Desalination and Water Treatment
www.deswater.com

doi:10.5004/dwt.2017.20313

68 (2017) 91–98
March

Factors affecting the yield of solar distillation systems and measures to improve productivity

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Received 26 May 2016; Accepted 3 November 2016

ABSTRACT

This paper analyzes the factors affecting the performance of solar distillation systems, including environmental factors (external or natural factors), elements of the design and operation (subjective factors). The subjective elements are analysed and recommendations are made. Thereafter measures to optimize these factors are suggested. Through these theoretical and practical measures, distillate yields of the stills are shown to increase from 30% to 68% compared with traditional solar stills.

Keywords: Passive solar still; Active solar still; Stepped solar still; Basin type solar still; SOLSTILL; Forced circulation solar still

1. Background

The demand for clean water for domestic use has increased rapidly, especially in certain water-scarce areas located in rural, remote and border areas, islands, arid areas, or in places with polluted and saline water sources. The occurrence of salinisation and drought in some southern and central provinces in Vietnam this year underlined the problem of water scarcity,a problem that Vietnam will face with growing intensity in the future. Therefore,the development and production of devices to distill water from alkaline, brackish or saline water sources and thus supply fresh water to people in affected areas is a critical issue for Vietnam and other countries whether clean water shortages are periodic or permanent .

There are many research and review papers that focus on solar stills and the factors that affect the output of solar distillation. Manchanda and Kumar [1] comprehensively reviewed and analyzed the designs and performance parameters of passive solar stills while Sampathkumar et al. [2] reviewed in detail different types of active distillation systems. Velmurugan and Srithar [3] appraised certain modifications to solar still systems and the irresulting respective performance enhancement. Focusing on the single basin passive solar still, Murugavel et al. [4] evaluated the progress in improving the effectiveness of this type of still. Similarly, Kabeel and El-Agouz [5] examined single type passive solar stills, with emphasis on performance enhancing modifications. Badran [6] studied another aspect experimentally – the performance of a single slope solar still using different operational parameters. Other research by Kaushal and Varun [7] evaluated the effect of different designs and methods on solar still output. Muftah et al. [8] comprehensively reviewed the performance of existing active and passive basin type solar stills and investigated the effects of climatic, operational and design parameters on the output of these stills. Recently(2016), Sharshir et al. [9] reviewed in details factors affecting solar stills productivity and improvement techniques while Kabeel et al. [10] introduced, explained and discussed the effectiveness of different solar stills into which different condenser arrangements were integrated.

All the above mentioned papers, although comprehensive and thorough, have the same drawbacks that all previous researches and papers reviewed had, namely, they were from countries with different climatic conditions and different levels of technology and manufacturing expertise to that which prevails in Vietnam. This would lead to inconsistencies and differences in improvements to the named stills' output and performance as compared to those outputs and performances claimed or reported.

Furthermore, there has been very little information relating to factors affecting forced circulation solar stills with enhanced water recovery.

Therefore this paper will present the results of the numerical and experimental research carried out in one location in Vietnam, namely, Ho Chi Minh City so that there is consistency in the factors affecting solar stills' production as well as the gains of the stills' outputs due to the measures taken to optimize these factors. In addition, there will be a focus on the factors affecting the performance of forced circulation solar stills with enhanced water recovery improvement techniques.

2. Solstill – A simulation program for solar distillation systems

The development of SOLSTILL, a simulation program for estimating the performance of basin type solar stills was first described by Nguyen[11–12].

Models for both standard free convection solar still and forced convection solar still with enhanced heat recovery are included in this program. For the conventional free convection systems, the SOLSTILL program also enables simulation of more complex systems with many more parameters compared to the existing models found in the literature. A new model incorporating heat and mass transfer in forced convection solar stills with enhanced heat recovery is described in this paper. The comparison of experimental and simulation results indicates that the program can predict distillate production at an acceptable level of accuracy.

Based on the widely used relations from Dunkle [13], this study analyzes the transient performance of the solar still in which all coefficients and still parameters are calculated using equations within the model. The weather data used for simulation will be either from actual measured data or data generated from the computer program developed by the author. The details of heat and mass transfer analysis and equations as well as the validation of SOLSTILL by comparing its outputs with experimental results can be found in Nguyen [11].

3. Analysis of factors affecting the production of solar stills

The important factors affecting the output of a solar still can be summarized in Fig. 1.

