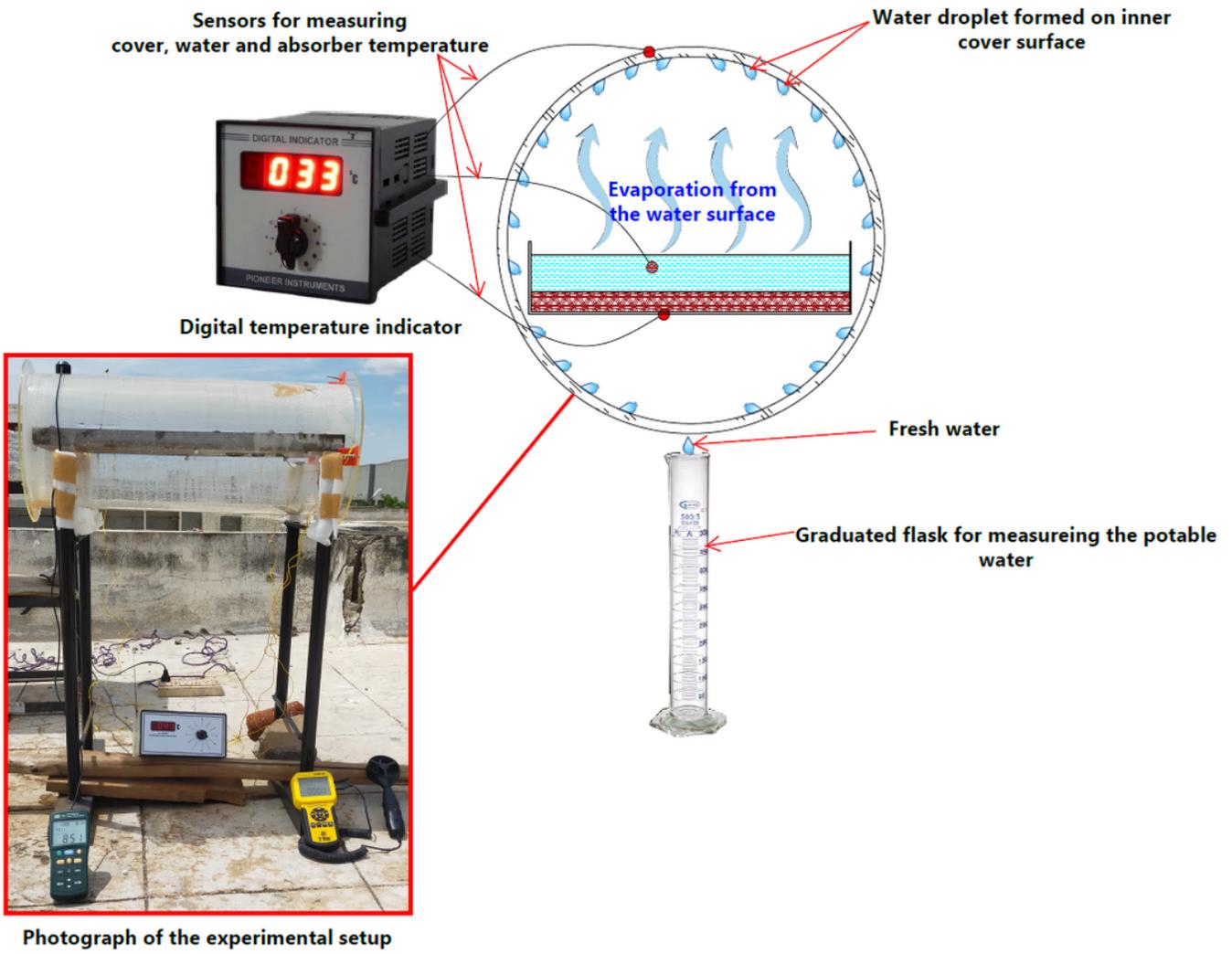


Figure 3

Mechanism and photograph of the experimental setup

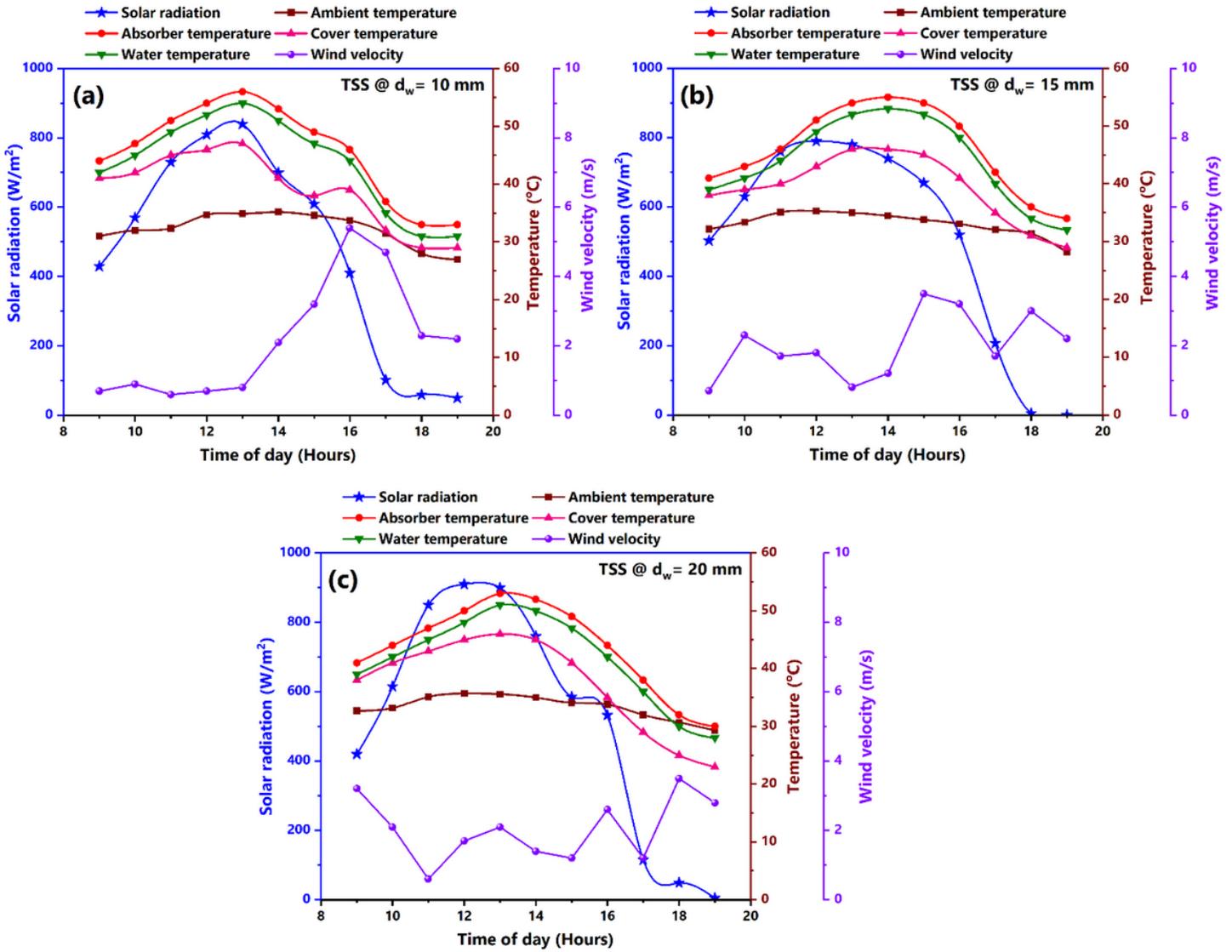


Figure 4

Variations on wind velocity, solar radiation, ambient, absorber, water, cover temperature of TSS without energy storage for water thickness of (a) 10, (b) 15 and (c) 20 mm

