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Experimental investigation of a poly-energy multi-effect still in Algeria

Amina Abdessemed, Ilies Boubekeur, Noureddine Boublai and Cherif Bougriou

ABSTRACT

The present paper presents a realization of a poly-energy four-stage still, which can operate with three different sources of: electrical resistance (photovoltaic panel), photo-thermal solar collector and vegetable or animal waste. In this work, the effect of the position and the number of trays on the water productivity of a multi-effect still has been experimentally investigated for the first time. A plate was used, then placed in different heights, and then two and three and finally four trays were used. It is concluded that the effect of the tray position has a great influence on the production of distilled water in contrast to the number of trays, and when increasing the number of trays, the production of the distilled water is increased. The maximum production obtained from distilled water is 1 l/h.m². The use of a solar panel for the production of distilled water is unnecessary in oil-producing countries where energy is subsidized. These devices or their components are generally imported and their cost is very expensive. The damping time of these devices is very long.

Key words | energy cost, multi-effect, poly-energy, still, trays

Amina Abdessemed
Physical Department, Faculty of Sciences,
University of Hadj Lakhdar,
Batna 1,
Algeria

Ilies Boubekeur
Noureddine Boublai
Cherif Bougriou (corresponding author)
Mechanical Engineering Department, Faculty of Technology,
University of Batna 2,
Algeria
E-mail: *c.bougriou@univ-batna2.dz*

INTRODUCTION

One of the major problems in the world, and particularly in the third world, is the unavailability of fresh water, especially in arid areas. Desalination systems using traditional fuels have been used in many countries of the Middle and Near East to produce fresh water. It is interesting to note that many of these countries where desalination has been widely used are characterized by a high intensity of incident solar energy. Many experimental and numerical studies on the basic types of solar energy have been reported in the literature. Therefore, solar stills can be used as one of the most suitable solar desalination units for low-capacity, low-cost, simple-to-operate and self-reliant water supply systems (Taghvaei *et al.* 2014).

Solar stills can be classified into various types including passive single basin (Kalidasa Murugavel *et al.* 2010; Ahsan *et al.* 2014), active single basin (Gude *et al.* 2012; Taghvaei *et al.* 2014, 2015), passive multi-basin (Al-Karaghouli & Alnaser 2004), active multi-basin (Karimi Estahbanati *et al.* 2015), tubular (Arunkumar *et al.* 2013) and inverted absorber (Dev *et al.* 2011), which have been constructed and studied to date. Moreover, valuable reviews on solar stills can be found in the literature (Velmurugan & Srithar 2011; Xiao *et al.* 2013).

Many researchers have studied the performance of solar multi-stage distillers, such as Kamal (1988), who studied a static solar distiller with a dual slope theoretically and experimentally. The theoretical model is based on the resolution of the energy equations of the water, the basin and the glass cover. Forecasts of the effects of salt water depth and thermal insulation thickness are found to be accurate when the coverage angle is near its optimal value (25.2° Doha latitude). Experimental research was done to

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verify the theoretical model by examining the influence of design parameters that are not adapted in theory.

Suneja *et al.* (1997) presented a parametric study of a solar distillation system with a double-acting inverted absorber. The results obtained were compared with those of the conventional double-acting solar distiller. They observed that the double-acting reverse-absorbent solar distiller gives a higher result than the conventional double-acting solar distiller.

The choice of a solar still depends essentially on its operating characteristics. Chaker & Menguy (2001) studied particularly the overall and internal efficiency of a spherical solar distiller. The results obtained show the influence of external operating parameters (irradiance and meteorology) as well as the effect of the internal operating parameters (water temperature to be distilled).

Valsaraj (2002) presented an experimental study on a single-slope-solar distiller. To heat the water, he used a folded and perforated aluminium foil floating above the water. In this modification, solar radiation is intercepted by the leaves floating on the surface of the water. The thermal energy gained by the sheet is transferred to the water molecules at the top layer, from where the water molecules will escape into the empty air directly through the holes in the sheet.

