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Experimental and numerical performance analysis and optimization of single slope, double slope and pyramidal shaped solar stills

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ABSTRACT

In this work, the annual performance of single basin single slope, double slope and pyramidal shaped solar stills has been investigated experimentally and theoretically. Experiments were conducted in Ma'an area in Jordan throughout the year from January 2015 to December 2015 on clear days using solar stills with different orientations and different tilt angles of 15°, 30° and 45°. Mathematical models of solar radiation and solar desalination were developed to simulate the availability of solar radiation in Ma'an region, Jordan (Latitude: 30.7 N, Longitude: 35.7 E), and the performance of the solar stills. The average basin area was found to be of 0.64 m^2 and 0.82 m^2 in January and July, respectively. Model simulations were validated against experimental measurements and a reasonably good agreement was obtained. Annual optimal tilt angles of 30.3°, 45°, and 65° were suggested for south oriented single slope, double slope and pyramidal shaped solar stills, respectively. Under optimal settings, the single slope solar still was found to be the best system with improvement in productivity of about 28%. On a seasonal basis, a south oriented double slope solar still with tilt angle of 35° was found to perform, slightly, better than the other stills in summer.

1. Introduction

Approximately, 70% of our planet surface is covered by water, of this percentage 97% is salty water located in the ocean. The percentage of fresh water available is about 3% of the total water on our planet. Unfortunately, the distribution of fresh water reservoirs, worldwide, is uneven. Arid regions (e.g., Jordan and most of Middle East countries) suffer from sever freshwater stress which overwhelm the weaker population and living stock. Freshwater resources are limited and depleting, yet the demand on drinking water is escalating. Such an issue brings about a great danger that would, certainly, result in disturbing humanity, economic collapse, and deteriorating of living standards. These consequences have drawn our attention for the need to search and find other sources of freshwater.

Techniques for obtaining fresh water such as: reverse osmosis, multi-stage flash desalination, electro-dialysis and many others are available. However, these techniques are known of their drawbacks in terms of their cost, maintenance and energy consumption [1,2]. Among many, solar desalination of brackish water is emerging as an inevitable option, mainly in remote arid regions, due to its low cost and simplicity. Arid regions in Middle East and North Africa are recognized of their high intensity of solar radiation [3]. This makes the direct use of solar energy for water treatment represents a promising option for these communities.

Solar energy can be utilized to obtain drinkable water from brackish water through the use of solar still. Such systems capture the evaporated (or distilled) water by condensing it onto a cool inclined surface. A simple conventional passive solar still consists of a glass cover, still basin and collecting channels. The glass cover could be single, double sloped and pyramidal. The brackish water in the black painted basin is heated by the transmitted solar power that has been absorbed by the basin linear. In this system, the basin and the brackish water can be considered as an evaporator, and the glass cover as a condenser. Solar desalination is an economically effective and environmentally friendly method over all the conventional desalination methods. There are several types of solar stills, the simplest type of which is the single basin still. The yield of single basin still, however, is low and falls in the range of 1.5–3 L/m^2 [4,5,6].

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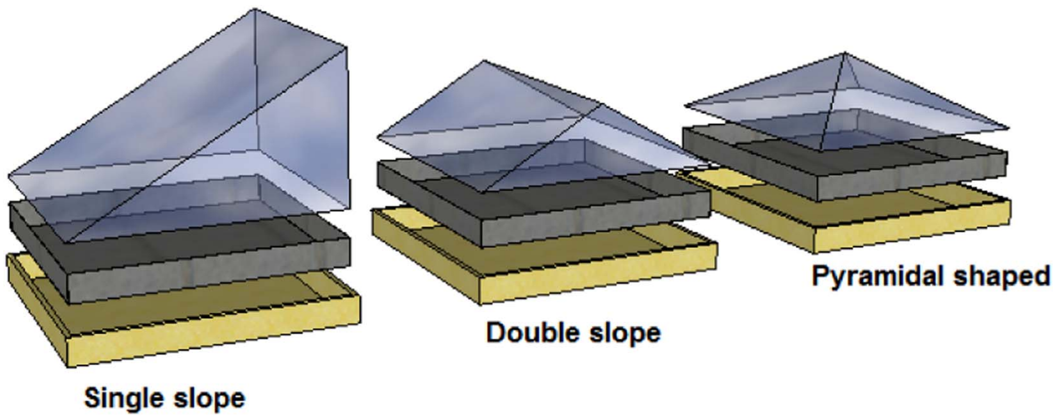

Scheme 1. Solar stills with different cover geometries.

