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Experimental investigations on a multi-stage water desalination prototype

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ABSTRACT

The present work proposes a new multi-stage distillation system that was designed in UDES with the objective of increasing its productivity and improving its efficiency. The aim was to develop a simple and economic multi-stage solar still to produce freshwater for domestic and socioeconomic sector uses from seawater and brackish waters that are abundant in many remote areas of the Algerian Sahara. We study the effect of cooling water temperature and collected experimental data in order to optimize their influence on the yield of the multi-stage distillation process for the first four-tray device. The preliminary results showed a significant improvement of the overall productivity. The effect of the boiler temperature T_b is presented for different values. Indeed, the total productivity of the still is affected by the increase of the cooling water flow rate on top of the tray. The experimental results show that the first tray of the system produces about 35 l of freshwater per day and the temperature of the evaporator efficiency is fixed at 96°C. The results that permit the determination of the output of each tray of the still are presented in this study. The analysis of the distilled water showed that its quality was within the international standards (World Health Organization guidelines).

Keywords: Distillation; Desalination; Multi-stage still; Solar; Energy

1. Introduction

Different semi-arid and arid regions in the developing countries show a great interest to the desalination of sea and brackish water using solar distillation process to alleviate the increasing shortage of freshwater. The development of desalination technologies combined with the use of renewable energies is a very attractive and promising prospect especially for the remote regions that have greatest water shortages and higher solar radiation availability [1–3]. Solar distillation is a simple technique, which can be easily adapted in the semi-arid and arid areas when water salinity does not exceed 10 g/l. This thermal process

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is an efficient solution to purify water in order to provide clean drinking water and irrigation of agricultural surfaces. It has many advantages as it uses a still of a simple design that can withstand rough conditions, it requires no maintenance and low cost. In fact, there are many types of solar stills, some of them have been developed and commercialized [4–6]. Till now, many experimental and theoretical studies are undertaken in order to modify the solar still using different configurations and improve its yield [7–9].

Multi-stage distillation is one of the important and technically viable applications for water purification. The machinery is reliable and robust to produce clean water for domestic and socioeconomic uses from seawater and brackish waters that are abundant in many remote areas of the world. Several experimental and numerical investigations on multi-stage still have been reported in the previous studies such as the work of Malik et al. [10], Kumar et al. [11], Fernández and Chargoy [12], and Adhikari et al. [13].

In 1995, Adhikari et al. [13] have developed a simulation model for studying the steady-state performance of a multi-stage stacked tray solar still. It shows great potential in terms of higher distillation yield per unit area. The model proposed is validated by the results of simulated experiments on a three-stage unit having an immersion-type electric heater as the heating source. They found that the theoretical values are in good agreement with the experimental results. Furthermore, they have developed a techno-economic model for a multi-tray solar still [14]. A flat-plate solar collector is using as the heat generator. In order to produce fresh drinking water, Khedim [15] has made a multi-stage still with five trays connected to a flat-plate solar collector. He could characterize this new seawater solar desalination system operating at an atmospheric pressure with heat recovery. It should be noted that the method of recovery and use of the same amount of solar energy collected several times is intended to significantly reduce the energy consumption so that solar energy becomes an alternative to the water desalination technique. The thermodynamic characterization allowed a good performance of the system. Therefore, the rate of distilled water obtained is 4.0 kg/h corresponding to a daily production of 30 kg. On the other hand, the energy consumption per kg of distilled water is estimated 0.3 kWh/kg and the cost of a kg of water is 0.03 €. Analysis of previous works shows that mainly lumped-parameter type models are used for the theoretical modeling of the operation of multi-stage tray solar stills.

A mathematical model has been developed by Jubran et al. [16] to predict the productivity of a multi-stage solar still with expansion nozzle and heat recovery features in each stage of the system. These new features of the still can produce up to 9 kg/m^2 d with a distillation efficiency of 87%. The cost analysis indicates that the unit cost for distilled water for these three-stage still is $25.6/1,000 gallons. Water desalination with heat recovery is a good solution for a better output. Later in 2009, experimental and numerical investigation of the concept of cylindrical multi-stage water desalination still was presented by Ahmed et al. [17]. The system was designed to recover latent heat from evaporation and condensation processes in four stages. Their preliminary experimental results showed a very good output compared to the ordinary basin type. Moreover, the total daily yield was found to be about three times more than the maximum productivity of the basin-type solar still. A feasibility study showed that the cylindrical type found to be much better than the rectangular one in terms of safety factor and maximum deflection. An economic cost analysis has been performed to estimate the unit cost of the distilled water produced by the solar still. It was found that the unit cost for distilled water obtained from these three stages solar desalination system is $0.02544/gallon. It is found that the multi-stage, stacked tray solar still produces more distillate than that produced by the ordinary solar still [16,18].