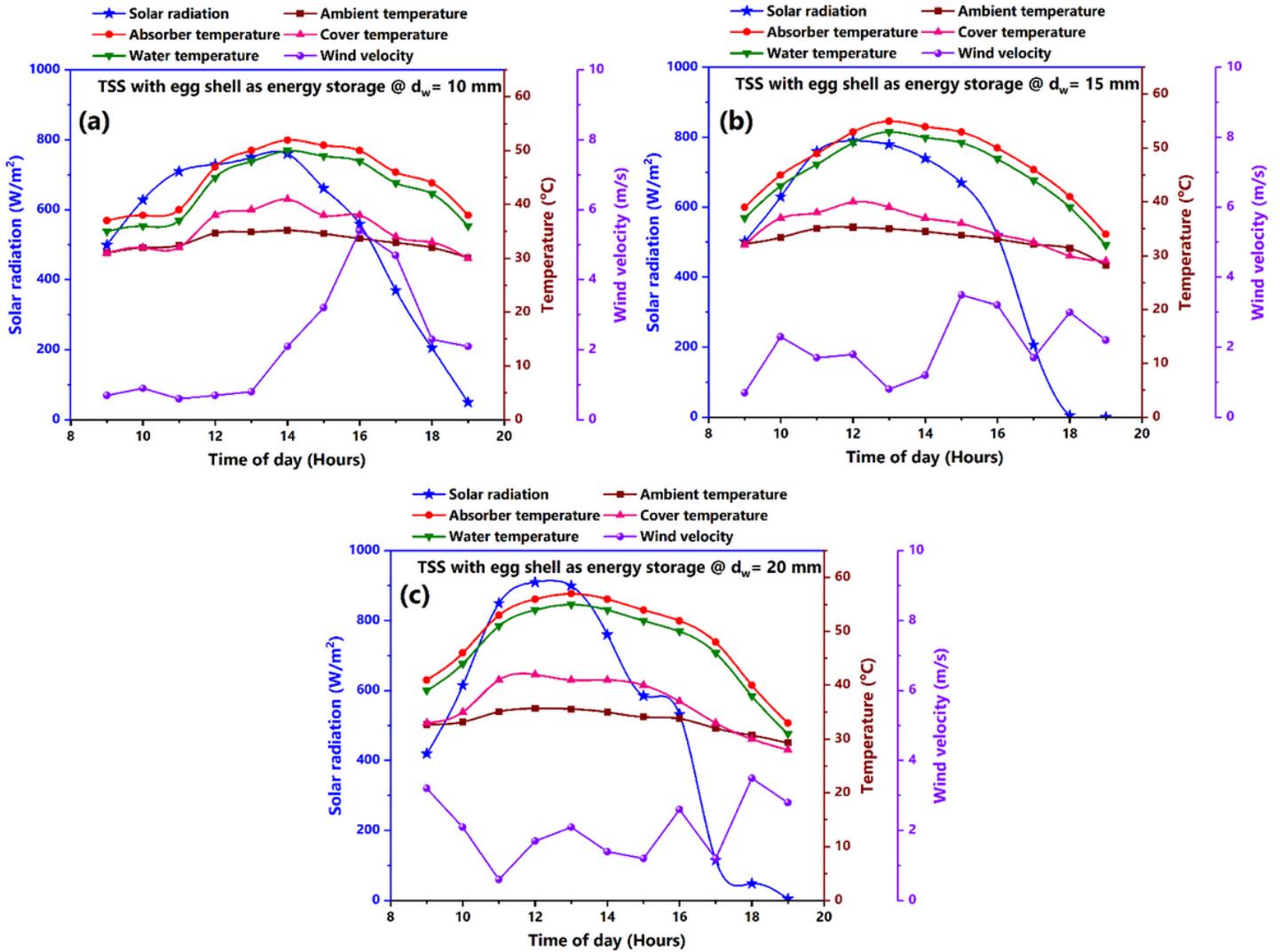


Figure 5

Variations on wind velocity, solar radiation, ambient, absorber, water, cover temperature of TSS with eggshell powder as energy storage for water thickness of (a) 10, (b) 15, and (c) 20 mm

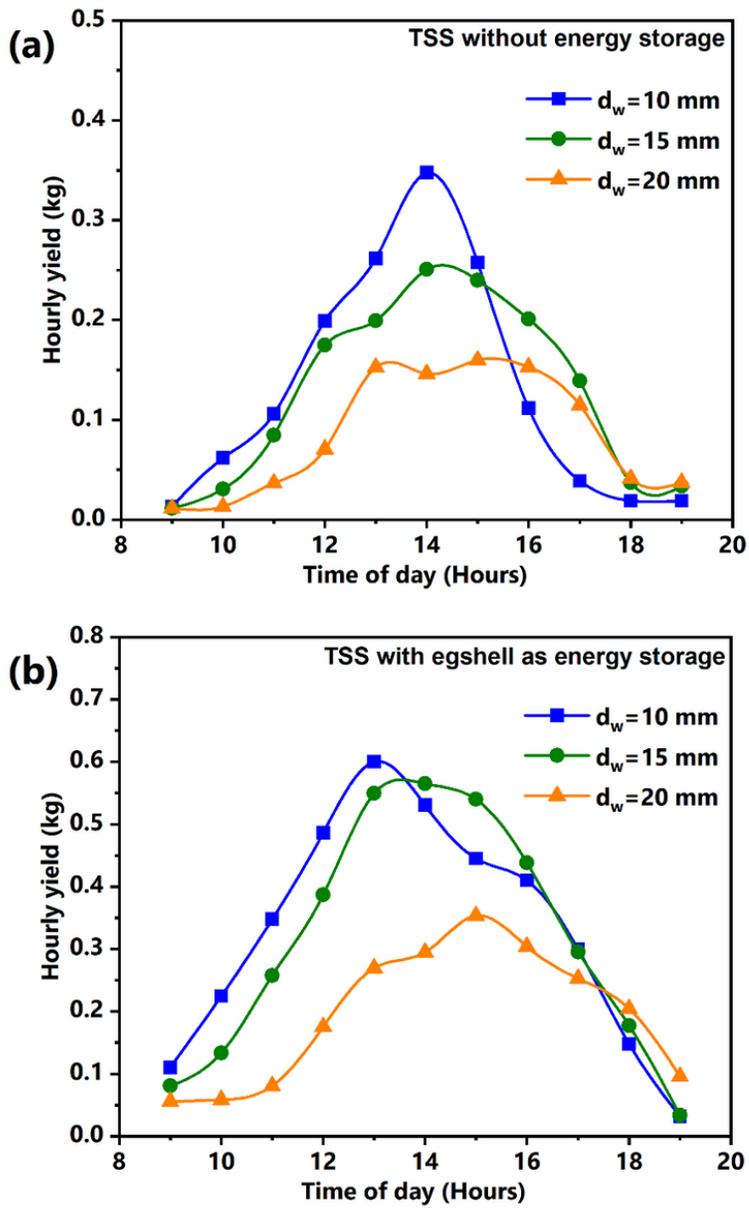


Figure 6

Hourly potable water produced from TSS without and with eggshell as energy storage material at various thicknesses of water in the absorber