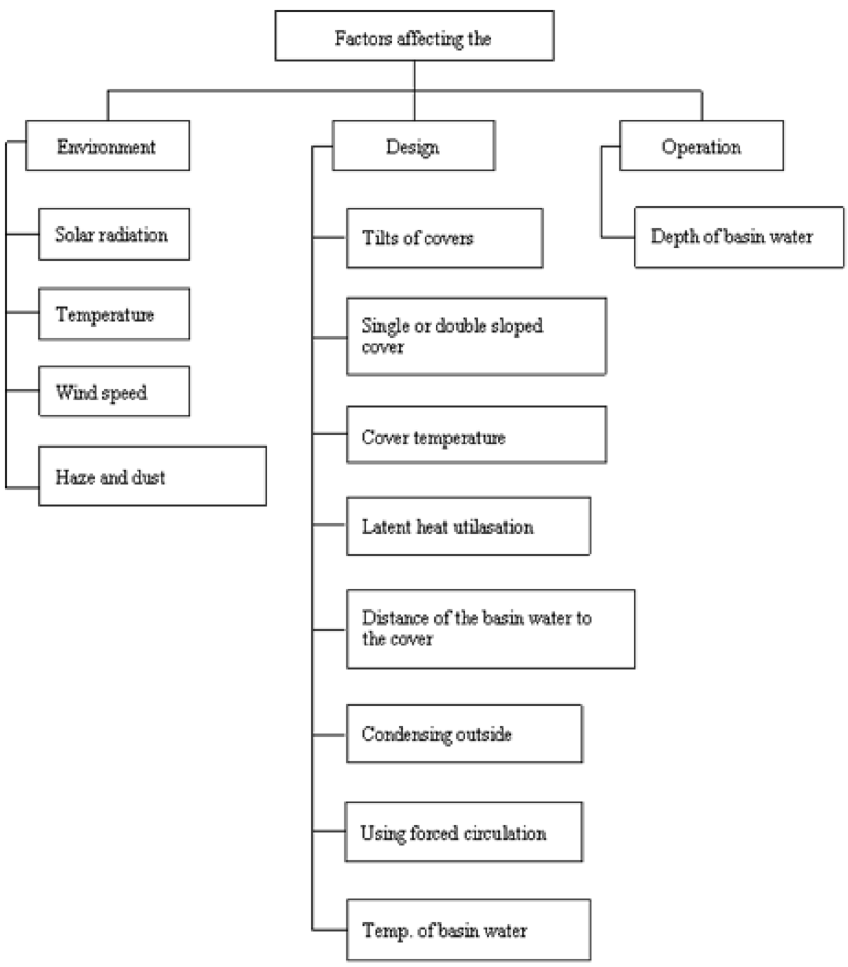

Fig. 1. Factors affecting the outputs of solar distillation systems.

3.1. The impact of solar radiation

Solar radiation is the main and the most important factor to yield distilled water. The greater the radiation received, the greater the volume of distilled water produced and vice versa. However, the greater the radiation,the greater the heat loss of the still. Therefore, the insulation of the still needs to be carefully considered.

3.2. Effect of wind speed

Wind speed values were varied from 0 m/s to 6 m/s when inputted into SOLSTILL [12]. Hourly solar radiation data and ambient temperature data is included in the software.

The results showed that as the wind speed increased from 0 to 3 m/s, the higher wind speeds gave greater water output. This can be explained by noting that high wind speeds will cool the glass cover faster, leading to an increased temperature difference between the water and the cover layer. However, when the wind speed increased from 3 to 6 m/s, the distilled water output increased only 1.6%. As noted above, the wind speed is too high and leads to heat loss, so that the gain in water output is almost negligible. This result is consistent with Cooper's survey [13]. In his research, as Cooper increased wind speeds from 0 to 2.15 m/s, the output of the still rose by 11.5%; when wind speed was increased from 2.15 m/s to 8.81 m/s, the output of distilled water increased by only 1.5%.

3.3. Effect of ambient temperature

The influence of ambient temperature on (i) insulated distillation devices and (ii) un-insulated distilling equipment was studied, and the results are shown in Fig. 2. In case (i), the decrease in ambient temperature leads to a higher distilled water output; while in the case of (ii) the opposite is observed. This can be explained as follows: for the distillation equipment with good insulation, lower temperature will help cool the glass cover faster, thereby increasing the temperature difference between the water layer and cover sheet. However, when the distillation equipment is not insulated, low ambient temperature increases heat loss of the device, leading to a reduction in water temperature in the equipment. Low temperatures still cool the glass cover, but the results in Fig. 2 show that the impact of increased heat loss is more important than the impact of lower glass temperature.