Shatat and Mahkamov [19] performed experimental and numerical studies indicating that the freshwater production capacity of the evacuated tube solar collector with aperture area of 1.7 m^2 using four-stage still system was found to be about 5 $kg/m^2/d$. This amount is higher than that of multi-stage stills coupled with flat-plate collectors. The system produces about 9 kg of freshwater per day and has a solar collector efficiency of about 68%. They determined rational design parameters of a multi-stage solar still using transient mathematical modeling. The proposed model suggests that for the evacuated tube solar collector, the evaporation area in each stage should be 1 m^2, with the total number of stages equal to 4 or 5.

It is also worthwhile pointing out that in these studies cited above, the tray is V-shaped filled with stagnant water to be distilled. This configuration is the most widely used and studied. In the considered case, the tray is a plate inclined on which a flow rate of the cooling water moves on the top surface of the stage. It is allowed to spread evenly to form a thin film and flow down the tray in order to increase the condensation rate. This technique has not been studied, up to now, to our best knowledge in multi-stage still. We have looked at a different design and wish to generate more interest and work in this area. Therefore, this study is relevant to understand the temperature parameter that is sensitive and acting directly on the distillation process through the evaporation and condensation of water. The multi-stage system of laboratory scale is a research tool to identify the variables and quantify their effects on productivity [20,21].

The aim of this work was to undertake thermodynamic measurements to study and realize a seawater multi-stage distillation system of high performance with heat recovery. We studied the effects of water boiler temperature and tray surface temperature on tray yield of the realized system. Our investigation is focused on the first and second stage to examine the evolution of the distillation yield of the stage as function of tray surface temperature. Moreover, this system can be connected to a solar heating system that will allow operation of these types of devices with clean renewable energy sources. In the future, the multi-stage distillation can become economically a viable alternative technology for many dry areas in North Africa and other countries. The experimental results showed a significant improvement of the system yield due to the low cooling water temperature and we observed that the productivity of the system increases when the temperature of the boiler increases. Finally, we evaluate the physical and chemical properties of distilled water produced by multi-stage system.

2. Experimental device

The experiments were carried out through multi-trays distillation system that was designed and realized by our team in the Development Unit of Solar Equipment UDES/Algeria. The distillation equipment consists of two components: the distillation unit and an external water distribution system for the boiler and for feeding the distillation trays. Schematic diagram of the distillation apparatus is shown in Fig. 1. All outside walls of the distillation unit are made of stainless INOX. The inside dimensions of the insulated distillation casing are 630 mm in height, 350 mm in width and 230 mm in depth.

In the considered case study, four stages are mounted on top of each other, and each stage contains four or five small plates to create between them a sufficient spacing for heat transfer. The sealing is maintained between the stages and cooling water to prevent any cooling water leakage through the contact surfaces. Insulation is also used to reduce heat losses of the solar still to the ambient.

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 length of the tray on the other hand is determined by the tilt angle. Different trays are made of aluminum 0.4 mm thick and their inclination was $\alpha = 14^{\circ}$. To increase significantly the production and transfer of vapor, we have designed a new structure of the tray. Each tray is characterized by the inclusion of gaps between three and five small plates, which depend on the number of the stage. This system allows water vapors to transfer through trays up to the top stage.

