Experimental Study and Performance Analysis of Phase Change Material Integrated Stepped Slope Solar Still

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Abstract. The major challenge in developing countries is to provide drinking water to the people, several techniques are employed but the challenge is to make cost effective and its sustainability over a period. Most of the developing countries work on saline water conversion to neat drinking water, distillation is one of the old and handy techniques in this conversion; where sunlight is used as energy drive for the process because elevating the temperature of saline water is enough for distillation and also for its free of cost availability. Solar still distilled water costs very less than the conventional method of deriving water from saline water and also people need not to worry about the purification of obtained water. Hence various analysis on increasing the performance of solar stills is required to increase the productivity to meet the rising demand for clean drinking water. The experimental work is carried out with three stepped solar stills, one without phase change material, one with paraffin wax as phase change material and other with calcium nitrate as phase change material. Solar stills are integrated with phase change materials to increase the productivity of clean drinking water by storing the solar energy in the form of latent heat to release in the dark hours for enabling solar sill distillation even during night time. There will be change in the total productivity based on the size of solar still, phase change material used, basin design and exergy efficiency, therefore these parameters have to optimized for better yield of neat drinking water from saline water. Experimentation was carried in the month of February and March of 2020 to estimate and compare the yield of three solar stills for the time period of 24 hours, certainly solar stills equipped with phase change materials resulted in higher total production than solar still without phase change material though their day time productivity was low. Solar still equipped with calcium nitrate as phase change material yielded 8.17 % more clean drinking water than the solar still equipped with paraffin as phase change material, though calcium nitrate is economical than paraffin wax but maintenance of solar still with calcium nitrate as phase change material is a hefty task.

Keywords: Phase change material, solar sill, drinking water

1. Introduction
An experimental study to estimate production of clean drinking water from conventional stepped solar still, solar still with condenser and solar still with reflector and condenser was conducted, in the above mentioned setups suction fan is connected to withdraw water vapour. Stepped solar still with condenser alone yielded about 66 % more clean drinking water than the conventional stepped solar still, whereas stepped solar still production of clean drinking water is 165 % more than the conventional one [1-3]. In the process of desalination of saline water solar stills are used because of its simple construction and economic benefits, stepped solar stills are mostly commonly used in the
production of clean drinking water hence stepped solar stills are investigated with humidification and dehumidification; as result of coupling this system the production of clean drinking water increased by a margin and also it is observed that increasing the air flow rate in the system significantly improved the production of clean drinking water [4-6]. Stepped solar stills are investigated with the internal and external reflectors, the reflectors are used in stepped solar still to improve the energy absorption in solar still because of proper utilization of input energy would yield more output, when the conventional solar still is compared with the stepped solar still coupled with internal and external reflectors, the later one produces 125 % more clean drinking water from saline by proper utilization of input energy [7]. When a stepped solar still is integrated with internal reflectors is compared against conventional stepped solar stills is experimented and analysed for the yield of neat drinking water from saline water in the same climatic conditions, the internal reflectors in the stepped solar still increased exergy efficiency thereby efficiency of the modified stepped solar still increased by 20 % [8-9]. A single slope stepped solar still coupled with solar air heater and aluminum as thermal storage material under the absorber plate for a still are of 0.5 m² is compared with the passive stepped solar still for the same area and climatic conditions, the productivity of active single slope stepped solar still is more when compared with the passive one [10]. In order to bound the limit of parameters like glass cover inclination and radiation form factor a theoretical study had been conducted in stepped solar still and it is found that clean water production from saline water is sensitive to angle of glass cover inclination and radiation form factor computed between hot saline water and glass cover [11-12]. An effluent settling tank and stepped solar still combined setup is analysed, the effluent is filtered in settling tank big and finely stable particles are settled in the tank, stepped solar still with 50 trays is analysed with two different depths; 10 mm for 25 trays and 5 mm for 25 trays, the effluent tank helped in storing thermal energy absorbed from solar radiation resulted in increased productivity when compared with conventional stepped solar still [13-14]. As the demand for clean drinking increases, need for improving the performance solar still is also an essential one in order to meet this requirement various techniques can be employed like coupling of reflectors, phase change materials for heat storage, fins, collectors, condensers and heat sinks with conventional solar still will increase the efficiency of solar still in desalination of saline water and also solar photovoltaic–thermal systems and greenhouse type stills can be employed to increase the productivity [15-16]. To transform saline water to clean drinking water is a needy one; solar desalination is one of promising technique for desalination, in this type of desalination solar radiation is used as a source of energy whether it is active or passive solar still, here the output of clean drinking water depends highly on the metrological parameters like solar radiation and wind velocity, hence these parameters are uncontrollable by humans but it would affect output of clean drinking water [17-18]. Due to cheap and convenience clean water production form saline water is carried out through solar still desalination when compared to conventional single slope solar still the output of solar still coupled with flake graphite nanoparticles, and cooling fins yielded 73 % more clean drinking water and also depth of saline water from glass cover affected single slope solar still efficiency [19]. Global warming is a serious threat to world nations hence solar thermal systems is a best choice to replace the conventional energy system in that way solar stills are used for production of neat drinking water from saline water due to their poor efficiency they are coupled with phase change materials to improve their performance and in order to reduce harmful emissions which increase global warming solar stills integrated with phase change materials would be the best choice in clean water production even after payback time economic analysis [20]. Increasing exergy efficiency of single slope solar still is an essential one to increase distilled water output quantity, hence insulation of solar still is very, and the total average benefit in the collected distilled water is 28 percent, 43 percent and 60 percent respectively for coated and uncoated metallic wiry sponges and black rocks [21 - 22]. In this work stepped solar still is chosen for experimentation, three setups conventional stepped solar still, solar still embedded with paraffin wax for energy storage and solar still embedded with calcium nitrate
are investigated in same climatic conditions to optimize the parameters of stepped solar still in the production of clean drinking water from saline water.