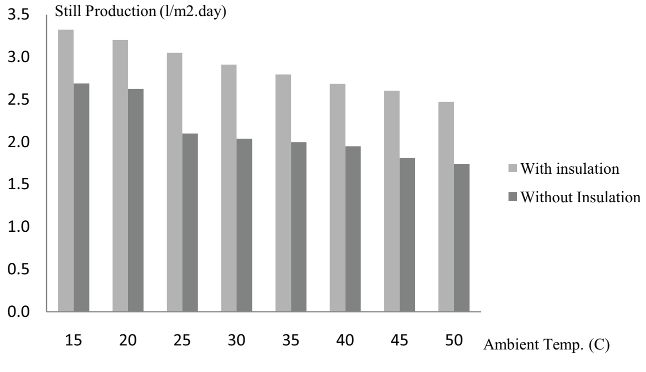

Fig. 2. Effect of temperature on the output of solar stills [12].

The change of ± 5ºC in well insulated distillation systems will make the average distilled water output change ± 4.5%. This result is consistent with the results of the Khalifa and Hamood [14]. Their research has shown that when the ambient temperature rose from 26.7°C to 37.8°C, the outputs may rise 11%; and when temperatures reduce from 26.7°C to 15.6°C, the outputs fall 14%.

The change of ± 5ºC ambient temperature for insulated distillation devices make the distilled water output ± 2.5% change, as a result of SOLSTILL [12].

3.4. Effect of the haze and dust

Solar stills, being placed outdoors to receive direct solar radiation, cannot avoid dust on the surface of coated glass. This reduces the coefficient of radiation incidents, thus reducing the efficiency of the distillation equipment. Additionally, if dust enters the inside surface of the glass, it can affect the condensation flow down to the collecting gutters with the distilled water dripping halfway down the glass. So, it is necessary to regularly check and clean the inside and outside of the cover to achieve the highest efficiency.

The simulation results of SOLSTILL show very clearly the dependence of distilled water output to the intensity of solar radiation that the distillation equipment receives [12].

3.5. Effect of glass cover's tilt

Distilled water output depends very much on the elements of the cover's angle and tilt direction. To ensure the distilled water will not drip while halfway down to the collecting gutters, the tilt of the covers must be more than 15°. On the other hand, it is necessary to reduce the average distance between the water surface and the tilted covers, the tilt of the covers must be not more than 20°[14]. The SOLSTILL program also produces similar results, with the still output dropping rapidly when the cover slope angles are greater than 30º [12].

3.6. The effects of single sloped and two sloped (roof type) covers

SOLSTILL can also used to simulate the distillation equipment using one cover (single sloped) and two covers (double sloped, also known as roof type); the tilt is 15º in both cases. This assumes that the coverings the two types of devices have is the same and their axes lies along the east-west direction. The yields of the two distillation devices are shown in Fig. 3.

The results show that the distillation device with double sloped cover works better in late spring and summer while the distilling equipment with single sloped cover works better in other seasons. This can be explained by the fact that in the late spring and summer, sunrise and sunset is to the south of the East–West axis. Therefore the kind of roof type cover will benefit from having the second roof (that means a south heading) in the early morning and late afternoon. At other times of the year, the still with single sloped cover will get all the available solar radiation and over a

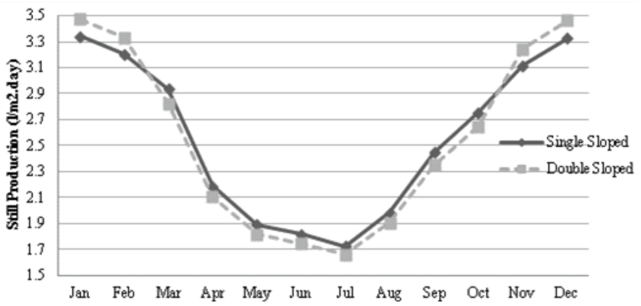

Fig. 3. The output of distilled water per month single roof and roof type double [12].

year, this still performs a little better. This is consistent with the experimental results of Garg and Mann [15].

Therefore, theoretically, one sloped cover should give a little more output compared to those having two slopes. In practice, however, the use of single slope introduces additional difficulties during system construction, requiring additional materials, and has more problems in terms of structural stability in high winds compared to the roof type still. This may be the reason why the roof type stills are still more favoured.

