EXPERIMENTAL INVESTIGATION AND COMPARISON OF DESALINATION USING CONVENTIONAL SOLAR STILL, STEPPED-CUP SOLAR STILL WITH AND WITHOUT BIOMASS

by

Ramji CHANDRAN[a*], Raja KANDHASAMY[a], Chandra Sekar VELAN SUBRAMANIAN[a], Srinivasa Raman VEERANAN[a], and Dhanabalan SUBRAMANIYAN[b]

[a] Department of Mechanical Engineering, University College of Engineering Dindigul, Dingidul, Tamilnadu, India
[b] Department of Mechanical Engineering, M. Kumarasamy College of Engineering, Karur, Tamilnadu, India

Original scientific paper
https://doi.org/10.2298/TSCI190409356C

Desalination of water has become one of the vital areas of research because of the increasing demand for fresh water. The usage of solar stills is one of the conventional methods for the process of desalination. In this paper, a novel design variation is given to the conventional solar still to increase the productivity of desalination. The plain basin plate of the conventional still is replaced with steps with cup shaped trays. Experiment has been done to measure the hourly desalinate productivity of both conventional solar still and the stepped-cup solar still in the month of May in Tamilnadu, India. Further, a biomass boiler is connected to the stepped-cup solar still to increase the heat inside the still. Productivity of the stepped-cup solar still with the biomass boiler set-up has been measured and compared with the productivity of conventional solar still. Results have shown that the proposed stepped-cup solar still design has increased the productivity by 12% compared to the conventional still. Also, the productivity of the stepped-cup solar still has shown an enormous 70% increase on the addition of the biomass when compared to the conventional solar still.

Key words: *desalination, stepped cup solar still, biomass heating*

Introduction

Earth is the only human living planet having water in our solar system, out of which 97% of water is salty and only 2.6% is fresh water. The fresh water sources like ponds, lake, and river are getting polluted due to environmental pollution and hence there is an increasing scarcity of and demand for fresh water. Desalination of sea water could bring the complete solution for the fresh water problem. In the early decades of the new millennium, various methods have been developed to desalinate the sea water such as reverse osmosis (RO), multi-stage flash (MSF), multi-effect distillation (MEF), and electro dialysis. Of these, the reverse osmosis and the electro dialysis are cost-effective conventional methods. Though there are various methods to distill fresh water from sea water the simplest method is the conventional solar still. Solar energy which plays an important role in the process of desalination is obtained from the Sun.

* Corresponding author, e-mail: ramjic.06@gmail.com

Earth's surface receives 70% of the total solar energy radiation which is about 174000 TW. Solar stills are used in the process of desalination by using solar energy radiation as an energy source. The best desalination technique is the one which has high efficiency at low cost, and solar stills are low in cost, simple in construction and easy to operate. Since the efficiency of the solar still is comparatively low this paper advocates a modification in design.

Various design modifications to a basic solar still are advocated in the literature to increase the efficiency of desalination. Moustafa *et al.* [1] investigated and compared basin type stepped solar still with wick-type still. The wick-type evaporator collector system showed an increase in overall efficiency when compared to the basin-type system. A flat plate collector added to a single basin solar still was designed by Tiris *et al.* [2] and was found that there was a 52% increase in the productivity. Zurigat *et al.* [3] constructed a regenerative solar desalination unit using double glass cover which increased the productivity by 20%. Asymmetrical and symmetrical greenhouse type solar stills were studied by Al-Hayek *et al.* [4]. Saravana Kumar *et al.* [5] and Govindasamy *et al.* [6] said that emission reduction can be done by using corn oil and Spirulina Algae. A triple-basin solar still was constructed by El-Sebaii [7] for enhancing the productivity. Velmurugan *et al.* [8, 9] incorporated a mini solar pond for improving the productivity of solar still and also discussed about several applications of solar pond [10]. A stepped solar still was designed by Velmurugan *et al.* [11] and its performance was analyzed. An altered stepped solar still with a flashing chamber was constructed and examined by El-Zahaby *et al.* [12].