2. Materials and Methods

As experimentation and analysis is to be carried for three solar still setups, dimensions of the solar still is to be chosen because it would affect the productivity of clean drinking water from saline water, based on the literature review three setups are made with necessary modifications, the area of the solar still is 0.81 m² (900 mm x 900 mm); high side wall depth is 600 mm and low side wall depth is 300 mm; the absorber plate is made of aluminum sheet with a thickness of 4mm which is divided into four steps each of 860 mm x 160 mm. The solar still basin plates are coated with black paint to increase absorptivity of solar radiation and also insulated with saw dust and thermocol to increase exergy efficiency in turn which would increase productivity of clean drinking water from saline water. The insulation layer is supported by a plywood and the basin is covered with a glass of 4 mm thick inclined at 30° horizontally. In order to embed phase change materials in the solar still copper tubes of 6mm diameter is chosen in which paraffin wax and calcium nitrate is embedded and placed in the steps under saline water which would absorb heat energy from solar radiation during daytime to release the heat energy during night time for production of clean drinking water from saline water. LM35 sensor in combination with Arduino Uno mega 2560 used to measure the basin liner, saline water, glass still inter temperature and atmosphere temperature is measured using by Arduino application of serial monitor and the average value is taken for theoretical calculation. Pyranometer and Anemometer are used to calculate solar radiation and wind velocity respectively, a flask collector of 1-liter capacity is used to measure hourly yield of clean drinking water. Figure 1 represents the experimental setup of PCM integrated Stepped Solar Still. The experimental investigation is carried at Latitude: 11°16' 12'' N - Longitude: 77°36' 15.29'' E - Altitude: 272 m to maximize the amount of incident solar radiation; the whole experimental setup is kept in south direction at 185° to receive maximum solar radiation throughout the year.

Figure 1: Experimental Set up of PCM Integrated Stepped Solar Still

3. Energy Balance Equation

3.1 Energy Balance Equation for Water Mass

Saline water in the basin can be represented by energy balance equation as shown

\[ I_1 + Q_{bw} + c_{bw} \frac{dT_{bw}}{dt} = Q_{cw} + Q_{rw} + Q_{ew} + I_2 \]

In the above equation \(Q_{bw}\) indicates convective heat transfer from basin to water, heat capacity of water in the basin is represented by \(C_{bw}\), whereas basin water temperature is represented by \(T_{bw}\), evaporative heat transferred from water to glass is indicated by \(Q_{ew}\), heat radiated from water to glass is \(Q_{ew}\), convective heat transfer from water to glass, solar irradiation received in the still by the water after penetrating through glass cover is \(I_1\) and solar irradiation reaching the basin liner surface
after passing through glass and water $I_2$ in the still, can be determined as follows:

$$I_1 = (1 - \alpha_g)I$$  
$$I_2 = (1 - \alpha_g)(1 - \alpha_w)I$$

In two modes heat is transferred from basin saline water to the glass through radiation and convection. The heat transferred through convection from basin saline water surface to glass cover happens through humid air, it is expressed by the following equation

$$Q_{cw} = h_{cw}A_w(T_{bw} - T_g)$$

Coefficient for convective heat transfer from basin saline water to glass cover is indicated by $h_{cw}$. Cross sectional area of water basin liner is $A_w$, and glass cover temperature is indicated by $T_g$. The difference in temperature of saline water in basin liner and glass cover arises because of radiative heat transfer, which can be estimated using Stefan – Boltmanz’s law

$$h_{rw} = \varepsilon_{eff}A_w(T_{bw} - T_g) = \varepsilon_{eff} A_w \sigma (T_w^4 - T_g^4)$$

