Augmentation of distillate yield in “V”-type inclined wick solar still with cotton gauze cooling under regenerative effect

P.U. Suneesh¹,², John Paul³, R. Jayaprakash⁴*, Sanjay Kumar⁴ and David Denkenberger⁵

Abstract: Water flowing over bare glass is not evenly distributed over the width of the glass cover. Effective temperature reduction in the glass cover is not possible in this case. Thin cotton gauze is used over the glass cover to solve this problem. The amount of water required to cool the glass cover is low and the flowing water is collected and fed into a hot water reservoir. Water from the hot water reservoir is directed to the wick absorber by a drip valve. The system was tested in two ways (i) regenerative effect with cotton gauze (ii) regenerative effect without cotton gauze. The inclined wick absorber ensures that the surface is always wet due to capillary action and there were no dry spots. Excess flow in the wick absorber is pumped back to the hot water reservoir. Due to low thermal inertia of the wick and regenerative effect, the system has quick start-up times, as well as higher operating temperatures. This resulted in higher distillate yield than simple solar stills. Since the hot water reservoir remained warm enough during the night hours, a reasonable amount of nocturnal distillate output was also obtained. Optimum inclination of the wick absorber was found to be 20° and mass flow rate through the wick absorber was 200 ml/minute. The system with cotton gauze produced distillate yield of 6,300 ml/m² whereas the system without cotton gauze produced distillate yield of 5,600 ml/m².

ABOUT THE AUTHOR
P.U. Suneesh is an assistant professor in the Department of Applied Science, MES College of Engineering, Kuttippuram, Kerala affiliated to Kerala Technological University. He received his MSc degree in Physics from Calicut University and MPhil degree in Solid State Physics from Bharathidasan University, Trichy, Tamilnadu. He has more than 10 years experience of teaching Physics to undergraduate engineering students. He has published eight research papers in reputed journals. His research interests include Renewable energy, Nano gas sensors, and Desalination. His research work is associated with Research and Development Centre, Solar Energy Laboratory, Department of Physics and Civil and Architectural Engineering, Tennessee State University, Tennessee, USA. The major goal of this work was to increase the distillate yield using locally available cheap/waste materials. South India is famous for textile industry and plenty of cotton waste materials are available.

PUBLIC INTEREST STATEMENT
A solar still converts salt/brackish water into potable water using solar radiation. The basin heats up due to radiation and eventually water in the basin/absorber evaporates and condenses on the glass cover. The temperature gradient between the evaporating surface and condensing surface plays an important role in the distillate yield. In this work, the temperature difference between the glass and the basin was increased by cooling the glass cover using water flow over the glass cover. For low flow rates (75 ml/min, 150 ml/min etc.), water flowing over the glass cover is not evenly distributed. This can be solved using very thin cotton gauze over the glass cover. For high flow rates, the flow will be turbulent and more amount of water is required to cool. The flowing water sorted in the hot water reservoir for regenerative effect.
1. Introduction

A chronic drinking water shortage is one of the most important issues in the developing countries, and drinking water from dirty water sources causes serious damage to health, especially in infants, children, and elderly people. The lack of potable water is a big problem in many areas. Underground water, where exists, is sometimes salty and cannot be used for drinking. Solar stills can be used for low-capacity and self-reliant water supply systems, since they can produce drinking water by solar energy only, and do not need other energy sources such as fuel or electricity. Renewable energy sources have been used to supply thermal and/or electrical energies for desalination in remote areas. Among these sources is solar energy, which has gained increasing attention because of its abundance in locations suffering from lack of fresh water. Wick-type solar stills are widely accepted and are known for their high distillate yield. Wick-type stills show improved distillate yield compared to the conventional water-filled stills (Velmurugan, Gopalakrishnan, Raghu, & Srithar, 2000). A study reported on improved design of a single slope coupled to a wick in order to enhance still output. The energy absorbed by the absorber basin is mostly transferred to the water. In water filled systems, much of the morning solar energy is used for providing sensible heat so (Minasian & Al-Karaghouli, 1995) most of the water filled systems show high distillate yield after noon.