Researchers have improved the performance of the solar still by incorporating various thermal storage materials into the still. A multi basin solar still was developed by Senthil Rajan *et al.* [13] enhance the productivity. To further increase the performance of the still sensible heat materials like sand, cement block, glass, and latent heat storage materials such as wax were added. A 73% increase in productivity was obtained by using sensible heat storage material when compared to the conventional solar still. Kalidasa Murugavel *et al.* [14] incorporated sensible heat storage materials such as cement concrete pieces, quartzite rock, washed stones, iron scraps, and red brick pieces into the still and found that an inch quartzite rock showed increased productivity than the other materials. Pradeep Mohan Kumar *et al.* [15] carried out computational analysis and optimization of Spiral Plate Heat Exchanger. Velmurugan *et al.* [16] integrated fins, sponges and pebbles into a stepped solar still and analysed its performance. Avudaiappan *et al.* [17] analysed the flow using using simulation method. Dhandayuthabani *et al.* [18] Inclusion of graphite to the medium increases stability and thermal conductivity of PCM.

Omara *et al.* [19] constructed a modified stepped solar still with and without reflector and found that there was a 20% increase in the daily efficiency of modified solar still than a conventional solar still.

In this paper, a new design variation is given to the stepped cup still. The steps of the solar still are replaced with a cup shaped tray. An experimental investigation is carried out on the stepped-cup solar still in the climatic condition of Tamilnadu, India.

Experimentation

The conventional solar still is constructed using galvanized steel of 1.6 mm thickness in which the base of the solar still is made of a steel box of 600 mm length and 600 mm breadth. The solar still basin plate is mounted at the height of 550 mm at the top and 200 mm at the bottom. The glass is mounted over the still at an angle of 30°. A transparent tempered glass cover is used in this experiment which acts as a condensing cover and also allows the solar radiation to reach the basin plate. The thickness of the glass is 4 mm, height of the glass is 700 mm and the breadth is 600 mm. The solar still is completely sealed with silicon to prevent the vapor escaping out. Water temperature and glass temperatures are measured using thermocouples. On account of solar radiation the temperature of the water inside the still increases and condensation process takes place. The water vapor gets condensed on the glass cover. A stopper is provided at the bottom of the glass to collect the condensed water in the collection tank.

The stepped-cup solar still is constructed with the same dimensions as of the conventional solar still. The plain basin plate of the conventional solar still is replaced with steps at an angle of 30°. The steps of the still are trays that are curved cup like structures. This stepped-cup tray structure can provide more volume of sea water to flow inside the still thereby increasing the amount of condensation. The stepped cups are made up of galvanized steel. The diameter of the cup is 80 mm and height of the cup is 40 mm. A channel is provided at the top for the sea water to enter the still. The entered water flows down and fills the cup in each step due to gravity. Water temperature and glass temperatures are measured.

The amount of solar radiation obtained may vary from time to time throughout the day. This may cause variation in temperature inside the still and thus varying the efficiency of desalination. To maintain a constant temperature biomass set-up is connected to the still. The term biomass refers to the renewable energy produced from burning or decaying of the organic materials like plant and animal waste and in this experiment the organic waste burnt is the coconut husk. The calorific value of coconut husk is 4300 KCal/kg. The dimensions of the biomass boiler are 133 mm outer diameter and 550 mm height. The lower portion of the boiler is called the furnace. The biomass material *viz.*, coconut husk is burnt in the furnace to supply heat to the boiler. The ashes are removed and the coconut husk is added so as to maintain the boiler temperature at 80 °C. Hot water from the biomass boiler enters and flows continuously through the still. Each cup of the still contains two heat exchanger tubes arranged in parallel. Hot water flowing through the tube delivers heat to the sea water present inside the still. This arrangement further increases the temperature of the sea water and thus increases the efficiency of desalination. The inlet and outlet temperatures of heat exchanger are measured using digital temperature indicator. Inlet temperature of heat exchanger is maintained at 80 °C. Valves and pressure gauge are equipped to ensure safety. Hot water is circulated continuously throughout the experiment and the circulation is done by motor pump in the water circuit. The fresh water is collected and the quantity is measured. Figure 1 gives the experimental set-up of stepped-cup solar still with biomass.

