Solar desalination via multiple tray distillation

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Abstract - *Small scale desalination of brackish water by distillation using solar energy is a clean, economical and technically competitive solution for small scale production of fresh/distilled water in remote areas. Regions of prime relevance are those characterized by lots of sunshine and readily available brackish water resources, the likes of the vast expanses of the greater In-Salah Sahara desert area. In this work we present an experimental study of a new concept of solar desalination.*

Résumé – *Le dessalement à petite échelle des eaux saumâtres en utilisant l'énergie solaire est une solution propre, économique et techniquement compétitive pour une production à petite échelle d'eau fraîche/distillée dans les zones reculées. Les régions prioritaires sont celles caractérisées par une grande insolation et des sources rapides et disponibles d'eaux saumâtres, semblables aux étendues énormes de la région de In-Salah. Dans ce travail, on présente une étude expérimentale d'un nouveau concept du dessalement solaire.*

Keywords: Desalination – Distillation - Tray distillation - Multi-étages

1. INTRODUCTION

Over the last three years, we have developed and completed an experimental study [1-5] of a solar desalination equipment consisting of a new design of multiple tray distillation. The new feature in the equipment is that the trays are flat and inclined with water cooling on the top surface of the trays to enhance condensation and thus increase output.

Start up of this project was motivated by several reasons with the most important ones being the need to build a desalination prototype that runs on solar energy to produce fresh or distilled water from brackish or other water stocks. Unlike other technology intensive processes such as reverse osmosis, our solar distillation equipment is simple, low cost and requires minimum maintenance to keep it in operation.

Because of the inherent low throughputs of these types of equipment, solar distillation would be suitable for small scale desalination and production of distilled water at competitive costs in remote areas where sunshine and brackish water are plentiful.

On large scale, the distillation process is not economically competitive because of energy consumption. But still, there exist large scale desalination plants functioning on the principle of distillation such as the multi-effect or membrane distillation processes.

These types of large scale installations offer slightly improved economics when using exhaust heat from fossil fuel burning power plants or other forms of waste heat.

At the present time, large scale desalination by reverse osmosis is the most economically sound process for the production of potable water.

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Our project was inspired by the works of many teams of research and academia scientists investigating different designs of tray/multiple-tray distillation models with varying levels of complexity such as those studied by Yuan *et al.* [6], Jubran *et al.* [7], A. Khedim [8], B. Bouchekima [9], and Shatat *et al.* [10].

However, these investigations and others, focused on modeling of the 'pan' type tray configuration. In our case, we have investigated the capabilities of a different kind of equipment, namely an apparatus with inclined, water cooled flat trays to simplify the system and improve performance.

2. EXPERIMENTAL

2.1 The apparatus

The overall configuration of our desalination equipment is similar to those described in the literature in that the system consists of a distillation unit and a heating device. We started our investigation with an indoor electrically heated unit as shown in Figure 1.
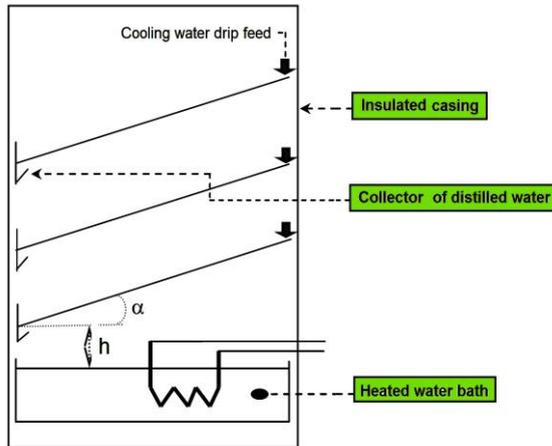
Fig. 1: Indoors Electrically Heated Model

Inside dimensions of the distillation unit are 630 mm high, 350 mm wide and 230 mm deep. The first tray of the distillation apparatus is positioned at a height ' h ' above the water bath level and tilted at an angle ' α '.

The evaporator, 285 mm by 220 mm by 130 mm deep, is equipped with a 500 Watt electric heater which provides adequate heating power.