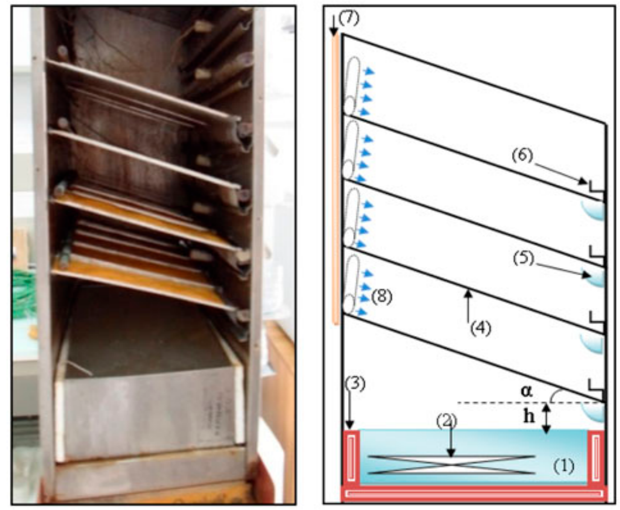

Fig. 1. Schematic diagram of the distillation device: (1) evaporator, (2) electric heater, (3) insulation, (4) tray, (5) distilled water channel, (6) cooling water channel, (7) cooling water distribution system, and (8) cooling water.

In order to create a great temperature gradient, cooling water flow on trays is applied to enhance the evaporation–condensation processes. We have used a mechanism for distributing cooling water evenly over the tray and to ensure a constant and uniform temperature in the tray. We indicate that the equipment operates at ambient pressure. The boiler is made of lacquered sheet thickness 0.4 mm, which is one of the important elements in this investigation. Its dimensions are characterized by 385 mm in length height, 250 mm in width, and 130 mm in deep. The evaporator is mounted with a tubing system that serves the dual function of a water level indicator gauge and water level adjustment fixture. Water vapor is produced from an electrically heated water bath—the boiler. The heat source is a 500 W electric heater coil, which provides adequate heating power for this bench scale system. Temperature control is within 1°C of the set point and within the range of 60–95°C. Different thermocouples are placed in appropriate areas in the water bath, on the tray and other points inside and outside the distillation chamber to monitor temperature.

2.1. Distillation process

In principle, the tray or multi-tray distillation process is fairly simple and can be very efficient from an energy requirements standpoint. For the sake of this investigation, for example, water in the boiler is heated to a given temperature and maintained constant. Vapors—as they rise from the boiler—come into contact with the cold bottom surface of the first tray where they condense. As the condensed water droplets grow larger in volume and thus heavier, they start making their way downwards under the pull of gravity and dripping into the collection channel at the bottom edge of the tray, see Fig. 1. The latent heat released during the condensation step is transferred to the thin film of water trickling down on the top side of the tray.

It is worthwhile noting at this point that, in our design, the top side of the tray is covered with a thin, loose fill cotton cloth to ensure a uniform wetting of the entire top surface of the tray to maximize productivity of the equipment (Fig. 2). Some percentage amount of the water flowing on the top of the first tray evaporates and condenses on the bottom side of the second tray and so on up to the third or nth tray.

3. Results and discussion

In this study, the aim was to increase distillation yield using new type of multi-stage still, which fabricated and tested in UDES/Algeria. The experiments are focalized on different effects that affect directly on the production of the system. We attempt to quantify the temperature effect of the water to be distilled in the boiler and of the cooling water on the distilled water volumetric flow rate of the distillation system. In our experiment, we used the Bou Ismail well water of electrical conductivity 2,090 μS/cm and salinity 1 g/l and pH 7.32 at $T = 23.3$°C. The boiler is filled with 18 l and its temperature was varied to cover the range from 75 to 96°C. Different

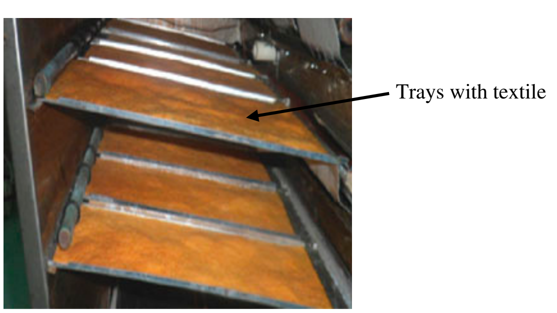

Fig. 2. Stages covered with cotton cloth.