Figure 1. Photograph of the experimental set-up of stepped-cup solar still with biomass

Error analysis

Digital temperature indicator, Kipp-Zonan solarimeter, vane type digital anemometers, and beaker are used to measure temperature, solar intensity, wind velocity, and the amount of distillate collected. The errors occurred in these measuring instruments are tabulated in tab. 1.

Table 1. Error analysis

Instrumentation	Error [%]
Digital temperature indicator	1 1/32 = 0.03125
Digital anemometer	0.1/0.1 = 1
Kipp-Zonansolarimeter	1/250 = 0.004
Beaker	5/60 = 0.0833

Results and discussion

A solar still was constructed with aforementioned dimensions. Experiment was done for the desalination of sea water using this set-up under the climatic condition of Tamilnadu, India and the results have been analyzed.

Conventional solar still

Sea water was passed into the conventional solar still *via* inlet. The water gets condensed and was collected at the outlet placed at the bottom of the still. The water temperature and glass temperature of the conventional solar still was measured periodically at every hour using thermocouples. The variation of the water temperature throughout the day is plotted in fig. 2(a). It is seen that the temperature is low at morning, high around noon and decreases in the evening. Hourly productivity is plotted against time and is shown in fig. 4(c). It is apparent that the productivity of the desalinated water increases with increase in temperature.

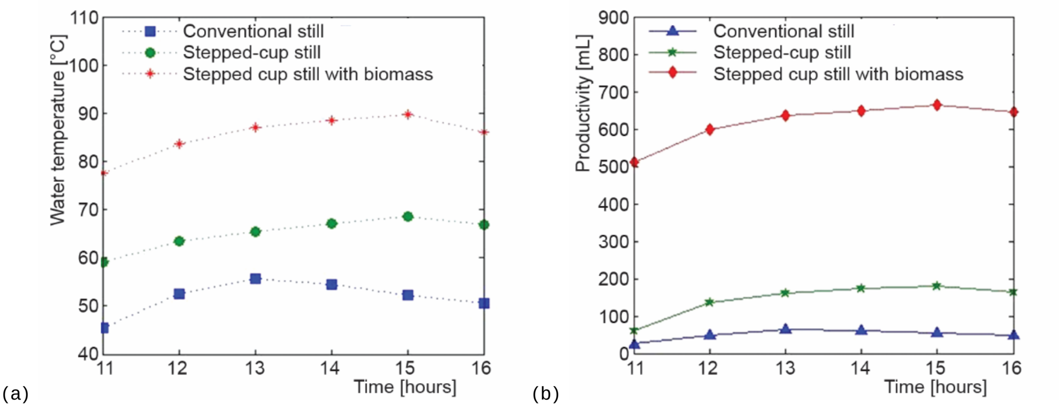


Figure 2. (a) Variation of water temperature with time, (b) variation of productivity *vs.* time in conventional, stepped-cup, and stepped-cup with biomass stills

Stepped-cup solar still

Desalinated sea water from the stepped-cup set-up was collected every hour. The water temperature, glass temperature and productivity of the collected desalinated water were measured. The variation of the water temperature throughout the day is plotted in fig. 2(a). It is seen that the temperature is low at morning, high around noon and decreases in the evening. In fig. 2(b), the productivity of desalinated water is plotted against time. The productivity increases at higher temperatures. It has been observed that the efficiency of desalination process increases due to the stepped-cup design proposed in this paper. Productivity reaches peak value around 14.00-15.00 hours and decreases slightly after 15.00 hours. There is no drastic decrease in the productivity after 15.00 hours due to the stepped-cup design. The stepped-cup design retains the temperature inside the still and produces output almost at a constant rate. This construction provides 12% increase in the efficiency compared to the conventional solar still.