Heat transfer coefficient of radiative heat transfer from basin saline water to glass cover is $h_{rw}$. Stefan-Boltzman’s constant $\sigma = 5.67 \times 10^{-8}$ W/m²K⁴, the effective emittance of saline water surface to the glass cover is $\varepsilon_{eff}$. A part of heat energy is utilized for evaporating saline water from the basin that is can be represented by the following equation

$$Q_{sw} = h_{sw}A_w(T_{bw} - T_g)$$

### 3.2 Energy Balance Equation for Glass Cover

Energy balance in the glass cover can be written by the following equation, $I$ is the solar radiation falling on glass cover, $Q_{rg}$ is radiative heat transfer and $Q_{cg}$ is convective heat transfer to atmosphere from glass cover respectively

$$I_1 + Q_{rg} + Q_{cg} = Q_{cw} + Q_{tw} + Q_{sw} + I$$

$$Q_{rg} = h_{rg}A_g(T_g - T_a) = \varepsilon_g A_g \sigma (T_g^4 - T_a^4)$$

$A_g$ is the aperture area of glass cover, radiative heat transfer coefficient between atmosphere and glass is represented by $h_{rg}$ is the radiation heat transfer coefficient between glass and atmosphere, atmosphere temperature and sky temperature is represented by $T_a$ and $T_s$ respectively and from the ambient temperature 60 C less is taken as sky temperature. From glass cover to atmosphere convective heat transfer happens it is represented by

$$Q_{cg} = h_{cg}A_g(T_b - T_a)$$

### 3.3 Energy Balance Equation for Basin

Energy balance equation for basin is represented by

$$I = Q_b + \theta_{bot}$$

$$Q_b = h_bA_b(T_b - T_w)$$

The above equation represents heat transferred from basin to saline water and also there is a loss of heat from basin to atmosphere though insulated with saw dust and thermocol which is determined by following equation, $U_{bot}$ represents heat transfer coefficient between atmosphere and basin liner

$$Q_{bot} = U_{bot}A_b(T_b - T_a)$$

Clean water production from saline water hourly yield can be calculated from the following equations

$$\frac{dT_w}{dt} + T_w \left( \frac{h_{tw} + h_b}{c_w} \right) = \frac{1}{c_w} \alpha_w I (1 - \alpha_g) + h_{tw} T_g + h_b T_b$$
For calculating theoretical hourly yield of clean drinking water; temperature of glass cover, saline water and basin liner is acquired from Arduino controller which is used to calculate hourly yield of clean drinking water.

3.4 Energy Balance Equation for External Heat Transfer

Solar still energy balance equation is represented by the following equation

\[
I = Q_d + Q_{rg} + Q_{cg} + Q_{bw} + Q_{aw} + Q_{bot} + Q_{swv}
\]

\[
Q_d = m_w h_f g
\]

From solar radiation available energy is represented by I, which is transferred to various components of still through various modes of heat transfer; portion of energy is used for distillation of saline water to produce clean drinking water but a quantity of heat is lost to atmosphere from glass cover due to convection and radiation. Quantity of clean water produced is represented by \(m_w\) and \(h_f g\) represents the latent heat of water. The radiation heat loss and convection heat loss is estimated by the following equations

\[
Q_{rg} = \varepsilon_g \sigma A_g (T_{g} - T_{sky})
\]

\[
Q_{cg} = h_{cg} A_g (T_g - T_a)
\]

\(T_g, T_{sky}\) and \(T_a\) represents temperature of glass cover, sky and ambient respectively, \(h_{cg}\) is heat transfer coefficient for convection. The heat loss through walls of still is calculated by following equation

\[
Q_{bw} = \frac{T_{bw1} - T_{bw2}}{R_{bw}}
\]

Conductive heat resistance is represented by following equation, \(A_w\) represents front and back wall area

\[
R_{bw} = \frac{1}{A_w} \left( \frac{l_1}{k_1} + \frac{l_2}{k_2} \right)
\]

