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Effect of water flow rate on internal heat and mass transfer and daily productivity of a weir-type cascade solar still

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ABSTRACT

In this paper, a cascade solar still (CSS) was designed for water purification with a view of enhancing the daily productivity. The work studied the influence of water flow rate on the internal heat and mass transfer and daily productivity of CSS. Dunkle's relation was employed to predict the still behavior because of its wide application in the literature. However, Dunkle relation could not satisfy our CSS behavior due to the special geometry and operational conditions. Therefore, the internal heat and mass transfer coefficients were determined using the experimental data obtained from the modified cascade solar still designed in this work. The results showed a decrease in the internal heat and mass transfer rates as well as daily productivity with an increase in water flow rate. In this regard, the daily productivity was found to be 7.4 and 4.3 kg/m^{2}day, for minimum and maximum flow rates, respectively.

1. Introduction

Fresh water is an urgent need for human life as a person's survival drinking water. About 97% of available water sources are saline and/or include harmful bacteria and 2% is frozen in glaciers and polar ice caps. Hence, only 1% of the world's water is useable for drinking and domestic usages [1]. Water scarcity problem is generally observed in warm arid countries of Middle East and North Africa that cause socioeconomic problems in these regions. Solar water distillation is a technology with very long history that can be used for water purification in remote areas and arid zones because of great solar potential and abundance of saline/brackish water sources. Delyannis [2] presented a historic background of desalination and renewable energies. Various technologies are being used for desalination such as multi-stage flash, multiple effect, vapor compression, reverse osmosis, ion exchange, electrodialysis, phase change and solvent extraction [3]. These technologies are costly, especially when the large amount of fresh water production is not desirable. On the other hand, using conventional energy sources (hydrocarbon fuels) to drive these systems has harmful environmental impacts. Various types of solar still have been investigated by researchers [3–7]. Passive solar stills which divided into basin and inclined types are good options for providing drinking water from brackish water in arid coastal zones when the weather conditions are fair and the demand is not too large. Many researches have been carried out to improve the daily productivity and thermal efficiency of the basin and inclined types by making modifications in structure and materials [8–13]. Velmurugan et al. [1] investigated the integration of fins at the basin of the still and showed the increase of daily productivity from 1.88 to 2.8 kg/m^{2}day as compared to other types. Al-Ghamdi et al. [14] studied transient performance of a single basin solar still with phase change material as a storage medium. They reported that the still integrated with the heat storage system was efficient for water distillation during the lack of sunlight, particularly at night. Recently, inclined solar stills have received many attention due to higher productivity than the basin types and offering better orientation and minimum air gap. Some drawbacks have been observed in inclined solar stills such as fairly complicated construction and channelization onto the evaporation surface. Performance of various configurations of the inclined solar stills has been studied by some researchers [15–19]. Aybar [18] tested an inclined solar still with and without wicks. The results showed that the wicks increased the distilled water generation by two or three times of bare plate. Sadineni et al. [19] designed a weir-type inclined solar still and showed that the productivity of the weir type still was approximately 20% higher than basin type. In addition, some surveys have been carried out on the other aspects of solar stills such as identification of the effective parameters on internal heat and mass transfer of the conventional basin stills [20–27]. Heat transfer in solar still is basically classified as external and internal heat transfer. External heat transfer is mainly governed by radiation, conduction and convection that are independent of each other. Internal heat transfer is occurred by radiation, convection and evaporation where convection and evaporation are coupled together. Researchers predicted the internal heat transfer coefficient based on the following equation:

$$Nu = (h_{cw} \cdot d) / k = C(Gr \cdot Pr)^n \tag{1}$$

where C and n are constants.

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Dunkle [21] found an empirical expression for convection heat transfer coefficient considering the following limitations:

The Dunkle's relation is valid only for parallel evaporation and condensation surfaces under the mean operating temperature range about 50 °C and independent from average distance of condensation and evaporation surfaces. Dunkle calculated C and n as 0.075 and 1/3, respectively. Different models for internal heat and mass transfer have been presented by various researchers [20,23,28]. Hongfei et al. [23] suggested a group of improved heat and mass transfer correlations in basin type solar stills by experimenting on a multi-stage stacked tray solar still. Tripathi and Tiwari [24] investigated the effect of water depth on heat and mass transfer for active solar distillation. Tiwari A. and Tiwari G. [25], Phadatare and Verma [26] found that lowering the height of the basin water lead to increase and decrease in productivity during day and night, respectively.

In the present study, a cascade solar still (CSS) was designed based on the optimum inclination through the year in Zahedan city of Iran. The effect of flow rate on internal heat and mass transfer and daily productivity of still were investigated in four consecutive sunny days through June 28 to July 1, 2009. Also, constant values of C and n in Nusselt relation were calculated from the experimental data. Furthermore, Dunkle's model, which is widely used in many literatures, was used to show the necessity of investigation of internal heat transfer in the designed still.