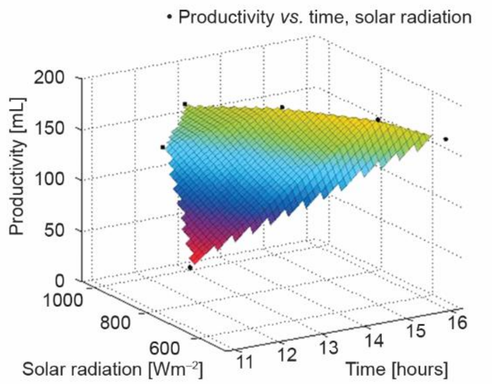
Stepped-cup solar still with biomass

Desalinated water was collected every hour after connecting the biomass boiler set-up to the stepped-cup solar still. The water temperature, glass temperature, inlet and outlet temperatures of the heat exchanger and productivity of the collected desalinated water were measured. It is observed that after the addition of biomass boiler higher temperature is maintained throughout the day. Productivity of desalinated water is compared with time and plotted in fig. 4(c). Net productivity increases due to higher temperature.

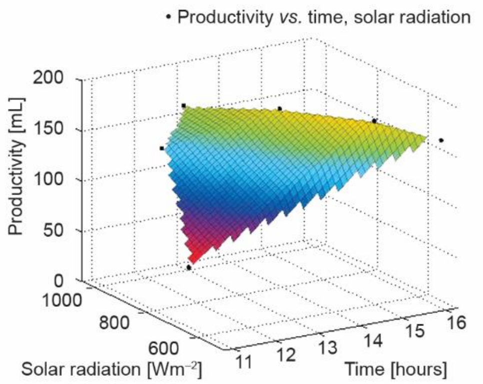
Productivity of desalinated water using stepped-cup solar still with and without biomass is compared with the productivity of a conventional solar still and is plotted in fig. 4(c). It is evident that the efficiency of desalination of sea water has increased by 12% using the stepped-cup design. Also there is an abundant 70% increase in the productivity after the addition of biomass boiler to the stepped-cup solar still when compared to the conventional solar still. Water has to be sprinkled over the glass at regular interval to avoid over heating of glass.

Effect of solar radiation on output

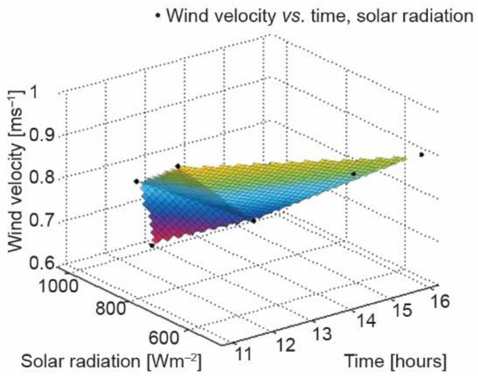
The effect of hourly solar radiation on the output of the conventional solar still with respect to time is shown in fig. 3(a). The solar radiation increases with time and reaches peak during the noon. During this time there is a 13% increase in the output of the still. The output thereafter decreases slowly as the amount of solar radiation decreases from 13.00 hours. The effect of hourly solar radiation on the output of the stepped-cup solar still with respect to time is shown in fig. 3(b). The solar radiation increases with time and gives a higher productivity than the conventional solar still. Maximum productivity of the conventional solar still is achieved by the stepped-cup solar still at lower solar radiation itself due to its stepped-cup design. The productivity increases and reaches three times the maximum productivity of conventional still by noon and is maintained almost constant for the remaining hours due to reduced heat loss.



(a)



(b)



(c)

Figure 3. (a) Effect of hourly solar radiation on productivity of the conventional solar still, (b) effect of hourly solar radiation on productivity of the stepped-cup solar still, (c) effect of wind velocity on solar radiation

Effect of wind velocity on solar radiation

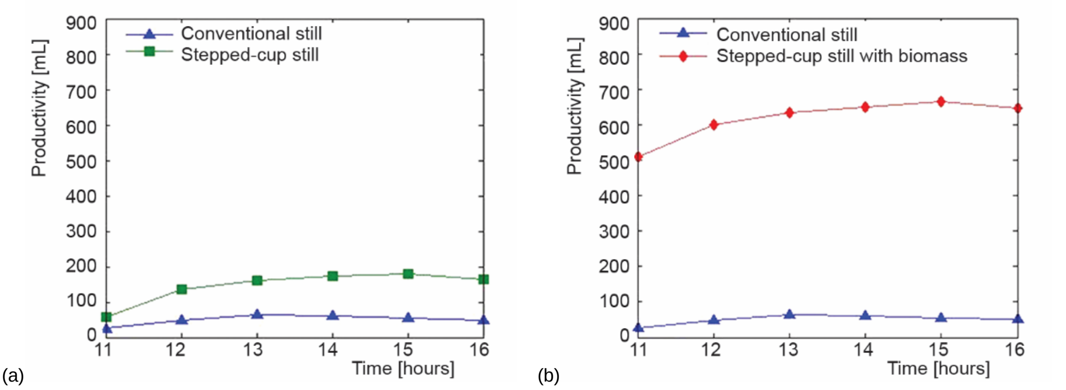
The effect of wind velocity on solar radiation is shown in fig. 3(c). Maximum water temperature is achieved when the wind velocity reaches its minimum value during 13.00 hours.