Temperature control is within 1 °C of the set point and within the range of 55 to 90 °C. Regulation and control of bath temperature is achieved by an ON/OFF switch.

The evaporator is mounted with a tubing system that serves the dual function of a water level indicator gauge and water level adjustment fixture.

To monitor the thermal phenomena associated with the process thermocouples are placed in appropriate areas in the water bath, on the tray and other points inside and outside the distillation chamber.

The solar model, shown in Figure 2, is slightly larger with a height of 890 mm, a width of 340 mm and a depth of 550 mm. The stock water in the evaporator is heated with a heat exchanger connected to a solar heater. This model can also be fitted with a 1200 W electric heater for indoor high temperature evaluations. The evaporator is 500 mm by 300 mm and 130 mm.
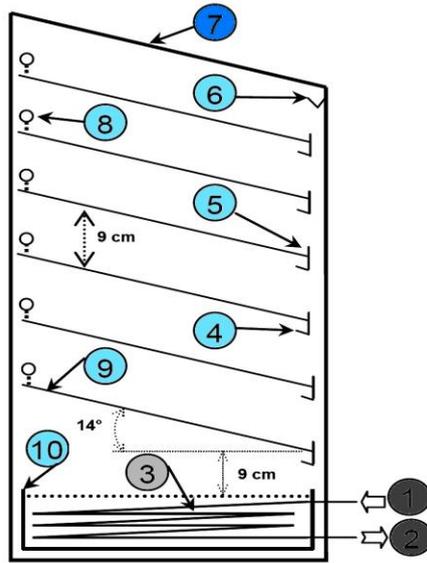
Fig. 2: Solar Heated Model

1- Heating water from solar heater; 2- Heating water back solar heater; 3- Heat exchanger; 4- Distilled water collection channel; 5- Tray cooling water collection channel; 6- Distilled water collection channel; 7- Top cover tray; 8- Drip cooling water tubing; 9- Level 1 trays; 10- Solar heated evaporator.

2.2 The process

In the case of the stacked multiple basin distillation, the operation consists of heating the stock water in the evaporator to produce water vapor. Condensation at the bottom of the first level basin releases latent heat of vaporization and causes heating of the stock water contained therein. Likewise, upon heating of the stock water in the first level basin, vapors are produced which in turn condense at the bottom of the second level and so on.

Our process is different in that the condensation surface is a flat sheet of metal, cooled from the top surface with running water to keep its temperature at a controlled level for maximum output. Our solar multiple tray model is built with six levels of trays arranged in new, unique configurations as shown schematically below.
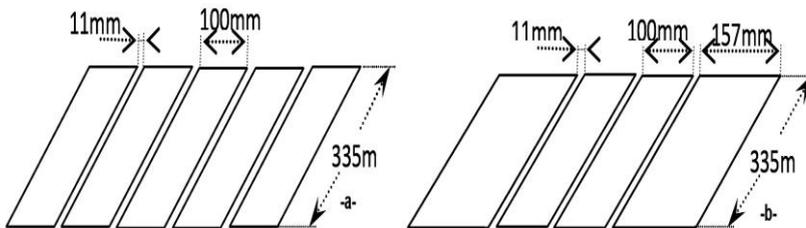
Fig. 3: Tray Configuration: **a-** Level 1, **b-** Level 2

For instance, level 1 consists of 5 side by side trays, 100 mm wide as shown in Figure 3. Similarly, level 2 consists of 4 trays; the outer 2 trays are 157 mm wide, whereas the inner 2 are 100mm wide. Spacing between adjacent trays is 11 mm. Levels 3 and 4 are identical to levels 1 and 2.

3. RESULTS AND DISCUSSION

3.1 Electrically heated model

3.1.1 Effects of evaporator temperature on production

Analysis of the data showed that the output of distilled water increases exponentially with increasing temperature of the evaporator as shown in Figure 4 below. In general, temperature dependent rate phenomena follow the Arrhenius model $X = X_0 \times \exp(-\Delta E / RT)$.