Performance of a tilted-wick-type solar still with the effect of water flowing over the glass has been studied (Janarthanan, Chandrasekaran, & Kumar, 2006) and the conclusion was that glass cover temperature decreases significantly due to the water flowing over the glass cover which causes fast internal evaporation during peak sunny hours. The authors recorded an optimum rate of water flow 1.5 m/s over the glass cover. Several approaches have been used to cool the glass cover and to utilize the latent heat of condensation released into the glass cover (Tiwari & Bapeshwara Rao, 1984; Tiwari, Madhuri, & Garg, 1985), cooling by flowing water film on top of the glass cover. The main focus was to maintain a temperature difference between basin water and condensing cover in order to get high distillate output. Different types of wick materials have been used (Kalidasa Murugavel & Srithar, 2011) on a basin-type solar still and it was concluded that using a thin cotton wick optimized output. Performance of a “V”-type solar still with a charcoal absorber has been studied by Selvakumar, Kumar, and Jayaprakash (2008) and its advantages included the center collection of all the condensation. An inclined solar water distillation system was designed and tested under actual environmental conditions of northern Cyprus, and the system produces fresh water and hot water simultaneously (Aybar, Egelioğlu, & Atikol, 2005). Experimental performance evaluation of a stand-alone point focus parabolic solar still was conducted by Gorjian, Ghobadian, Tavakkoli Hashjin, and Banakar (2014) with two plate heat exchangers to pre-heat the salt water. The maximum productivity of 5.12 kg within 7 h in a day was measured with the maximum average solar insolation of 626.8 W/m². Somwanshi and Tiwari (2014) reported that solar still output enhances by flowing water from an air cooler over the glass cover. It was seen that for different climatic zones in the Indian plain, annual yield can be increase between 41.3% and 56.5%. Moreover, the distillate output increases slightly with an increase in the mass flow rate and tends to saturate around 0.075 kg/s. A solar water heater coupled with a still was studied by Sampathkumar and Senthilkumar (2012). The work reported that the storage water temperature reached 60°C and increased the yield by 77% compared to the passive still. Sakthivel, Shanmugasundaram, and Alwarsamy (2010) conducted an experimental study on a regenerative solar still with an energy storage medium—jute cloth. The jute cloth was kept vertical in the middle of basin saline water and also attached to the rear wall of the still. It was found that cumulative yield in the regenerative still with jute cloth increases approximately by 20% and efficiency increases by 8% with low cost as the jute cloth is very cheap and easily available. Malaiyappan and Elumalai (2016) have reported improved nocturnal output using a helical copper coil, aluminum fins, a long hollow stainless steel tube, and an iron plate coupled with the basin. The solar still with various basin materials arranged in a lengthwise direction was more effective, compared with the one arranged breadthwise. Refalo, Ghirlando, and Abela...
(2015) conducted experiments with a solar chimney and condenser coupled with solar still and found that the modified still generated 5.1 L/m² day with the majority of the yield (59%) condensing in the condensers of the still.

In the current work, an inclined wick-type solar still with water flowing over the top cover integrated with a hot water reservoir has been constructed. Unlike other solar stills with water flowing over the glass plate, the water flow over the glass here is made uniform by placing a thin layer of cotton gauze (Suneesh, Jayaprakash, Arunkumar, & Denkenberger, 2014). The cooling water is conveyed to a water reservoir which in turn is connected to the inclined wick absorber by a valve. The excess flow produced inside the still is pumped back to the water reservoir. This setup requires less amount of water to cool glass surface compared to other water flowing systems of its kind. So, a new attempt has been made using a regenerative effect for increasing yield rate due to supply of pre-heated water. Performance due to variation in mass flow rate inside the still and angle of inclination of wick absorber are also studied.

2. Materials and methods
A photographic view of the still is shown in Figure 1. Figure 2 shows the cotton gauze arrangement over the glass cover. Figure 3 shows a schematic diagram of solar still with a hot water reservoir. The length and breadth of wick absorber are 2 m and 0.75 m, respectively, and the area of wick absorber is 1.5 m². The wick absorber is inclined inward to the center of the still and the angle of inclination can be varied between 0° and 25°. Water fed into the wick absorber is spread under capillary action and no dry spots are produced. The excess water is pumped back to the water reservoir. An optimum inward slope is maintained for top cover, reported by Singh and Tiwari (2004) for India’s climatic conditions. An arrangement of water flowing over the glass cover of the solar still was made with the help of PVC pipe of ½ inch diameter. The length of the pipe was taken exactly equal to the width of the still so that the water would not flow in the lengthwise direction. An external water tank is used and is connected to distribution pipes on either side of the still as shown in the Figure 1. A number of holes were made in the pipe spaced equally to produce uniform flow over the glass cover. After the water flows over the glass, it is collected at the center of the still by a water collection channel and fed into the reservoir. The photographic view of the still with collection channels for distillate and water flowing over the glass is shown in Figure 4. A rectangular water reservoir of 50 l was designed; the side and bottom area of the water reservoir is insulated to minimize the heat loss. A valve is used to control the water flow from the hot water reservoir to the still. The water then trickles down through the wick, creating a layer of water all over the wick absorber. Some of the water evaporates and condenses as it touches the cool glass cover. The condensate flows into a central condensate channel and is taken out of the still. The rest of the fed water (excess flow), which is hot water, flows into another collection channel and is pumped back to the reservoir. A 20 W suction pump was used to pump the excess water to the hot water reservoir. The saline water is replaced periodically so that
Figure 2. Cotton gauze over the glass cover.