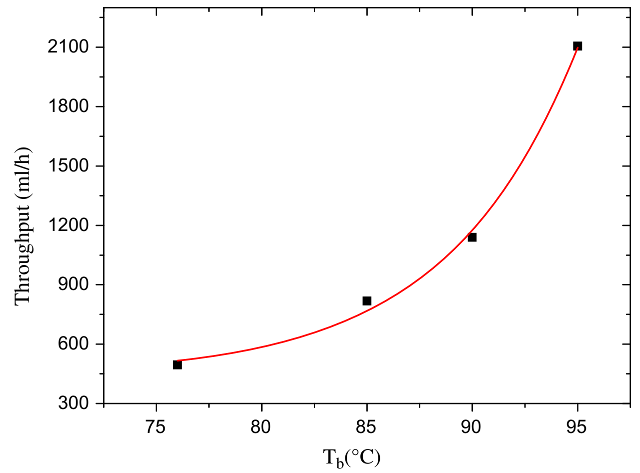

Fig. 3. Evolution of the distillation yield as a function of boiler temperature T_b.

temperatures are measured by K-type thermocouples connected to a data logger Fluke type for the acquisition of data, which are recorded on a memory card for a programmed time interval of 30 min.

3.1. Effects of water boiler temperature on each tray yield

In the first experiment, we fixed temperature of the water in the boiler T_b, which varies in the range 75°C < T_b < 95°C, then we measured the throughput of each tray under specific conditions. Water level in the boiler is closely monitored and kept constant by adding water when appropriate. The flow rate of the cooling water on the top surface of the tray is kept constant throughout the whole experiment of this part

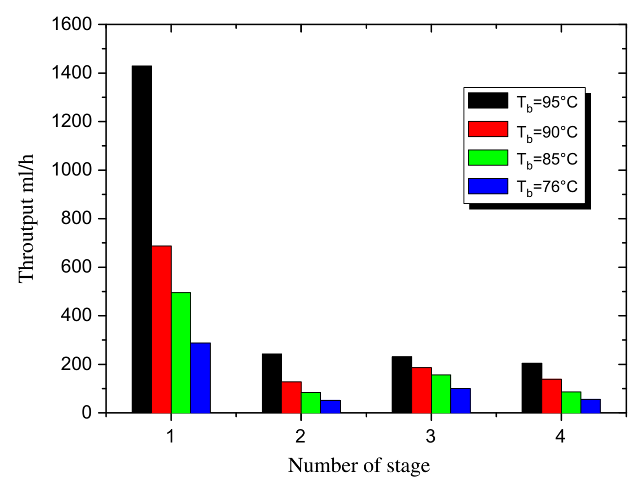

Fig. 4. Variation in the distillation yield as a function number of stage for different boiler temperatures values.

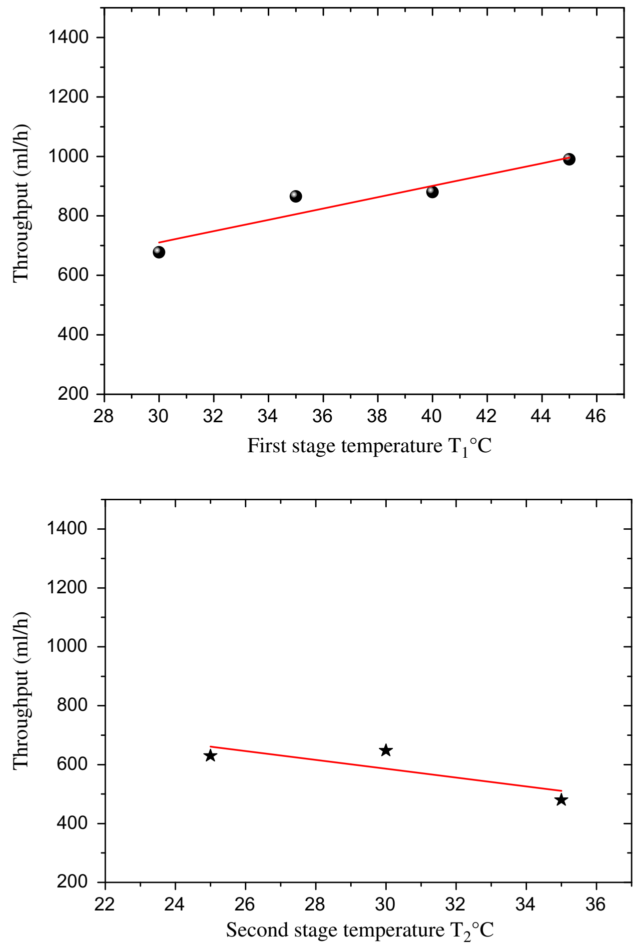

Fig. 5. Evolution of the distillation yield of the stage as function of tray surface temperature.