3.7. Effect of the temperatures of the covers

Cooper, Khalifa and Hamood, Garg and Mann [13–15] showed that, the glass covers can absorb approximately 4.75% of solar radiation energy, leading to an increase of the cover's temperature. On the other hand, the condensation of water below the glass surface creates a condensation water film, leading to a partially opaque glass surface and an increase in the glass' temperature. As a result, the temperature difference between the surface of the water and condensation glass cover will be reduced. Therefore, seeking to reduce the surface temperature of the glass is important in order to improve the water productivity (output) of the device [14].

To reduce the temperature of the glass cover, one can speed up the wind outside as mentioned in Section 3.2. However the wind is also a natural factor and it is difficult to control this. So Husham M. Ahm [16] proposed a different approach- use a water cooling membrane on a piece of glass using tap sprays on the glass surface every 30 s with the time interval for the spray test of 10 min and 20 min respectively. Results of regular sprinkling helped increase productivity to 31.8% and 15.7% respectively.

In Section 4 of this paper, the measures taken to reduce the temperature of covers and results achieved by this will be presented.

3.8. Utilising the latent heat of evaporation

To take advantage of the latent heat of water vapor in the condensation, numerous studies have used distillation device models with two flat tanks (double basin) and three flat tank (triple basin) [17]. This is a useful way to increase production of distilled water. However this device is complicated and costly. In Section 4 of this paper, the results of experiments to take advantage of the latent heat of evaporation will also be shown.

3.9. Effect of the distance between the water level and covered glass

The distance between the water surface coverings can affect the effectiveness of the solar distillation systems. As discussed in Section 3.5, if the distance between the water surface and coverings is small, the convective resistance of wet air flow inside the device is smaller, so that efficiency will be improved. But this gap is influenced by the inclination of coated glass. If the tilt of the cover is increased then the average distance between the water surface and coverings is widened, so the output of the still will decrease. In the latter part of this paper the measures on a stepped solar still to achieve the smallest distance between the water level and the glass in order to achieve highest distilled water output will be presented.

3.10. Using the external condensing device

In traditional solar basin distillation systems, the glass covers are used to condense distilled water. This method enables the device to have a simple structure, but it also has two disadvantages:

- Latent heat of vaporization released during condensation makes the temperature of the coated glass increase, resulting in increasing water vapor pressure near the coverings. This reduces the pressure difference between the water evaporative layer and the condensation surface.
- The condensation of distilled water under the glass surface creates a film or droplet layer, reducing the ability of solar radiation penetrating the glass cover and reaching the bottom of the absorbing surface.

The use of an external condenser and a recovery heat exchanger to take advantage of moist air stream with high temperature and humidity returned to the distillation system were also proposed and tested [12]. The results showed that the use of an external condenser could increase output by 25% (average daily output of 3.87 L/m^2 compared to 3.10 L/m^2), and the use of a recovery heat exchanger to circulate the moist air can increase by nearly 54% the output of distilled water (average daily output of 4.76 L/m^2 compared to 3.10 L/m^2).

In Section 4 of this paper, the results of theoretical and empirical research on the use of an external condenser for a solar passive (or natural convective) still will be presented.

3.11. The effect of the generation of forced convection inside the still

The process of heat and mass transfer inside a conventional solar still is a natural convective process. The low efficiencies of a conventional solar still may be overcome by changing the operation principles as follows:

- Using air as an intermediate medium and substituting forced convection for natural convection to increase the heat coefficients in the still, resulting in increased evaporation of water.

- Replacing saturated air in the standard still by “drier” air to increase the potential for mass transfer in the still, leading to higher outputs.
- Circulating the air-vapour mixture from the standard still to external water cooled condensers to gain efficiency from a lower condensing temperature. The cooler the cooling water available, the more effective this condensing process will be.
- Recovering some of the heat extracted in the condensing process and using it to preheat the air-vapour mixture entering the still.
- Substituting the condensing area of the flat sheet covers in the standard still by the external condenser with much larger heat exchange areas to increase condensation efficiencies.

In Section 4 of the paper, this issue will be presented in greater detail.

3.12. The effect of water temperature in the still

The water temperatures in the equipment greatly affect the output of distilled water. As mentioned in Section 3.7, water on the cover as a thin film cools down the glass before running into the still. By using the latent heat of steam in the steam condensation under the glass covers, water can be heated and fed into the device. This approach can be applied to both passive and active solar stills.

In Section 4 of this paper, the use of glass vacuum tubes to heat up the water in the basin of the still will be presented.

