Decentralized and cost-effective solar water purification system for remote communities

Hafiz M. Abd-ur-Rehman1,*, Sehar Shakir 2, Atta-ur-Razaq 1, Hamza Saqib 1, and Saad Tahir 1

1School of Mechanical & Manufacturing Engineering (SMME), National University of Sciences & Technology (NUST), H-12 Campus, Islamabad, Pakistan.
2U.S Pakistan Centre for Advanced Studies in Energy (USPCAS-E), National University of Sciences & Technology (NUST), H-12 Campus, Islamabad, Pakistan.
*E-mail: abd-ur-rehman_@hotmail.com

Abstract. In this study, a modified stepped solar still is proposed for water desalination. The overall objective of this work is to develop and test the proposed still design to identify the productivity enhancement as compared to conventional basin type solar still. The proposed design takes the advantage of its stepped configuration that allows the water stream to maintain a minimum desirable water column height and the water flow through the stages under the force of gravity. A minimum water depth in the still results in a higher rate of evaporation. The still is also incorporated with Fresnel lens to increase the water temperature that eventually increases the rate of water evaporation. Another important aspect of this design is the incorporation of phase-change-material (PCM) to increase the operational hours of the solar still. Consequently, daily productivity of fresh water is increased.

1. Introduction

Water is a natural resource that is a necessity of all living organisms. Water sources are normally brackish and contain harmful microbes such as bacteria which make water unsafe and unsuitable for drinking. Desalination using solar energy is one of the methods for purifying water. Desalination is a process of removing various minerals and slats from water. Water desalination is done to convert salty and brackish water to fresh water which can be used for drinking and other purposes such as irrigation. Solar still is the oldest solar distillation techniques for water purification. The major disadvantage of the conventional solar still is its low productivity that can be improved by effective design modifications in the conventional solar still. Numerous research works has been done with the goal to improve the performance, productivity and efficiency of the solar stills. Various parameters that influence the productivity include depth of water, the temperature of water at the inlet to still, free surface area of water, water glass temperature difference, wind velocity and solar radiation. Researchers around the globe have worked intensively on different solar still designs. Several modifications have been implemented and studied thoroughly.

Abu-Hijleh et al. [1] investigated the performance of a solar still with different size sponge cubes placed in the basin. The increase in fresh water output ranged from 18% to 273% compared to identical stills without sponges under identical working conditions. Their study proved that the daily output can be improved by incorporating sponges. Velmurugan et al. [2] incorporated fins in the solar still basin, due to which the production rate accelerated. Exposure area was further increased by utilizing sponges. The results were compared with ordinary basin type still. It was found that 15.3% productivity increased when sponges were used and 45.5% increased when fins were used. Sadhana et
al. [3] made an effort to investigate the performance of finned basin solar still. In order to obtain a fair comparison, they fabricated two similar double sloped solar stills. The absorbing plate of one of the solar stills is incorporated with fins in order to enhance the heat transfer rate from the basin liner to water, while another still base is flat. It was proved that the daily output of clean water from the finned basin solar still is 18% more than the conventional double slope solar still. Alaudeen et al. [4] in their work, used a stepped solar still to enhance the productivity of the conventional still. They integrated the stepped configuration with inclined flat plate collector. The setup consists of subsequent trays and flat plate collectors. This modification increases the exposure area which enhances the rate of evaporation. Kumar et al. [5] investigated the performance of a single basin double slope solar still in conjunction with a phase change material (PCM). Paraffin wax was used as the thermal energy storage medium under the liner of the basin. Overall 61% gain was recorded when Phase change material was used, where as a 34% nocturnal and 64% gain in the day time output productivity was recorded, which is a drastic improvement. El-Samadony et al. [6] carried out an experimental study on a modified stepped solar still with internal and external reflectors and an external condenser. Results were obtained with external condenser alone as well as with the reflectors. A detailed comparison between the modified-stepped solar still and the conventional setup was conducted. It was determined that the productivity of the modified still with the external condenser alone was 66% higher than that of the conventional solar still. Pandey et al. [7] conducted an experimental study in order to determine the effect of a separate condenser on the performance of a single slope solar still. They carried out a complete comparative study between a conventional solar still and one with a separate condenser. Their results showed that the basin type solar still with separate condenser was 19% more efficient as compared to the conventional type. Pandey [8] studied the effect of bubbling of ambient air and that of simultaneous air bubbling and cooling the glass cover. Bubbling of ambient helps to increase the rate of evaporation [9-11], thus increasing both the productivity and the efficiency. The literature review inferred that the solar distillation is an appropriate choice for a decentralized small-scale water desalination systems, especially in remote regions where inexpensive land and abundant solar radiations are available. Therefore, a novel design of a bubbler solar still is developed and tested to identify its productivity enhancement as compared to conventional solar still. One major advantage of this system is its stand-alone/off-grid functionality for electricity scarce remote areas.