Heat loss through side and bottom of solar still is calculated by the following equations, apart from the mentioned losses there is also unaccounted heat loss which is represented by \(Q_{un}\)
The efficiency of solar still is represented by the following equation:

\[ \eta = \frac{Q_d}{I} \]

4. Results and Discussion

It is very important to validate the numerical model results with experimental results, after the experimentation a nice correlation was observed, though; there is 10% deviation between theoretical and experimental model for stepped solar still step up without phase change material. The gap between theoretical model results and experimental model results is in the range of 15% for the stepped solar still with phase change materials. Temperature of saline water is an important parameter when it is high; evaporation will be quick and also when the difference between glass cover temperature and saline water temperature is more; evaporation and condensation will be more which will increase the productivity of clean drinking water from saline water. Solar still should be placed in a region where there will not be any interruption to solar radiation incidence for better utilization of energy in producing clean drinking water. Temperature of glass cover, saline water, basin liner and atmosphere are the major parameters which involve in defining the quantity of clean water production, hence the values obtained through sensor from Arduino is plotted against time to have a clear picture. In X axis time is taken and in Y axis temperature of various components is taken, values are plotted for all the three setups made; Figure 2 represents the stepped solar still without PCM, it is observed temperature of all components rise with increase in solar radiation till noon then it tends to decrease. Basin liner temperature is more than other components as it is made of aluminum and black coated, as the saline water is on top of basin its temperature is slightly lower than the liner. The glass cover temperature and atmosphere temperature are very close to each other; atmosphere temperature influences glass cover temperature to greater extent which in turn will affect the clean drinking water production, when the difference between glass cover temperature and saline water is more then there will be possibility for increased production.

![Figure 2: Temperature vs Time for Stepped Solar Still without PCM](image-url)
Figure 3: Temperature vs Time for Stepped Solar Still with Paraffin as PCM

Figure 4: Temperature vs Time for Stepped Solar Still with Calcium Nitrate as PCM

Figure 5: Water Productivity vs Time for all cases of Stepped Solar Still
Temperature of stepper solar still components with paraffin wax as phase change material and calcium nitrate as phase change material is plotted against time in Figure 3 and Figure 4 respectively, as observed the temperature difference between glass cover and saline water is more in the stepped solar still integrated with calcium nitrate phase change material because of that we can expect more yield from the stepped solar still with calcium nitrate as phase change material. In order to have clear picture on production of clean drinking from saline water hourly efficiency is plotted against time; time is taken in X axis and hourly efficiency taken in Y axis, from Figure 5 the observation indicates that stepped solar still without phase change material is less efficient than other two solar stills because it cannot yield during night hours and also still with paraffin wax compared to still with calcium nitrate is less efficient. The data plotted in figure 6 has correlation with Figure 2, 3 and 4 and it is expected that stepped solar still with calcium nitrate yield will be more. Clean water productivity is plotted against time in Figure 5, it is observed that stepped solar still embedded with paraffin wax yielded 15 % more than the stepped solar still without phase change material and also still with calcium nitrate yielded 8.17 % more than the still with paraffin wax. It is also observed that still without phase change material cannot yield during dark hours but its yield during day time is more than the other two stills, still with calcium nitrate yielded more during dark hours than the still with paraffin wax.

5. Conclusion
In the present decade need for clean drinking water has been increased to meet this demand desalination of saline water would be one of the promising method, various techniques can be employed in the mentioned process but cost efficient and renewable energy source usage in desalination of saline water will be appropriate for present environmental conditions, one such method using renewable energy is solar still desalination which uses solar radiation as energy source but the disadvantage of solar still is its efficiency and inability to produce drinking water during night time. To overcome the mentioned drawbacks solar stills are integrated with thermal energy storage systems, to increase yield and to produce clean drinking water during night time as well, phase change materials embedded in solar stills to increase their efficiency, in order to optimize the performance of solar stills with thermal energy storage systems, various designs of still and heat storage techniques are employed one such technique is stepped solar still design, when it is integrated with paraffin wax in copper tubes for energy storage the output increased compared with stepped solar still without thermal energy storage systems. Stepped solar still integrated with calcium nitrate in copper tubes for thermal energy storage performed better than the stepped solar still with paraffin wax as phase change material, hence
the experimental work on stepped solar stills with thermal storage systems of phase change materials concludes calcium nitrate as phase change material performed well than paraffin wax when embedded in copper tubes for integration with stepped solar still but the maintenance required for still with calcium nitrate

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