3.13. The effects of water depth in the still

The depth of water in the device greatly affects the yield of distilled water. Due to thermal inertia, the deep water layers will make the absorption process of solar energy take longer, thus slowing the increase of water temperature and affecting the amount of distilled water. The experimental results of a single basin solar still coupled with evacuated glass tubes [18] shows that a test witha1cm depth of water in the basin produces 5.265 L/m^2, which is 13.4% higher in comparison with a test using a 2 cm depth of water which produces only 4.555 L/m^2, as shown in Fig. 4. This agrees with the theoretical and experimental results in other research [11,12,14,19,20].

4. Measures to improve the productivity of solar stills

As analyzed above, the elements of the environment are the objective factors and cannot change. In this section we focus on the main measures taken in the design of the still.

4.1. Reducing the cover’s temperature

In the experiments on a stepped solar still [19], a cooling water flow is sprayed with 5 L/min for 30 s on the cover with the time between two injections being 10 min and 20 min. The schematic diagram of the experimented stepped solar still is shown in Fig. 5. Experimental results show that, for a day with average solar radiation of 600 W/m^2, the distilled water obtained is 4.45 L/m^2 and 4.35 L/m^2 corresponding to a period of 10 min and 20 min between two injections, compared with 4.08 L/m^2 in the case with no cooling water spray to the coverings, which rises to 9% and 6.6% respectively, as can be seen in Fig. 6.

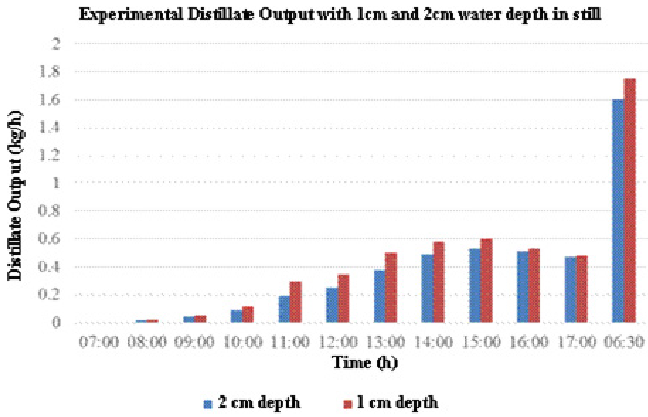

Fig. 4. Experimental distillate output with 1 cm and 2 cm water depth in the single basin solar still coupled with evacuated glass tubes [18].

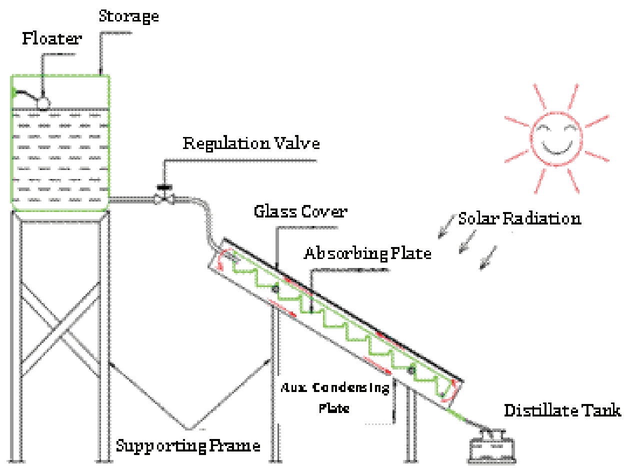

Fig. 5. The schematic diagram of the experimented stepped solar still [19].

Similarly, in the active (forced circulated) solar still [12], the forced convection also helps to cool the covering surface, increasing the production of distilled water. When the speed of air flow in the distillation system reached 0.005 m/s, the output of distilled water was 3.53 L/m^2 compared to 3.05 L/m^2 in the case of traditional devices, with an increase of 15.7%. This result is consistent with results of Husham M. Ahm [16], as stated in Section 3.7.

4.2. Taking advantage of the latent heat of evaporation

In this study, a double basin solar still (DBSS) combined with evacuated glass tubes has been fabricated and tested

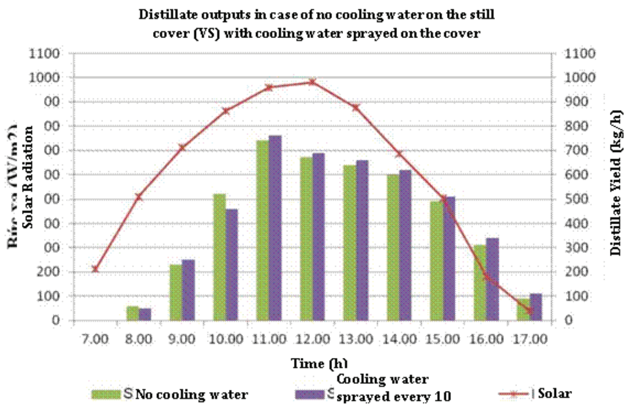

Fig. 6. Distillate outputs in case of no cooling water on the still cover (VS) with cooling water sprayed on the cover.