Effect of output in solar mode

Productivity of conventional solar still is compared with the productivity of stepped-cup solar still and is plotted in fig. 4(a). Increasing time tends to increase the water temperature of the still and hence increases the productivity. Stepped-cup solar still produces output at higher rate compared to the conventional still. In conventional solar still productivity is highest during 12.00-13.00 hours. Whereas in stepped-cup solar still water temperature increases during peak hours and it is maintained even after the peak hours. The productivity is highest during 14.00-15.00 hours because of the stepped-cup design proposed in this paper. Stepped-cup still maintains the water temperature till 15.00 hours. Stepped-cup still shows 12% increase in productivity compared to the conventional solar still.

Effect of output in biomass mode

Productivity of stepped-cup solar still with biomass is compared with the productivity of conventional solar still. It is plotted in fig. 4(b). Due to the introduction of biomass boiler, higher range of temperature is achieved and maintained inside the still. Stepped-cup solar still with biomass shows 70% increase in productivity than the conventional solar still.



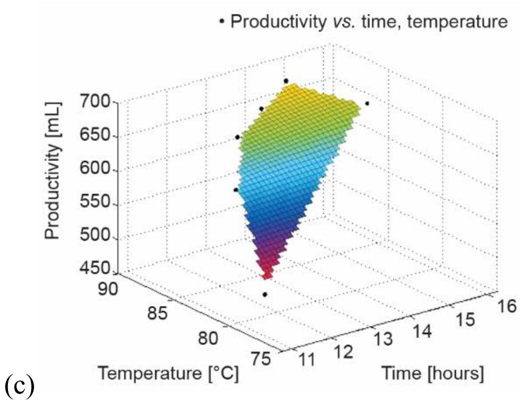


Figure 4. (a) Productivity of conventional still *vs.* stepped-cup still (solar mode), (b) productivity of conventional still *vs.* stepped-cup still with biomass (biomass mode), (c) water temperature *vs.* productivity in biomass mode

Effect of water temperature on output in biomass mode

In biomass mode, the water temperature is increased drastically by providing additional heat energy along with the solar energy. This is shown in fig. 4(c). The productivity increases by 4% as the temperature increases and reaches the peak value after noon hours. The output is maintained almost constant even after peak solar radiation hours.

Economic analysis

The payback period of the solar still can be predicted using the fabrication cost, operating cost, and maintenance cost. The net profit and payback period for three types of solar stills *viz.*, conventional solar still, stepped-cup solar still, and stepped-cup solar still with biomass are calculated and tabulated in tab. 2.

Conclusion

This paper proposes a novel stepped-cup design for desalination of sea water using solar still. There is 12% increase in the productivity of desalinated water on using this design when compared to the existing conventional solar still. The efficiency of desalination process is further increased by the introduction of biomass to the stepped-cup solar still. On the addition of the biomass boiler set-up, a significant 70% increase in the productivity compared to conventional solar still is observed on experimental investigation and comparison of results.