or adjusted to the appropriate flow rate to maintain a constant tray surface temperature. We notice that the whole surface of the tray was covered with a cotton textile in order to absorb water and to ensure the adequate wetting with constant temperature. At cooling water flow rate constant, the total output of the system for different boiler temperature values has been measured. Fig. 3 presents the experimental results of the effect of boiler temperature on the total throughput of the equipment, which mounted by four stages. It shows that the productivity of the system increases when the temperature of the boiler is increased. The production rate is more important when temperature of the boiler water is $T_b = 95$°C. Noticeably, the behavior of this evolution depicts an exponential law, which is shown by a solid line. In Fig. 4, we show the corresponding measure of yield for each tray with specific boiler temperature, which is carried out independently. We notice that the first tray produce more

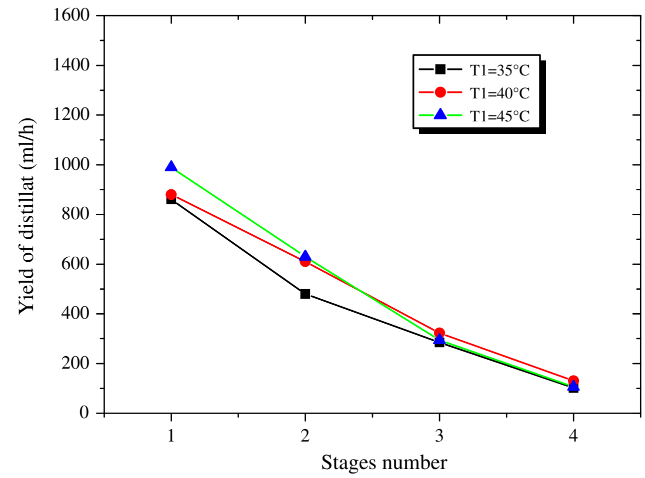

Fig. 6. Evolution of the distillation yield as function of the stage for a different constant tray surface temperature of the first stage.

than three others trays placed above it. The boiler temperature affects considerably the throughput of the equipment.

3.2. Effects of tray surface temperature on tray yield

In the second experiment, we explore the effect of tray surface temperature on yield of the first and second stage. In this case, we evaluated the performance of each considered tray distillation unit in order to optimize the temperature operating when the temperature of the water in the boiler T_b is fixed at $T_b = 95$°C. Fig. 5 presents the throughput of the first and second tray under the effect of the stage surface temperature. The results of these measurements show that the throughput of the first tray is more increasing when the first tray surface temperature T_1 varies in the range 35–45°C. The production rate of the stage is higher and maximum when $T_1 = 45$°C. Therefore, we indicate that the first tray surface temperature T_1 should be maintained close to 45°C to obtain the maximum flow rate of distillate. In contrast, the surface temperature of the second tray T_2 should be maintained close to 30°C. Different yields of trays are presented in Fig. 6 when the first tray surface temperature T_1 is variable. The variations of these curves indicate that as the tray surface temperature increases, the productivity decreases significantly.

4. Conclusion

An economical multi-stage still has been developed using inclined and flat tray with specific configuration to allow water vapors that transfer through trays up to the top stage. The system being tested is a laboratory prototype and its distillation efficiency can be considerably increased when design parameters are precisely determined. These parameters need to be optimized based on techno-economic considerations. Experimental investigation is carried out to realize an efficient multi-stage still using simple technical means with a minimum of know-how in order to get supply of drinking water. This study revealed the temperature effect of water boiler and stage surface that affect considerably the distillation equipment performance. The system was developed by creating a great temperature gradient; cooling water that flow on trays is used to enhance the evaporation–condensation processes and distill all types of water in arid and remote areas. The experimental results show that the productivity increased as the water boiler temperature increased due to the higher evaporation rates. The productivity differs from a tray to another, when the stage number increases the production rate of the tray strongly decreases. Indeed, the total yield of the system is affected very much by the tray surface temperature changes. The analysis of the distilled water produced by the system shows that its quality satisfies the requirements defined by the World Health Organization.

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