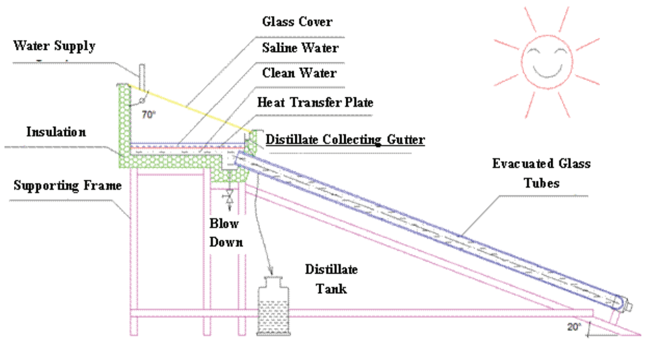

Fig. 7. Single basin solar still coupled with evacuated glass tubes.

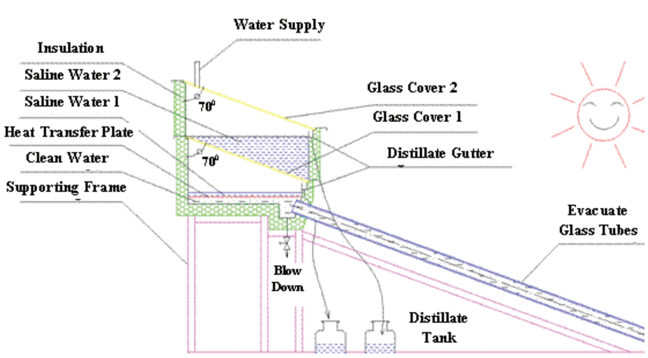

Fig. 8. Double basin solar still coupled with evacuated glass tubes.

to compare it with a single basin solar still (SBSS) with evacuated glass tubes. Figs. 7 and 8 respectively show the schematic diagrams of these two types of stills. Experimental results are shown in Fig. 9. The outputs of distilled water of the two types are 6.49 L/m^2 and 4.99 L/m^2 respectively on a day with 529 W/ m^2 of radiation. Thus by utilizing the latent heat of evaporation, the yield of the solar double basin still was increased by 30%.

In a study on improvement of the Caro cell solar distillation equipment [20], a heat exchanger with a coil size of 760 × 220 × 13 mm and a total length of pipe Φ 8 of 6.5 m, was fabricated and mounted just below the distillation equipment to utilize the heat of evaporation. On a good sunny day (700 W/m^2), the amount of water collected using this heat exchanger was 6.8 L/m^2 compared to 5 L/m^2 in the case of the original Caro cell still where an increase of 36% can be seen in Fig. 10.

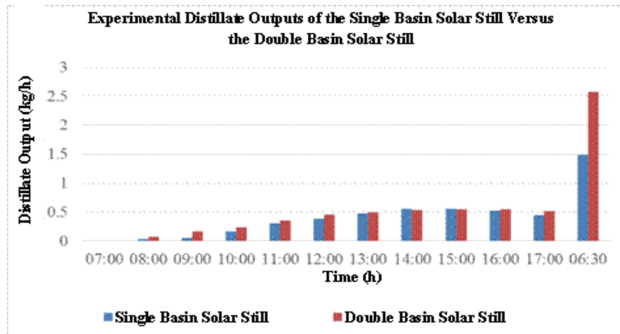

Fig. 9. Experimental distillate outputs of the single basin solar still versus the double basin solar still.

In the solar active still [12], taking advantage of latent heat of steam is achieved by circulating air flow through the recovery heat exchanger back to the distillation system. When the speed of air flow in the distillation equipment reached 0.005 m/s, the output of distilled water obtained was 5.94 L/m^2 compared to 3.53 L/m^2 in the case of no circulation, which rose 68%.

4.3. Reducing the gap between the glass cover and the water level

In order to reduce the gap between the glass and the water level in the still, a stepped solar distillation equipment was designed, fabricated and tested, as shown in Fig. 5 [19]. Some advantages of this device:

- Over a full year, the total energy radiation projected onto the tilted surface was larger than the horizontal surface.
- The stepped still maintains the distance between the water and the cover at only 1 cm, reducing natural convective obstacles.
- Creating good conditions for condensation to flow into the gutters as well as reducing thermal condensation resistance of the water condensing on coverings.