Abu-Arabi *et al.* (2002) presented a study of a conventional double-glazed solar distiller cooled by cold brine. The function of this brine is to lower the glass temperature and thus increase the difference in water–glass temperature. This results in improved performance, which is represented by a faster evaporation rate of the basin. The performance of the distiller is compared with that of a conventional single-glass solar distiller under identical atmospheric conditions.

A purely experimental study was presented by Al-Karaghouli & Alnaser (2004). Two solar distillers were manufactured and tested. Both have the same basin section and the same interior dimensions. The hourly amount of distilled water produced, the various temperatures and insulation were monitored for a period of five months (February to June). The highest daily production of distilled water was obtained in June for both types of distillers because the sunshine during that month was higher than the other months. The addition of Styrofoam insulation materials 2.5 cm thick on the sides of the solar distillers increased the water production rate. The average daily production of distilled water for the double basin is always 40% higher than that of the single basin.

Khedim *et al.* (2004) realized a simple technical means based on solar energy with a minimum cost for a modest drinking water supply. The method used consists in recovering and using the same quantity of thermal energy several times. Its goal is to reduce energy consumption so that solar energy becomes an alternative and competitive source in water desalination technology.

Fernández & Chargoy (1990) built a solar distiller based on the principle of a group of stacked trays for parallel distillation and heat recovery. Heat is supplied to the lowest tray to heat the sea water. Evaporation of the water in the hottest tank causes condensation on the cooler upper part, thus producing distilled water and heat. The undesirable flow of steam that bypasses the condenser to the tank immediately above the evaporator is quite detrimental to the overall efficiency of the solar distiller.

A new solar thermal desalination system has been developed and tested under field conditions by Schwarzer *et al.* (2009). The system has two components: a desalination tower with multiple floors and one or more solar collectors. The important advantages of this distiller are: the excellent quality of drinking water; autonomous capacity, the system only works with solar energy; self-regulation and self-ignition, the modular construction (larger systems can be easily implemented: 35 to 2,000 l/day); greater drinking water production rate (about 15 to 18 l/day/m^2) compared with the solar distiller with only one stage (3 to 6 l/day/m^2); the possibility of operation with other available energy sources (heat from waste, electrical energy from wind turbines, etc.).

A transient model was developed by Reddy *et al.* (2012) for a multi-stage solar distiller coupled to a plane sensor to determine optimal design and system configuration performance.

To appreciate the model developed by Adhikari *et al.* (2000), numerical calculations were carried out to optimize the various design parameters, namely: the number of stages, the surface area of the evaporation surface and the intensity of the solar radiation corresponding to the climate of Delhi, India. The effect of the useful life of the distillation unit on the cost of distilled water was also examined. They discussed the sensitivity of the cost of distilled water with reference to the lifetime of distilled water with reference to the useful life of the distillation chamber, the cost of the solar collector and other associated parameters.

Khedim (2003) studied in this context a multi-stage sea water distiller with heat recovery. It is therefore a matter of finding a mode of operation enabling the distiller to obtain the best efficiency when the thermal energy is recovered several times. This method of recovering and using several times the same amount of solar energy captured is intended to significantly reduce energy consumption. Experience shows that the system provides good performance.

Shatat & Mahkamov (2010) experimentally studied the performance of a multi-stage distiller coupled to a vacuum tube solar collector with an opening area of 1.7 m^2. The test results showed that the system produced about 9 kg of fresh water per day and a solar collector efficiency of about 68%. However, the overall efficiency of the laboratory testing facility was 33% due to excessive heat loss in the system.

The effect of the number of stages on the productivity of an active multi-effect solar distiller was studied experimentally for the first time by Karimi Estahbanati *et al.* (2015). In addition, the performance of the system in the continuous and discontinuous modes was compared. For this purpose, experiments were carried out within four similar solar distillers with different stages (stages 1–4) to precisely control the environmental conditions.