Figure 3. Schematic diagram of the solar still.

1. Water flowing over north and south facing glass is collected
2. Water is pumped to the hot water reservoir
3. Water flows from the reservoir to the tilt basin (flow under gravity)
4. Excess flow in the basin is pumped back to the reservoir

Figure 4. Photographic view of still showing collection channels for distillate and water flowing over glass.
no solids precipitate out. In the first mode of experiment (regenerative effect with cotton gauze), since cotton gauze spreads water uniformly over the glass cover, minimal water was used just to spread over the glass cover and the flow rate was 75 ml/min. The discharge amount per hour of water from the glass cover to the hot water reservoir was 4,500 ml (approximately). A 50 l hot water reservoir was sufficient to store the water for the 9 h (9.00 am–6.00 pm) of the experiment under regenerative effect. In the second mode of experiment, the still was tested without cotton gauze with same water flow rate over the glass cover.

The experimental study conducted from 9.00 am to 6.00 pm. Nocturnal output was also recorded. The performance of the still due to parameters like effect of water mass flow rate through wick absorber and angle of inclination of wick absorber were experimentally tested in typical sunny days. Solar radiation, temperature of hot water, and water collection at the outlet position were recorded at regular intervals.

3. Results and discussion

Variation of solar radiation and ambient temperature during the experiment is shown in Figure 5. Average radiation received was 665 W/m² and the ambient air temperature during the sunny days was measured between 24 and 36°C. The still technical and operational parameters are shown in Table 1. Accuracies and error for various measuring instruments are given in Table 2. The comparison of glass temperature of Figure 6 indicates a range of 34–53°C without cotton gauze and 34–48°C with cotton gauze. The temperature is relatively high for the still with water flow without cotton gauze. The test for the 15° inclined wick absorber with cotton gauze shows the effects of mass flow rate on the fresh water generation. As seen in Figure 7, the freshwater generation increases when the mass flow increases and then decreases for further increase in the mass flow rate. The test for the 20° inclined wick absorber shows optimum results. The results were of course also affected by environmental conditions, such as changing solar intensity, ambient temperature, and wind. In this study, the tests were performed and tabulated for 8 h. Average temperature of the hot water for the day ranges from 44 to 51°C for the 15° wick absorber, 43 to 48°C for the 20° wick absorber, and 43 to 46°C for the 25° wick absorber (Figure 8). Results of distillate output show that the best output is 6,300 ml/m² for 200 ml/min mass flow rate at an inclined angle 20° of wick absorber. The still shows significant distillate yield rate even after sunset irrespective of tilts and flow parameters. This is mainly due to the hot water in the reservoir. The average hot water reservoir temperature during the
The study was 46°C. Hot water from the reservoir enhances evaporation as the water acquires latent heat of condensation due to the regenerative effect which enhances nocturnal yield rate. The average nocturnal yield rate during the experiment was 1,571 ml/m². Performance of the still without cotton gauze is shown in Figure 9. Under optimal conditions, distillate yield drops to 5,600 ml/m². Figure 10 shows the variation in the hot water reservoir (average) temperature with respect to mass flow rate and tilt angle. The results reveal that water cooling with cotton gauze enhances the still performance.

Table 1. Still technical and operation details

| Sl. No. | Climatic conditions | Parameter                   | Value  |
|---------|---------------------|-----------------------------|--------|
| 1       | Clear sky           | Solar radiation (W/m²)      | 0–950  |
|         |                     | Ambient (°C)                | 24–35  |
|         |                     | Relative humidity (%)       | 22–35  |
|         |                     | Average wind velocity (m/s) | 1      |
| 2       | Design              | Basin absorptivity (αₐ)     | 0.90   |
|         |                     | Basin emissivity (Ɛₑ)       | 0.90   |
|         |                     | Absorptivity of cover (αₑ) | 0.08   |
|         |                     | Reflectance of cover        | 0.07   |
|         |                     | Transmittance of glass (τₑ) | 0.85   |
|         |                     | Specific heat of water (Cₚ) | 4,190 J/kg K |
|         |                     | Length (m)                  | 2      |
|         |                     | Breadth (m)                 | 0.75   |
|         |                     | Thickness of cotton gauze (m) | 2.00 × 10⁻⁴ |