The experimental results for distilled water output reached 4.9 L/m^2 with average radiation 635 W/m^2 compared to 3.05 L/m^2 in the case of traditional equipment, which rose about 60%, as shown in Fig. 11.

4.4. Separating the processes of evaporation and condensation in the device

Section 3.10 presented the use of an external condenser and a heat recovery to take advantage of moist air stream at high temperature and humidity returning to the still (forced convection).

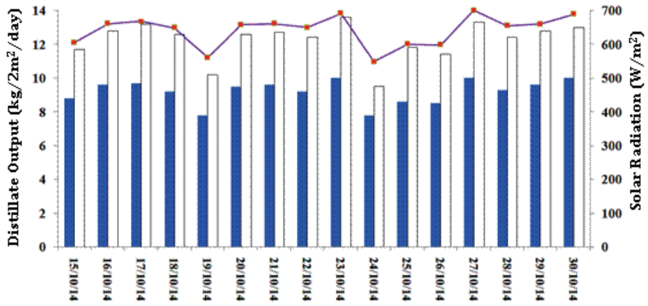

Fig. 10. Distillate outputs of 2 m² Carocell solar still, with versus without a heat exchanger.

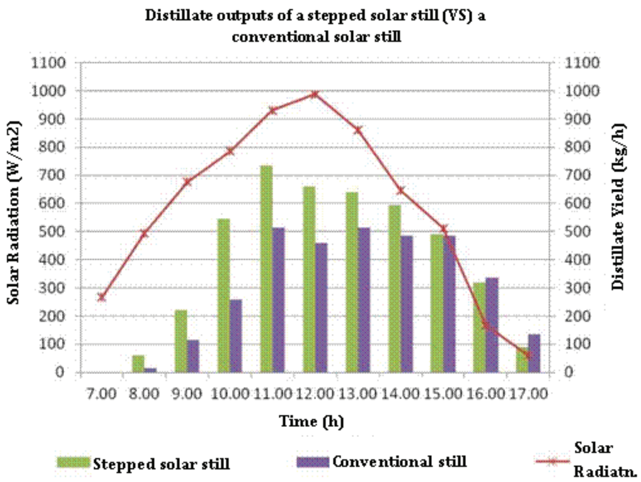

Fig. 11. Distillate outputs of a stepped solar still versus a conventional solar still.

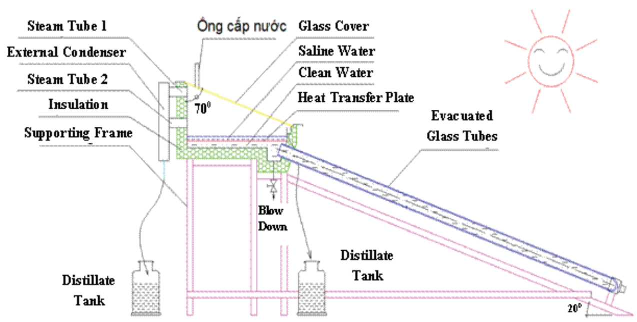

Fig. 12. Single basin solar still coupled with evacuated glass tubes and external condenser.

For a traditional (natural convective) still, the research group manufactured and tested a still with additional external condenser [18]. The schematic diagram of the experiment is shown in Fig. 12 and the experimental results of the solar still with external condenser in comparison with the still without the external condenser are shown in Fig. 13. The use of the external condenser

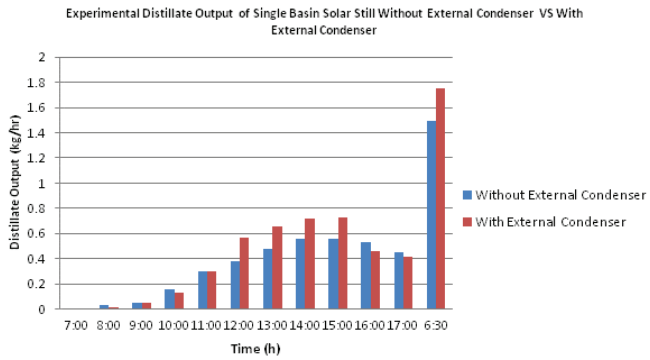

Fig. 13. Experimental distillate output of single basin solar still without external condenser versus with external condenser.