In our case X is the output of distilled water, T is the absolute temperature of the stock water in the evaporator, X_0 is a process constant, R is the gas constant and ΔE is an activation energy term.
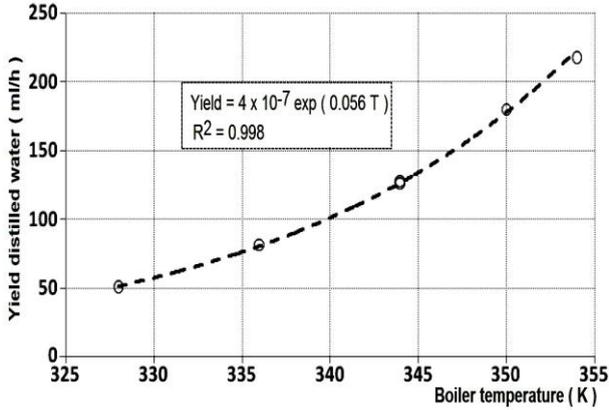
Fig. 4: Effect of temperature on output

For practical reasons and ease of interpretation, data following the Arrhenius model are plotted as natural $\log X$ versus $1/T$ as shown in Figure 5 below. Thus, the activation energy term and the process rate constant are obtained from the graph in which for our case, $\Delta E = 5.47 \times 10^4 \, J/mole$ and $X_0 = \dot{Q}_0 = 2.57 \times 10^{10} \, ml/h$.
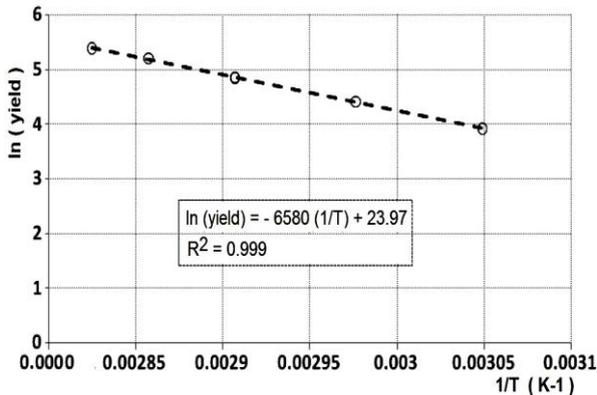
Fig. 5: Arrhenius plot of yield

3.1.2 Effects of cooling water flow rate on yield

The trays of the distillation unit are kept at a specified temperature by running cooling water at the appropriate flow rate and inlet temperature.

At a fixed evaporator temperature, the temperature of the tray goes down as the flow rate of the cooling water is increased. Cooler tray surface temperatures result in higher rates of condensation and thus increased production of distilled water.

Examples of the results of this evaluation are shown in Figure 6 below.
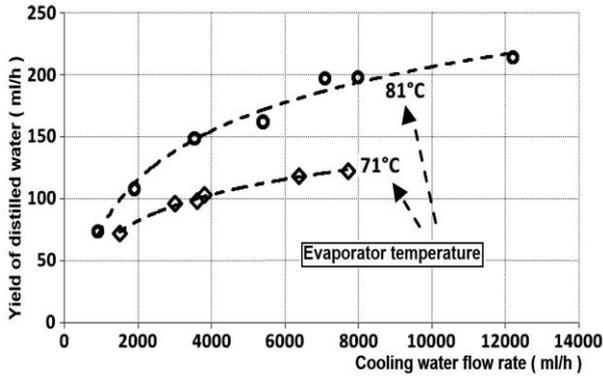
Fig. 6: Effect of cooling water flow rate on
yield at two different evaporator temperatures

The upper curve in the graph represents data collected with the boiler temperature maintained constant at 81 °C while the curve below it corresponds to similar data with the evaporator temperature at 71 °C.

3.1.3 Effects of boiler temperature at constant tray surface temperature

In this section, it is intended to investigate the effects of tray temperature on equipment output. Thus, the equipment production rate of distilled water was measured at four tray temperature, namely: 26, 35, 38 and 45 °C.