2. Experimental setup
The 3D design and schematics of experimental setup is shown in figure 1 and figure 2. It consists of a feed water tank that not only store saline water, but also acts as a secondary solar still. A fraction of water in the storage tank evaporates by solar irradiance. The water vapors condense on the top and side glass surfaces of the tank. The distillate is collected in a measuring cylinder attached to the tank. This tank also incorporates phase change material (paraffin wax) below the basin, which act as a medium to store thermal energy as latent heat to provide higher operating hours for the system. The base of the tank is adequately insulated using glass wool to prevent heat losses. A K-type thermocouple installed within this tank will continuously monitor the temperature of the water. The tank is properly sealed from all sides using silicone gel. All the stated modifications in the storage will ensure maximum productivity of clean water from secondary solar still. The pre-heated water from the storage tank is send to the main still via a stainless steel connecting pipe. This pipe incorporates a manually operated valve to control the flow rate of water as it flows from the storage tank to the main still. All the connection associated with this pipe are properly sealed to prevent any leakages. Main solar still is coupled with Fresnel lens to that concentrate solar radiations on the black absorber trays to maximize the thermal energy input in to the still. The trays are configured in a stepped-sloped configuration. A clear glass cover with a tilt angle equal to Islamabad latitude angle (33.7 degrees) is chosen and it will face south to receives maximum amount of solar irradiance. The stepped-sloped tray configuration is supported on a system of multiple threaded steel rods in the still for load distribution. The tray configuration is painted black to maximize the absorption of solar irradiance. Paraffin wax is incorporated as phase change material (PCM) below the basin to act as thermal heat storage medium. PCM provide effective night time functionality for the setup. A mesh of Aluminum fins is distributed within paraffin wax to increase heat transfer from the still base to the wax when solar irradiance is high and from the wax back to the tray base when solar irradiance is low. The base of the still is
properly insulated by using a combination of different insulation materials including saw dust and packing material to prevent heat loss from the base of the still. The trays incorporate sponges that act like baffle plates so that water remains in the tray for a longer duration. The sponges also absorb water and increase surface area for evaporation. The inclined trays incorporate black painted aluminum fins which enhance the surface area for heat transfer and act as barriers to slow down the flow rate of water as it flows through the still. The last tray incorporates a perforated pipe through which air is blown to form bubbles in the hot water coming from the stepped-sloped configuration of the main solar still. The bubbling of air through hot water greatly increases the rate of evaporation. Fraction of water evaporated in the main still condenses on the top and sides of the main still. The distillate is collected in a graduated beaker attached to the main still. Majority of the water vapors in the main still is sent to the external condenser. The condenser contains a coiled copper pipe through which saline water is passed before sending it to the storage tank. The vapors from the main still condense on copper coil surface and release the latent heat of condensation that is used to preheat the seawater. The distillate from the condenser is collected in a graduated beaker attached at the outlet of the condenser. The preheat water is sent to the storage tank to complete the cycle.

![Figure 1: 3D design of the experimental setup.](image)

### 3. Results and discussion
Experimental analysis was performed along with numerical analysis. The results for both types were computed, plotted and compared. Cumulative productivity of clean output water in L/m² was calculated for a 2 cm water depth over a period of 10 hours from 9:00 am to 7:00 pm. The output
productivity rate was maximum between 13 to 15 hours and the total productivity obtained from numerical analysis was 6.31L/m². The resulting graph is as shown in figure 3.

Figure 2: Schematic diagram of the experimental setup of modified solar still.

Figure 3: Cumulative productivity in L/m² for 2cm water depth

Figure 4: Effect of water-glass temperature difference on productivity.
The effect of the water-glass temperature difference on the Productivity (Evaporation rate) of output water over a period of 8 hours from 9:00am to 5:00pm was determined through numerical analysis and the results were plotted as shown in figure 4. The evaporation rate (productivity) in g/m$^2$ was plotted on the left-hand y-axis while the water-glass temperature in degree Celsius was plotted on the right-hand y-axis along with time in hours on the x-axis. It was found out that the two aspects namely evaporation rate and temperature difference are in direct relation. As the water-glass temperature difference increases, the productivity increases as well. The maximum productivity obtained was 280g/m$^2$ for a temperature difference of 3.2 degree Celsius at 1400 hours.