Solar stills have been meticulously investigated and tested for the production of desalinated water using solar energy. Sampathkumar et al., published an excellent review of different studies on active solar desalination [6]. Mathematical thermal model for various types of active single slope solar still was presented. Most of the studies carried in this area showed that the efficiency of the single-basin solar still is in the range of 30–50% [7,8,9,10]. Such low to moderate efficiency has been attributed to the significant loss of the latent heat of condensation across the glass cover.

The performance of the solar still is mainly influenced by three factors: (i) climatic such as ambient temperature, solar radiation intensity and weather condition; (ii) design such as still geometry and inclination angle; and (iii) operational such as orientation of solar still and brine water depth. Studies on the effect of the ambient temperature showed that an increase in ambient temperature by 10° from 23 °C could result in about 8% increase in still productivity [11].

Wind speed might be of two fold effects; in one hand an increase in wind speed may accelerate heat removal from the glass cover resulting in cooling down the glass cover and increasing, thereby, the rate of condensation and evaporation. While on the other hand, however, an increased wind speed may also result in increasing the rate of heat loss by convection from the system and then reducing the evaporation rate. With this in mind, conflicting results about the wind effect on still productivity have been reported in literature [12,13].

Water depth (water mass) was found to have a significant effect on the still productivity. It has been shown that the water depth inversely affects the production of solar still [5,10,14]. Experiment with deep basin showed that, the performance of the still decreases with an increase in water depth during daylight and the reverse is the case during overnight. This is because of the higher volumetric heat capacity of water. The effects of cover type and inclination were reviewed and investigated in many studies [10,15,16,17]. It was concluded that the optimal productivity can be achieved when the cover tilt angle is equal to the latitude of the location. In this regard, Altarawneh et al. [3], addressed the effect of surface tilt angle on the collected solar power and the optimal tilt angles trajectory over the year was obtained. They pointed out that tilt angles of 13^{o} and 55^{o} are preferred for summer and winter periods, respectively, with annual optimal tilt angle of about 28^{o}.

Solar desalination involves simultaneous heat and mass transfer. Many studies have addressed the internal mass and heat transfer relationship for different designs and under different conditions [18,19,20]. Tiwari et al. [21], showed that the internal heat transfer coefficient depends on the material and geometry of the condensing cover, and on the temperature difference between inner glass cover and water.

Thermal models for solar desalination were developed and validated against experimental measurements [5,18,20,22,23]. These models were found helpful for investigating the underlying mechanisms in solar desalination. However, in most of these models solar power input was calculated using simple relation and one cover configuration was considered. Furthermore, the still performance and the received solar power might be overestimated as no special treatments of the effective basin area and the useful fraction of the received solar power were considered.

In this paper the annual performance of single slope, double slope, and pyramidal shaped single basin solar stills is investigated experimentally and theoretically. A validated solar radiation model is integrated with a solar desalination thermal model consisting of well-known mass and heat transfer relations. The effective basin area is calculated and used in the differential equations used to model basin, water and glass temperatures. The effective basin area is employed in estimating the useful fraction of solar radiation reaching the system. Such calculations allow for obtaining the optimum settings under which the intercepted solar energy and the performance of the system can be maximized. A 1 m^2 single basin passive type still with different cover types was simulated. The model simulations were first validated against experimental measurements and then used to analyze the performance of the solar still under different conditions. The effect of inclination angle, unit orientation, water depth, insulation thickness, and wind speed, have been analyzed for summer and winter conditions in Ma'an area (southern region in Jordan).

2. System description

The solar stills used in this research, shown in Scheme 1, consists of $1m \times 1m \times 0.1m$ black painted 2 mm thick galvanized steel basin, four sided glass cover, insulation and internal channels for condensate collection. Nine different glass covers are used, these are: single sloped (15°, 30°, and 45°), double sloped (15°, 30°, and 45°), and pyramidal shaped (15°, 30°, and 45°). All glass covers were designed to receive solar radiation from all direction in order to maximize the collected solar power.

The glass covers used were similar to the ordinary window glass of 6 mm thickness with an average emissivity of 0.88. The glass cover was sealed with silicone rubber to prevent vapor leakage. A glass wool of different thicknesses, and a thermal conductivity of 0.032 W/m.K was used to minimize heat loss from the bottom and the side walls of the solar still.

As the sun rays pass through the glass cover and water reaching the basin linear, the water begins to heat up. The heated water evaporates from the basin resulting in increasing the moisture content of the air trapped between the water surface and the glass cover. Condensation occurs on the inner glass cover as the temperature of the glass is lower than the dew point of the vapor air mixture. Condensed water trickles down the inclined glass cover to an interior collection channels and out to a storage bottle.