The results of this study are summarized in Figure 7. The data indicated that the tray isotherms are not parallel, they appear to converge by extrapolation to one same intersection point, corresponding to the boiling temperature of the input stock water.
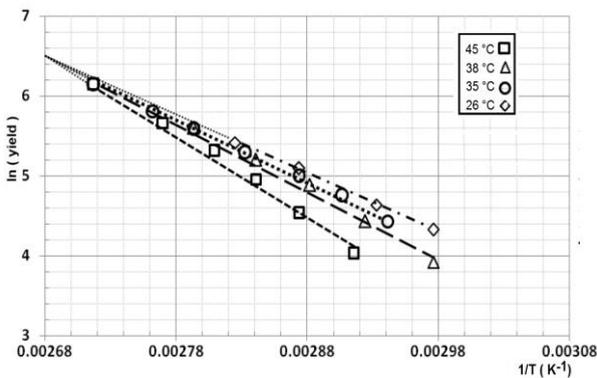
Fig. 7: Arrhenius plot of yield at different tray temperatures

3.2 The solar model

Effects of process variables on output

The solar model was tested indoors using an electrical heater as well as outdoors in both temperate and desert climates. The results of these evaluations are summarized in Figure 7 below. The graph legend abbreviations are as follows:
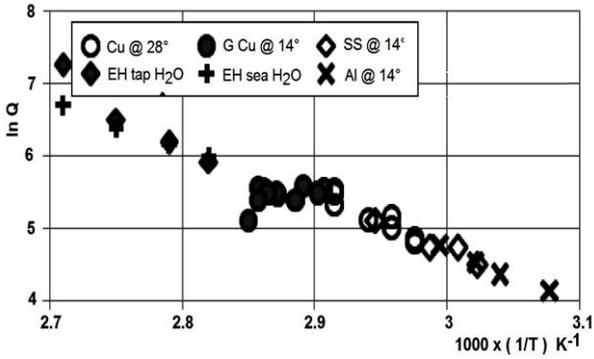
Fig. 8: Arrhenius plot of output under various conditions

Cu @ 28° refers to trials whereby the distillation box is equipped with copper (Cu) trays inclined at 28°. G Cu @ 14° is for data collected in Ghardaia using Cu trays inclined at 14°. SS @ 14° is for Stainless Steel (SS) trays at 14° inclination. EH tap H_2O is for indoor testing with Electrical Heating (EH) using tap water whereas EH sea H_2O is for similar trials but using sea water. Finally, Al @ 14° is for aluminum (Al) trays at 14° inclination.

Figure 7 shows that within experimental errors, the performance of the equipment follows the Arrhenius model. Although our experimental model is designed with the capability to hold six levels of trays plus the ceiling, we have observed that when operating the equipment with a solar heater one level of trays is best.

This holds true when the maximum attainable evaporator temperature is in the 80°C range. Adding a second level of trays does not improve production. The indoor trials using electrical heating showed that when operating the equipment at evaporator temperatures higher than 90°C, the lower 4 levels are responsible for the bulk of the equipment output.

Production of distilled water from levels 5, 6 and the roof are negligible.

3.3 Quality control and cost

Periodic measurements of electrical conductivity, σ_e, are used as a simple and quick way to check product quality and to monitor the process. From a product quality standpoint, the equipment produced good quality distilled water as evidenced by measured σ_e values as low as 1.6 to 5 μS/cm. The pH was also checked occasionally and was found to be in the range of 4.62 to 5.00. The feed water used for this work has a pH of 7.32 and a σ_e of 2090 μS/cm.

Finally, worst case scenario cost evaluation showed that one liter of distilled water produced with our solar distillation machine is 16 DA compared to 45 DA for a similar quality deionized water on the local market.

4. CONCLUSION

Temperature was found to be the critical process variable for the multiple tray distillation apparatus described in this paper. Like other temperature dependent processes, the output of the equipment follows the Arrhenius model.

From a design standpoint, one level of trays is recommended when the maximum attainable evaporator falls in the range of 80 °C, there is no gain using multiple trays.

For small scale applications, solar distillation is clean from the environment protection perspective and cost effective.

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