Table 2. Accuracies and error for various measuring instruments

| Sl. No. | Instrument      | Accuracy | Range       | % Error |
|---------|-----------------|----------|-------------|---------|
| 1       | Pyranometer     | ±30 W/m² | 0–1,800 W/m² | 3       |
| 2       | Digital thermometer | ±1°C   | 0–100°C   | 2       |
| 3       | Thermocouple    | ±1°C     | 0–100°C    | 2       |
| 4       | Anemometer      | ±0.2 m/s | 0.4–30.0 m/s | 1       |
| 5       | Measure jar     | ±10 ml   | 0–1,000 ml | 2       |

Figure 6. Variation of glass temperature.
Figure 7. Variation of distillate yields with respect to mass flow rate and tilt angle (with cotton gauze).

Figure 8. Variation of hot water reservoir temperature (average) with respect to mass flow rate and tilt angle (with cotton gauze).

Figure 9. Variation of distillate yields with respect to mass flow rate and tilt angle (without cotton gauze).
The efficiency of the still is given by:

$$\eta = \frac{M}{L \cdot I \cdot A \cdot t}$$

where $M$ is the mass of distillate output (kg); $L$ is the latent heat of vaporization (J/kg); $I$ is the intensity of solar radiation (W/m²); $A$ is the area of wick absorber (m²); $t$ is the time (s).

Figure 11 shows the variation of efficiency with respect to mass flow rate and tilt angle for the still with cotton gauze cooling. Analysis of the graph reveals that effect of mass flow rate is more important than absorber tilt angle. The average efficiency for tilt angles 15°, 20°, and 25° with mass flow rate of 150 ml/min is 63%, the average efficiency for the same angles with mass flow rate of 200 ml/min is 66%, while the average efficiency for the same angles with mass flow rate of 350 ml/min is 52%. An increase in the 150 ml/min flow rate causes a 14% point or 22% drop in the efficiency of the still. The optimum inclination of the wick absorber was 20° for each flow rate. The wick stayed wetted regardless of the tilt angle, so different mass transfer coefficients are not likely to explain the difference.
Figure 12. Variation of efficiency with respect to mass flow rate and tilt angle (without cotton gauze).

Larger tilt angles create more surface area to evaporate from, which would likely be beneficial. However, this would also indicate a lower absorber temperature, which may not be beneficial. The interaction of these effects might produce the optimum behavior. Efficiency of the still under optimum conditions of 20° tilt and 200 ml/min was 68%. The average efficiency of the still during the study was 60%. Higher mass flow rate means that the water heats up less as it moves across the absorber. This may mean lower efficiency. However, higher mass flow rate also means that the water heats up less as it moves across the glass, which would mean less loss to the air. It appears that this effect is stronger than the reduction in the efficiency at the absorber. Figure 12 shows the efficiency of the still without cotton gauze cooling. Efficiency of the still drops to 57% under optimum conditions of 20° tilt and 200 ml/min mass flow rate. The comparison of efficiencies under optimum conditions of the still with cotton gauze and without cotton gauze cooling reveals that efficiency of the still without cotton gauze cooling under regenerative effect decreases 11% points to 57%.

Comparing to a basin-type solar still of its kind (Hongfei & Xinshi, 2002) under similar conditions, we see that the efficiency is higher. This means that the advantage of regenerating the latent heat of condensation into sensible heat in the water flowing over the glass is greater than the disadvantage of losing heat to evaporation to the environment. However, it may be possible to overcome this disadvantage by having another layer of glass that would collect this evaporated water from the saline water flowing over the lower glass layer. This would have a further advantage of capturing all the water that is evaporated, meaning less supply saline water is required for a given amount of freshwater. Conversely, with the single glass layer system, if the average saline concentration is to be the same as a conventional solar still, the saline water would have to be changed more frequently. If the saline water is of limited supply and therefore cannot be changed frequently, this single glass layer system would be more appropriate for brackish water.

4. Conclusion

A “V”-type inclined wick solar still with water flowing over glass cover incorporating the regenerative effect was designed and tested under actual environmental conditions of Tamilnadu (India). The system generates fresh water, which is collected. Performance of the still due to variation in mass flow rate and angle of inclination of the wick absorber is studied. The optimum inclination of the wick absorber was 20° and mass flow rate was 200 ml/min. Efficiency of the still in optimum conditions with cotton gauze was 68% and average efficiency during the study was 60%. One main advantage of still is the improved distillate yield after sunset. In addition to the day time 9-h distillate output the system produces 1,571 ml/m² over-night.
Funding
The authors received no direct funding for this research.