2. Experimentation

Fig. 1 shows cross sectional view of a schematic diagram of cascade solar still (CSS).

The CSS was designed to increase the amount of distillated water production by providing a minimum air gap, suitable distribution of feed water on evaporation surface and better orientation to solar beams. Many various materials have been employed in structure of solar stills (i.e. wood, galvanized iron, aluminum, asbestos cement, concrete and masonry bricks). In this work, aluminum sheet was used due to better resistance to corrosion, low weight and easy formation. Stepped structure of absorber plate with 120 cm × 60 cm size was painted with matte black paint to increase the absorbtivity. Absorber was made of 15 steps where each step consists of a horizontal and vertical surface with the lengths of 5 and 3 cm, respectively. Therefore, the evaporation surface area was considered about 0.45 m^2 with 30° still inclination corresponding to the latitude of Zahedan (around 32°). Singh and Tiwari [29] proved that the annual maximum yield is possible, when the condensing glass cover inclination is considered as a latitude of the place. A glass cover with 3 mm thickness on top of the absorber creates an enclosure with 2.5 cm air gap. Each step was equipped with a 5 mm height and 59 cm length weir to force the flowing water to pass through the evaporation surface, which leads to the increase of the residence time of water in the still. Moreover, the weirs are to keep the water film as shallow as possible (with low heat capacity) and cause to improve the water distribution upon the evaporation surface while avoiding dry spots. Hence, the channeling was diminished by even distribution of water on the absorber plate. A schematic top view of water flow path onto the absorber surface is shown in Fig. 2.

The still was well insulated inside the aluminum frame to decrease the heat loss. The feed water injected to the still flowed continuously during the operation. Little precipitation was observed in the continuous flow which implies that the still rarely needs to be cleaned.

The feed water passing through the steps is heated by solar energy. The evaporated water gets condensed on the inner side of the glass cover after releasing the latent heat. The condensed water trickles into the collection channels provided at the lower ends of glass, under gravity, while the concentrated feed water was taken out from the still. Four Pt-100 resistance sensors measured the temperature at different points of the still. Two sensors were placed in water flow path at the inlet and outlet of the still and the other two sensors were used to detect the absorber temperature. The glass cover temperature was measured by using a thermocouple with a digital indicator. The experimental data were recorded hourly using a data logger connected to a computer. Hourly wind velocity, solar intensity and ambient temperature values were reported by a local meteorological station in Zahedan.

All experiments were carried out between 8 AM and 7 PM local time for 0.065, 0.1, 0.15 and 0.2 kg/min flow rates in four consecutive sunny days from 28/06/2009 to 01/07/2009.

3. Thermal analysis

The solar energy heats the water in the still and evaporates it. The generated vapor is freely transmitted from water surface to the top due to buoyancy force caused by density reduction. Humid air circulation is induced by temperature difference between brine and condensation surfaces causing heat and mass transfer. This process within the still occurred by natural convection mode.

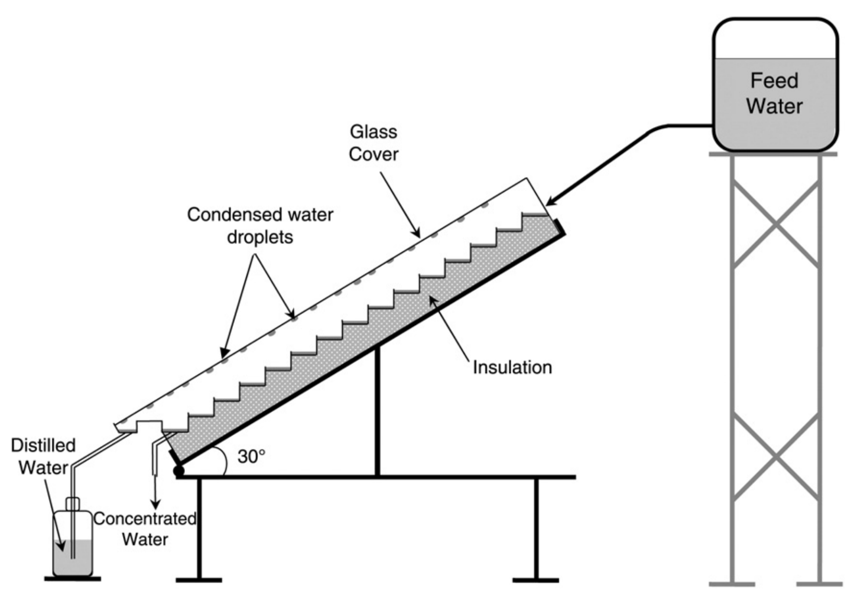

Fig. 1. Cross sectional view of a schematic diagram of cascade solar still.