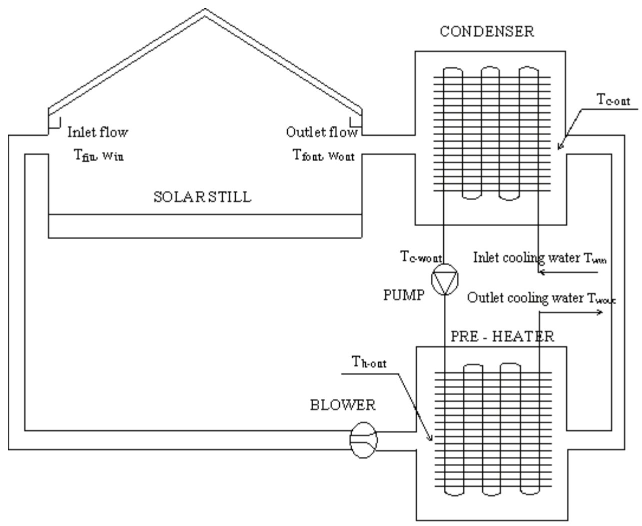

Fig. 14. Schematic diagram of a forced circulation solar still with enhanced water recovery.

resulted in the distilled water output reaching 6 L/d, almost 15% higher than the output of a still without external condenser, which achieved 5.23 L/d on a day with an average radiation intensity of 517.54 W/m².

4.5. Creating forced convection in the device

Theoretical and empirical research was conducted to assess the impact of forced convection on the solar distillation equipment [12]. The schematic diagram of the experiment is shown in Fig. 14. A conventional solar still with a collecting area of 2.67 m² (2.44 m × 1.095 m), with an inside fan to change the speed of air flow, was made to measure parameters and process experimental data. Results for a typical day is shown in Fig. 15 where the water output increased 30%–100% compared to a conventional solar still.

The simulation results of SOLSTILL for the production of distilled water for a whole year with the weather conditions of Ho Chi Min h City, Vietnam and the device performance in three cases(i) forced convection with external condenser and no moist air circulated back to

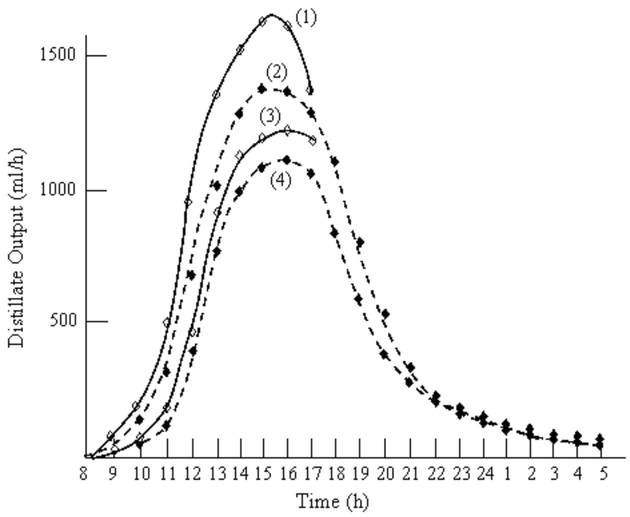

Fig. 15. The effect of forced convection in the device to produce distilled water. (1) Data empirical forced convection; (2) The data forced convection theory. (3) Data empirical natural convection; (4) Data natural convection theory.

the still; (ii) forced convection with external condenser and moist air circulated back to the still and (iii) traditional distillation equipment (natural convection), show that the outputs and still efficiencies in the three cases are respectively 3.87 L/m^2, 4.76 L/m^2, 3.10 L/m^2 and 42.9%, 53.9%, 34.1% [12].

4.6. Increasing the working temperature of water in the still

To increase the working temperature of the water in the equipment in order to increase the production of distilled water, the research group used vacuum tubes to heat the water in the basin [18]. Experimental results corresponding to the day with solar radiation of 514 W/m^2 for the production and performance of the device was respectively 5.86 L/m^2 and 50.3%, compared with production of 3 L/m^2 and efficiency of 34.1% of a conventional solar still.

5. Conclusion

This paper analyzed the factors affecting the performance of solar distillation systems, including environmental factors (external factors or natural), elements of the design and operation (subjective factors). The subjective elements as well as the measures taken to optimize these factors were thoroughly analysed. With these measures, the distillate yield of solar stills was increased from 30% to 68% compared with traditional distillation systems. This has scientific significance and practicality enabling the application of this technology to solar water distillation using a source of clean and renewable energy. It provides a viable way to alleviating the problem of the availability of clean water, especially in those areas and communities in Vietnam where water resources are increasingly polluted and salty as evidenced in provinces throughout the country recently.

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