For the present paper, a solar still with four stages is realized. The still is poly-energy because it can work with three different sources of energy: electrical resistance, photo-thermal solar collector and vegetable or animal waste.

The aim of this work is based on the study and design of a solar still for four stages to get distilled water that will alleviate drinking water needs in daily life. In this work, the effect of the number and position of the trays on the water productivity of a multi-effect solar still was experimentally investigated. The effect of different energy costs of the distillate was also studied.

DESIGN OF THE DESALINATION SYSTEM

System description

This distillation system consists of two different units: one is the source of heat (solar collector) and the other is the distillation unit of four stages. The distillation unit made can work with electrical resistance, photo-thermal solar collector and vegetable or animal waste.

The system in the present research consisted of a basin chamber whose role is to bring water in the stages of the distiller. It acts as the evaporator of the water using the tube coil which conveys the coolant fluid of the solar collector (plane, parabolic, etc.). The basin also contains electrical resistance that runs on a normal or solar power grid (photovoltaic). The distiller tested has trays of circumflex accent type, and a schema of the experimental set up is presented in Figure 1. As illustrated in this figure, the basin chamber was made of four separated stages which are located on top of each other.

Trays are the most important elements for distillation and are made of galvanized iron; they form a barrier for water vapour to condense in contact with the cold walls of the trays containing cold water. The effective evaporation surface is 0.40 m^2.

The volume of the water in the basin is 17 L and the quantity of water carried by each stage is 6 L. The water depth of the first stage is about 3.5 cm and the equivalent depth of the trays is 2.5 cm.

The angle of the trays was experimentally determined at 5°, but an angle of 8° was considered to make sure all drops are collected. To prevent heat loss, the outer surface of the basin is covered with 3 to 6 cm layer of polystyrene. The side wall in the first tests is in Plexiglas for a second reason to see inside the distiller and the physical phenomenon of distillation. This wall is covered with a 6 cm layer of polystyrene.

Figure 1 | Experimental setup.

Experimental procedure

The experiments were performed at the University of Batna 2, Algeria, in the winter and spring seasons, respectively. Batna is a city located 350 km south-east of Algiers in an arid region, and its geographical coordinates are: latitude: 35° 45′ north, longitude: 6° 19′ east. In the first tests, we used a single tray which is placed at the first stage (height of 15 cm), second (height of 30 cm), third (height of 45 cm) and fourth stage (height of 60 cm) successively. At each position of the plate, the temperature and the condensate flow rate are measured.

In the second experiments, we used two plates and we repeated the same procedure done in the first tests, then we used three plates and finally four plates.

The distillate production of every stage was measured every 15 minutes for 4 hours using measuring cylinders with a precision of 10 ml. The temperatures of stages and ambient temperature were recorded by thermometers with probes with an accuracy of ±0.1 °C (Figure 1).

RESULTS AND DISCUSSION

In order to put in evidence the effect of temperature on the one hand and the amount of distilled water on the other hand, our analysis was devoted to the results obtained for a multi-stage solar still whose architecture is in the form of trays stacked one on top of the other with all probabilities as possible and at different heights from 15 cm to 60 cm, the pitch being of the order of 15 cm.

It is found that the temperature of each stage increases progressively until it reaches an almost steady state. In the case of two stages, three and four stages, the lower stage temperature is always higher than the stage located above.

Note that the height is in this case the determining factor for the amount of the distillate obtained; in fact, variations in heights at the different temperatures used are almost identical in the range from 80 °C to 90 °C since they are all equal to the temperature of the inlet manifold set by the heating of the resistance used; however, the amount of the distillate increases with the raised tray at the high rise of 60 cm, and the distillate level is of the order of 1,800 ml for a period of 240 minutes used (McCabe *et al.* 2010).

In the case of two trays, the temperature of the various stages is between 55 °C and 60 °C for the steady state. The production of the distiller does not exceed 1,000 ml/4 h, and this production is less than that of a single tray (the previous case). The maximum is obtained for the trays arranged in the second and fourth stage.