Experimental analysis was performed on the final prototype over a time of 10 hours from 9:00am to 7:00pm. The maximum hourly productivity was obtained between 1:00pm and 2:00pm as 0.86 Liters. The hourly productivity of clean output water was noted and the results were plotted in a bar-chart as shown figure 5.

![Figure 5: Experimental productivity analysis](image)

Figure 6 shows a comparison between the cumulative productivity determined from numerical analysis and that obtained from the experimental analysis. The productivity obtained from experimental analysis is lower as compared to that obtained from numerical analysis due to heat losses and inefficiencies.

![Figure 6: Comparison between experimental and numerical results of hourly water productivity.](image)
4. Conclusion
A modified stepped solar still is designed, developed, and tested in efforts of developing a lost cost decentralized small scale water purification system for remote communities. The stepped configuration in the still are incorporated with sponges to increase the surface area for water evaporation. The pebbles are used in each stage to store the sensible heat and Phase change material (Paraffin Wax) is incorporated to extend the working hours of the solar still. Numerical analysis was conducted using Matlab to determine the effect of various modifications on the productivity of the still. The results show that the maximum productivity was achieved between 12:00-14:00 hours of the day. The cumulative productivity at the end of the day was 6.3 liters.

The developed design is original in its stand-alone/off-grid functionality in electricity scarce remote areas. The results of the proposed work will be a valuable reference for both researchers and engineers in the area of water desalination. It will also alleviate the sustainability concerns of conventional energy based water desalination systems by balancing the potable water requirements through renewable energy source. Moreover, it will provide the prospects of reducing the clean water scarcity in remote areas.

5. Acknowledgements
The authors acknowledge the support of National University of Sciences and Technology (NUST), H-12 Campus, Islamabad, Pakistan.

6. References
[1] H. M. Rababa’h, (2003). Experimental study of a solar still with sponge cubes in basin. Energy conversion and Management, 44(9), 1411-1418.
[2] V. Velmurugan, M. Gopalakrishnan, R. Raghu, & K. Srithar, (2008). Single basin solar still with fin for enhancing productivity. Energy Conversion and Management, 49(10), 2602-2608.
[3] V. Pal, A. K. Rai, & V. Sachan, (2015). PERFORMANCE STUDY OF A SOLAR AIR HEATER. International Journal, 6(7).
[4] A. Alaudeen, K. Johnson, P. Ganasundar, A. S. Abuthahir, & K. Srithar, (2014). Study on stepped type basin in a solar still. Journal of King Saud University-Engineering Sciences, 26(2), 176-183.
[5] A. Kumar, A. K. Rai, & R. Garg, (2015, February). Experimental investigation of a passive solar still with paraffin wax as latent heat storage. In Technologies for Sustainable Development (ICTSD), 2015 International Conference on (pp. 1-6). IEEE.
[6] Y. A. F. El-Samadony, A. S. Abdullah, & Z. M. Omara, (2015). Experimental study of stepped solar still integrated with reflectors and external condenser. Experimental Heat Transfer, 28(4), 392-404.
[7] Narayana Pandey and Dr. A. K. Rai, Performance Study of Solar Still with Separate Condenser. International Journal of Mechanical Engineering and Technology, 7(4), 2016, pp. 125–130.
[8] G. C. Pandey, (1984). Effect of dried and forced air bubbling on the partial pressure of water vapour and the performance of solar still. Solar energy, 33(1), 13-18.
[9] H. M. Abd-ur-Rehman, & F. A. Al-Sulaiman, (2017). A novel design of a multistage stepped bubble column humidifier for the humidification of air. Applied Thermal Engineering, 120, 530-536.
[10] F. A. Al-Sulaiman, H. M. Abd-ur-Rehman, M. A. Antar, & O. Munteshari, (2017). Experimental investigation of a bubble column humidifier heated through solar energy. DESALINATION AND WATER TREATMENT, 60, 58-69.
[11] H. M. Abd-ur-Rehman, & F. A. Al-Sulaiman, (2016). An experimental investigation of a novel design air humidifier using direct solar thermal heating. Energy Conversion and Management, 127, 667-678.