Table 2. Economic analysis of conventional solar still, stepped-cup solar still, and stepped-cup solar still with biomass

Particulars	Cost in rupees (1 Rupee = 0,014$)		
	Conventional solar still	Stepped-cup solar still	Stepped-cup solar still with biomass
Fabrication cost	5000	6000	15000
Operating cost	–	–	4 per day
Maintenance cost	1 per day	1 per day	2 per day
Cost of distilled water	10 per L	10 per L	10 per L
Cost of water produced/day	3	9	37
Net profit = cost of water produced-operating cost-maintenance cost	2	8	31
Payback period	5000/2 = 2500 days	6000/8 = 750 days	15000/31 = 484 days

References

[1] Moustafa, S. M. A., *et al.*, Direct Use of Solar Energy for Water Desalination, *Solar Energy, 22* (1979), 2, pp. 141-148
[2] Tiris, C., *et al*., Experimental Studies on a Solar Still Coupled with a Flat-Plate Collector and a Single Basin Still, *Energy Conversion and Management, 39* (1998), 8, pp. 853-861
[3] Zurigat, Y. H., *et al.*, Modeling and Performance Analysis of A Regenerative Solar Desalination Unit, *Applied Thermal Engineering, 24* (2004), 7, pp. 1061-1072
[4] Al-Hayek I., *et al*., The Effect of Using Different Designs of Solar Stills on Water Distillation, *Desalination, 169* (2004), 2, pp. 121-127

[5] Saravankumar, P. T., *et al.*, Ecological Effect Of Corn Oil Biofuel with Si, *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* https://doi.org/10.1080/15567036.2019.1576079, (2019)
[6] Govindasamy, P, *et al.*, Experimental Investigation of the Effect of Compression Ratio in a Direct Injection Diesel Engine Fueled with Spirulina Algae Biodiesel, *J. of Applied Fluid Mechanics*,*11* (2019), Special Issue, pp. 107-114
[7] El-Sebaii, A. A., Thermal Performance of a Triple-Basin Solar Still, *Desalination, 174* (2005), 1, pp. 23-37
[8] Velmurugan, V., *et al.,* Experimental Studies on Solar Stills Integrated with a Mini Solar Pond, *Proceedings*, 3rd BSME-ASME International Conference on Thermal Engineering, Dhaka, Bangladesh, 2006
[9] Velmurugan, V., Srithar, K., Solar Stills Integrated with a Mini Solar Pond – Analytical Simulation and Experimental Validation, *Desalination, 216* (2007), 1-3, pp. 232-241
[10] Velmurugan, V., Srithar, K., Prospects and Scopes of Solar Pond – a Detailed Review, *Renewable and Sustainable Energy Review, 12* (2008), 8, pp. 2253-2263
[11] Velmurugan, V., *et al.,* Productivity Enhancement of Stepped Solar Still – Performance Analysis, *Thermal Science, 12* (2008), 3, pp. 153-163
[12] El-Zahaby, A. M., *et al.,* Augmentation of Solar Still Performance Using Flash Evaporation, *Desalination, 257* (2010), 1-3, pp. 58-65
[13] Senthil Rajan, A., Raja, K., Multi Basin Desalination Using Biomass Heat Source and Using Analytical Validation Using RSM, *Energy Conversion and Management, 87* (2014), Nov., pp. 359-366
[14] Kalidasa Murugavel, K., *et al.,* Single Slope Still with Minimum Basin Depth and Energy Storing Materials, *Applied Energy, 87* (2010), 2, pp. 514-523
[15] Pradeep Mohan Kumar, K., *et al.,* Computational Analysis and Optimization of Spiral Plate Heat Exchanger, *J. of Applied Fluid Mechanics, 11* (2018), Special Issue, pp. 121-128
[16] Velmurugan, V., *et al.,* Integrated Performance of Stepped and Single Basin Solar Stills with Mini Solar Pond, *Desalination, 249* (2009), 3, pp. 902-909
[17] Avudaiappan, T., *et al.*, Potential Flow Simulation through Lagrangian Interpolation Meshless Method Coding, *J. of Applied Fluid Mechanics, 11* (2018), pp. 129 -134
[18] Dhandayuthabani, M., *et al.*, Investigation of Latent Heat Storage System Using Graphite Microparticle Enhancement, *J. of Thermal Analysis and Calorimetry*, https://doi.org/10.1007/s10973-019-08625-7, 2019
[19] Omara, Z. M., *et al.,* Enhancing the Stepped Solar Still Performance Using Internal Reflectors, *Desalination, 314* (2013), 2, pp. 67-72

Paper submitted: April 9, 2019
Paper revised: May 11, 2019
Paper accepted: June 1, 2019