In the case of the various arrangements of the three trays in the distiller, the temperature of the trays varies between 50 °C and 56 °C. The maximum production of distilled water corresponds to the arrangement of the trays placed near the source of the heat (1,300 ml/4 h). The top stage produces more than the third stage.

For four stages, the temperature of the trays varies from 55 °C to 47 °C. The production of distilled water is higher in the first stage and then in the last stage. The production of the last stage is higher than the second and third stage probably due to the condensation of water vapor at the lid of the distiller. The overall production of the distiller is about 1,600 ml/4 h (Figure 2).

When the number of stages increases, the flow of condensate of distilled water increases. In Algeria the prices of electricity, distilled water produced, distiller and solar panel are 0.025 €/kWh, 0.025 €/l, 250€ and 600 € respectively. Distilled water is sold at 0.1 €/l.

By neglecting the other costs (maintenance, manpower, interest rates, price updates, etc.), the amortization of the distiller, which operates with an electrical resistance supplied with power from the electricity grid, is:

$$250 = 0.1x - 0.025x = 0.075x$$

and let

$$x = 250/0.075 = 3{,}333 \text{ litres}$$

In the case where the distiller produces 0.4 l/h, there is a need of:

$$t = 3{,}333/(0.4 \times 24 \times 365) = 0.9 \text{ year}$$

If the distiller operates by solar energy, in the case of the solar panel operating on average 12 h/d, the amortization time of the installation is:

$$850 = 0.1\,x$$

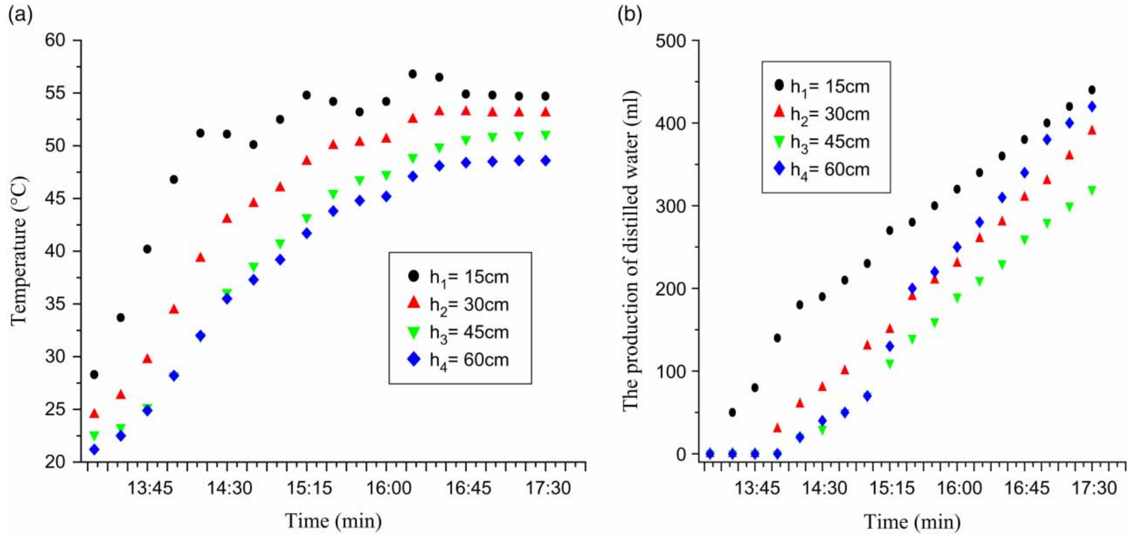

Figure 2 | Variation of (a) temperature and (b) productivity of distilled water versus time for the solar still with four stages.