Author details
P. U. Suneesh1,2
E-mail: suneeshtvr@gmail.com
John Paul2
E-mail: john.me13@yahoo.com
Jayaprakash3
E-mail: jprakash_jpr@rediffmail.com
Sanjay Kumar4
E-mail: prof ssinha@gmail.com
R. Jayaprakash3
E-mail: john.me13@yahoo.com
P. U. Suneesh1,2
E-mail: suneeshtvr@gmail.com

References
Aybar, Hikmet S., Egelioğlu, F., & Atikol, U. (2005). An experimental study on an inclined solar water distillation system. Desalination, 180, 285–289. http://dx.doi.org/10.1016/j.desal.2005.01.009
Gorjian, S., G pobadian, B., Tavakkoli Hashjin, T., & Banakar, A. (2014). Experimental performance evaluation of a stand-alone point-focus parabolic solar still. Desalination, 352, 1–17. http://dx.doi.org/10.1016/j.desal.2014.08.005
Hongfei, Z., & Xinshi, G. (2002). Steady state experimental study of a closed recycle solar still with enhanced falling film evaporation and regeneration. Renewable Energy, 26, 295–308.
Janarthanan, B., Chandrasekaran, J., & Kumar, S (2006). Performance of floating cum tilted-wick type solar still with the effect of water flowing over the glass cover. Desalination, 190, 51–62. http://dx.doi.org/10.1016/j.desal.2005.08.005
Kalidas Murugavel, K., & Srithar, K. (2011). Performance study on basin type double slope solar still with different wick materials and minimum mass of water. Renewable Energy, 36, 612–620. http://dx.doi.org/10.1016/j.renene.2010.08.009
Malajyoppop, P., & Elumalai, N. (2016). Productivity enhancement of a single basin and single slope solar still coupled with various basin materials. Desalination and Water Treatment, 57, 5700–5714. http://dx.doi.org/10.1080/19443994.2014.1003973
Minsian, A. N., & Al-Kaorioughi, A. A. (1993). An improved solar still: The wick basin type. Energy Conversion and Management, 36, 213–217. http://dx.doi.org/10.1016/0196-8904(94)00053-3
Refalo, P., Ghirlando, R., & Abela, S. (2015). The use of a solar chimney and condensers to enhance the productivity of a solar still. Desalination and Water Treatment, 56, 1–14. http://dx.doi.org/10.1080/19443994.2015.1106096
Sakthivel, M., Shanmugasundaram, S., & Alwarsamy, T. (2010). An experimental study on a regenerative solar still with energy storage medium—Jute cloth. Desalination, 264, 24–31. http://dx.doi.org/10.1016/j.desal.2010.06.074
Sampathkumar, K., & Senthilkumar, P. (2012). Utilization of solar water heater in a single basin solar still—An experimental study. Desalination, 297, 8–19. http://dx.doi.org/10.1016/j.desal.2012.04.012
Selvakumar, B., Kumar, S., & Jayaprakash, R. (2008). Performance analysis of a “V” type solar still using charcoal absorber and boosting mirror. Desalination, 229, 217–230.
Singh, H. N., & Tiwari, G. N. (2006). Monthly performance of passive and active solar stills for different Indian climatic conditions. Desalination, 168, 145–150. http://dx.doi.org/10.1016/j.desal.2004.06.180
Somwanshi, A., & Tiwari, A. K. (2014). Performance enhancement of a single basin solar still with flow of water from an air cooler on the cover. Desalination, 352, 92–102.
Suneesh, P. U., Jayaprakash, R., Arunkumar, T., & Denkenberger, D. (2016). Effect of air flow on “V” type solar still with cotton gauze cooling. Desalination, 337, 1–5. http://dx.doi.org/10.1016/j.desal.2013.12.035
Tiwari, G. N., & Bapeshwara Rao, V. S. (1984). Transient performance of a single basin solar still with water flowing over the glass cover. Desalination, 49, 231–241. http://dx.doi.org/10.1016/0011-9164(84)85035-3
Tiwari, G. N., Madhuri., & Garg, H. P. (1985). Effect of water flow over the glass cover of a single basin solar still with an intermittent flow of waste hot water in the basin. Energy Conversion and Management, 25, 315–322.
Velmurugan, V. J., Gopalakrishnan, M., Raghu, R., & Srithar, K. (2000). Single basin solar still with fin for enhancing productivity. Energy Conversion and Management, 49, 2602–2608.