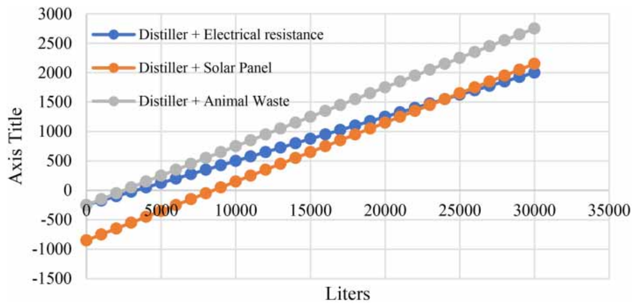

Figure 3 | Installation cost versus distillation water production.

Let

$$x = 850/0.1 = 8{,}500\,\text{litres}$$

Then,

$$t = 8{,}500/(0.4 \times 12 \times 365) = 4.9\,\text{years}$$

In the case where the distiller operates with animal waste, the amortization of the installation is:

$$250 = 0.1\,x$$

$$x = 2{,}500\,\text{litres}$$

$$t = 7{,}500/(0.4 \times 24 \times 365) = 0.7\,\text{years}$$

The production of distilled water from the distiller operating on the public electricity grid and the one with a solar panel will be equivalent only after at least 14 years, i.e. after the lifetime of the installation (Figure 3).

CONCLUSION

The first stage produced the greatest amount of distilled water because of its high temperature and in the case of many stages the best production of distilled water always corresponds to the lowest stages.

The increase or decrease of the temperature of each stage influences the yield of distillation. The production becomes more important if we increase the number of trays where the distiller is well insulated. The maximum production obtained from distilled water is 1 l/h.m².

The use of a solar panel for the production of distilled water is unnecessary in oil-producing countries where energy is subsidized. These devices or their components are generally imported and their cost is very expensive. The damping time of these devices is very long.

REFERENCES

Abu-Arabi, M., Zurigat, Y., Al-Hinai, H. & Al-Hiddabi, S. 2002 Modeling and performance analysis of a solar unit with double-glass cover cooling. *Desalination* **143** (2), 173–182. DOI: 10.1016/S0011-9164(02)00238-2.

Adhikari, R. S., Kumar, A. & Garg, H. P. 2000 Techno economic analysis of a multi stage stacked tray (MSST) solar still. *Desalination* **127** (1), 19–26. DOI: 10.1016/S0011-9164(99)00189-7.

Ahsan, A., Imteaz, M., Thomas, U. A., Azmi, M., Rahman, A. & Nik Daud, N. N. 2014 Parameters affecting the performance of a low cost solar still. *Applied Energy* **114**, 924–930. DOI: 10.1016/j.apenergy.2013.08.066.

Al-Karaghouli, A. A. & Alnaser, W. E. 2004 Experimental comparative study of the performances of single and double basin solar-stills. *Applied Energy* **77** (3), 317–325. DOI: 10.1016/S0306-2619(03)00124-7.

Arunkumar, T., Jayaprakash, R., Ahsan, A., Denkenberger, D. & Okundamiya, M. S. 2013 Effect of water and air flow on concentric tubular solar water desalting system. *Applied Energy* **103**, 109–115. DOI: 10.1016/j.apenergy.2012.09.014.

Chaker, A. & Menguy, G. 2001 Internal efficiency of a spherical solar distiller. *Review of Renewable Energies* (special issue, 10th JITH) 53–58.

Dev, R., Abdul-Wahab, S. A. & Tiwari, G. N. 2011 Performance study of the inverted absorber solar still with water depth and total dissolved solid. *Applied Energy* **88** (1), 252–264. DOI: 10.1016/j.apenergy.2010.08.001.

Fernández, J. L. & Chargoy, N. 1990 Multi-stage, indirectly heated solar still. *Solar Energy* **44** (4), 215–223. DOI: 10.1016/0038-092X(90)90150-B.

Gude, V. G., Nirmalakhandan, N., Deng, S. & Maganti, A. 2012 Low temperature desalination using solar collectors augmented by thermal energy storage. *Applied Energy* **91** (1), 466–474. DOI: 10.1016/j.apenergy.2011.10.018.

Kalidasa Murugavel, K., Sivakumar, S., Riaz Ahamed, J., Chockalingam, K. K. S. K. & Srithar, K. 2010 Single basin double slope solar still with minimum basin depth and energy storing materials. *Applied Energy* **87**, 514–523. DOI: 10.1016/j.apenergy.2009.07.023.

Kamal, W. A. 1988 A theoretical and experimental study of the basin-type solar still under the Arabian gulf climatic conditions. *Solar and Wind Technology* **5** (2), 147–157. DOI: 10.1016/0741-983X(88)90074-4.

Karimi Estahbanati, M. R., Feilizadeh, M., Jafarpur, K., Feilizadeh, M. & Rahimpour, M. R. 2015 Experimental investigation of a multi-effect active solar still: the effect of the number of stages. *Applied Energy* **137**, 46–55. DOI: 10.1016/j.apenergy.2014.09.082.

Khedim, A. 2003 Measurement and thermodynamic characterization of a new solar water desalination system with heat recovery. *Review of Renewable Energies* (11th JITH).

Khedim, A., Schwarzer, K., Faber, C. & Müller, C. 2004 Decentralized production of drinking water using solar energy. *Desalination* **168**, 13–20. DOI: 10.1016/j.desal.2004.06.164.

McCabe, W. L., Smith, J. C. & Harriott, P. 2010 *Scilab Code for Unit Operations of Chemical Engineering*. Indian Institute of Technology, Bombay, India.

Reddy, K. S., Kumar, K. R., O'Donovan, T. S. & Mallick, T. K. 2012 Performance analysis of an evacuated multi-stage solar water desalination system. *Desalination* **288**, 80–92. DOI: 10.1016/j.desal.2011.12.016.

Schwarzer, K., Vieira da Silva, E., Hoffschmidt, B. & Schwarzer, T. 2009 A new solar desalination system with heat recovery for decentralised drinking water production. *Desalination* **248** (1–3), 204–211. DOI: 10.1016/j.desal.2008.05.056.

Shatat, M. I. M. & Mahkamov, K. 2010 Determination of rational design parameters of a multi-stage solar water desalination still using transient mathematical modelling. *Renewable Energy* **35** (1), 52–61.

Suneja, S., Tiwari, G. N. & Rai, S. N. 1997 Parametric study of an inverted absorber double-effect solar distillation system. *Desalination* **109** (2), 177–186. DOI:10.1016/S0011-9164(97)00063-5.

Taghvaei, H., Taghvaei, H., Jafarpur, K., Karimi Estahbanati, M. R., Feilizadeh, M., Feilizadeh, M. & Seddigh Ardekani, A. 2014 A thorough investigation of the effects of water depth on the performance of active solar stills. *Desalination* **347**, 77–85. DOI: 10.1016/j.desal.2014.05.038.

Taghvaei, H., Taghvaei, H., Jafarpur, K., Feilizadeh, M. & Karimi Estahbanati, M. R. 2015 Experimental investigation of the effect of solar collecting area on the performance of active solar stills with different brine depths. *Desalination* **358**, 76–83. DOI: 10.1016/j.desal.2014.11.032.

Valsaraj, P. 2002 An experimental study on solar distillation in a single slope basin still by surface heating the water mass. *Renewable Energy* **25** (4), 607–612. DOI: 10.1016/S0960-1481(01)00094-5.

Velmurugan, V. & Srithar, K. 2011 Performance analysis of solar stills based on various factors affecting the productivity – a review. *Renewable and Sustainable Energy Reviews* **15** (2), 1294–1304. DOI: 10.1016/j.rser.2010.10.012.

Xiao, G., Wang, X., Ni, M., Wang, F., Zhu, W., Luo, Z. & Cen, K. 2013 A review on solar stills for brine desalination. *Applied Energy* **103**, 642–652. DOI: 10.1016/j.apenergy.2012.10.029.

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