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Effect of different carrier gases on productivity enhancement of a novel multi-effect vertical concentric tubular solar brackish water desalination device

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ABSTRACT

A novel multi-effect vertical concentric tubular solar brackish water desalination device is introduced in present study. The device consists of four closely spaced concentric pipes, in which the feed water gets preheated by hot brine water to guarantee the evaporation efficiency. An experimental investigation and analytical analysis were carried out to signify the effect of carrier gas-water vapor mixture on productivity enhancement of the device. Different carrier gases were used in the performance evaluation: carbon dioxide, helium, nitrogen, oxygen, air and argon. The water yield and the top/bottom temperature values of condensation surface of the device with different carrier gases were tested. In addition, the present investigation is presented an approach to predict the theory yield based on the internal heat and mass transfer mechanism. The experimental results indicate that, when the heating temperature is 80 °C and the carrier gas is helium, the water productivity rate can reach to 1.19 kg/h. It is increased by 30.76% than the carrier gas of air. The numerical results had been calculated and a consistent agreement with the experimental results had been obtained of different operation temperatures. The D_v under different heating temperature were obtained according to the experimental results.

1. Introduction

Safe and pure drinking water is an important need for life existence and sustainability. While the earth is covered by approximately 70% water, more than 97.5% of the water is salt and brackish water [1]. Especially, the shortage of fresh drinking water will appear more obviously for remote or arid regions, but according to what we know, the existence of great amounts of brackish water in these regions cannot be ignored. Most of the standard high-capacity desalination methods such as multi-stage flash, reverse osmosis and multi-effect evaporation, et al. are fossil energy intensive, which lead to global warming as well as health hazards on life. However these regions are blessed with ample amount of solar energy, so it is attractive alternative to utilize solar energy for the desalination brackish water to meet potable water need of the residents. Among solar desalination technologies, solar still is used to produce fresh water from brackish water by utilizing solar energy directly and is suitable to supply water in these regions for small-scale application due to simple structure and cost less. However, they have the major drawbacks of lower productivity compared with conventional solar desalination methods and generally a single effect [2]. In order to overcome the limitation, many technologies have been developed to enhance the water production rate and increase the efficiency of solar still [3–6].

Early in 1988 the concept of the tubular solar still (TSS) was proposed by Tiwari et al. [7]. It is noticed that the area of the condensing surface of tubular solar still is larger than that of the evaporating surface leading to more yield, which leads to a need for knowledge of the structure optimization and performance improvement.

A novel TSS system was designed by Ahsan et al. [8] to improve the water production rate of the solar still. The new design has a polythene film cover instead of the old vinyl chloride sheet. They revealed that the hourly evaporation, condensation and production rate were affected by the humid air temperature and relative humidity fraction. In further research, a new mass and transfer model of the TSS was proposed according to the humid air properties inside the device [9]. Zheng et al. [10] proposed a novel nonconcentrical multi-sleeve horizontal tubular

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solar still and experimentally investigated how the water production rate is affected by different carrier gases. The results indicate that, when the heating temperature is 85 °C, the best carrier gas is oxygen and the maximum yield can reach to 0.58 kg/h. Chang et al. [11] experimental investigated and analytical analyzed a triple-effect vertical concentric solar desalination device. The Gain Output Ratio (GOR) of the device can reach about 1.89 and the payback period of the unit is about 4.0 year.

Xie et al. [12] experimentally and analytically studied the performance of a low temperature multi-effect tubular solar still (TSS) under different vacuum pressures. Results show that the peak value of the energy utilization efficiency was 81%. Shitosh et al. [13] introduced an experimental comparison study on a simple tubular still and green net covered tubular solar still. Experimental study shows that tubular solar still covered with green net can increase the yield.

Elashmawy et al. [14] proposed a tubular solar still integrated with a parabolic concentrator tracking system (PCST-TSS) and investigated experimentally the performance compared with other tubular solar stills. According to the results from the investigation the water production rate of the unit can reach to 1.66 L/day. PCST-TSS costs only $199 with 45.3% initial cost reduction compared to TSS, which shows PCST-TSS is suitable to provide water for a single house-hold. An experimental investigation of a compound parabolic concentrator-concentric tubular solar still (CPC-CTSS) coupled with a single slope solar still by Arunkumar et al. [15]. It was found that the yield strongly depends on the evaporative heat transfer coefficient. They also have tested the performance of CPC-TSS and CPC-CTSS with different augmentation systems [16].

Although a substantial amount of research work has already been carried out to redesign the structure of TSS and to attempt for enhancement of heat and mass transfer between the evaporation surface and condensation surface. It appears that the role of thermophysical and transport properties of the different carrier gases and their effect on the productivity enhancement of the vertical solar desalination device has been left almost completely unknown. Hence, we propose to improve the yield of the multi-effect vertical concentric tubular solar brackish water desalination device by using different carrier gases relative to air is analyzed in detail use a numerical model of gas-vapor mixture with natural convection to verify. Furthermore, the multi-effect vertical tubular solar brackish water desalination device presented in this paper can reuse the latent heat of condensation successfully and guarantee larger effective evaporation area to gain high energy utilization efficiency.

2. The design and operating principle of the device

2.1. Structure parameters and characteristics

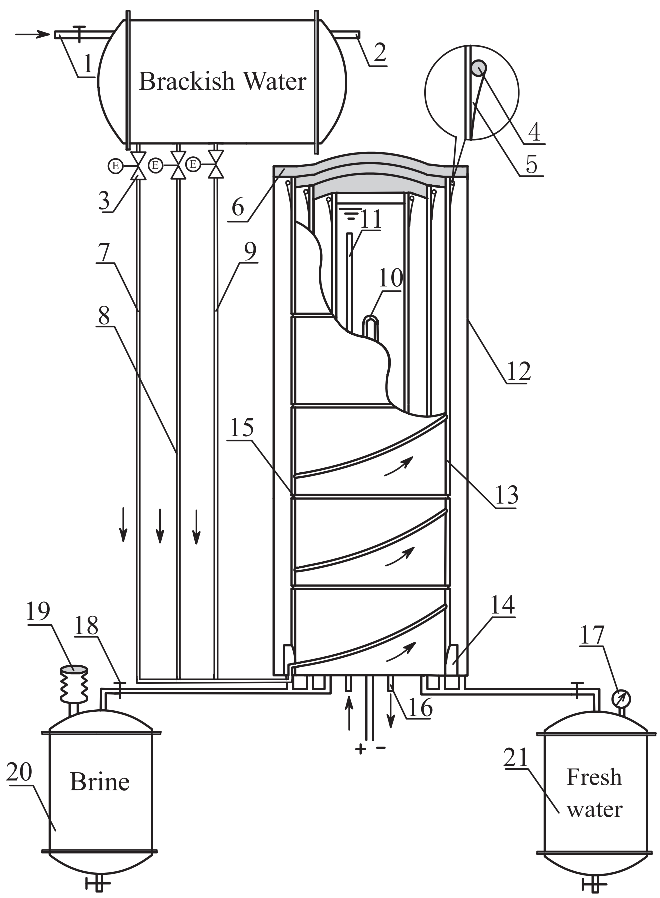

Fig. 1. Structure layout of multi-effect vertical concentric tubular solar brackish water desalination system.
1-The brackish water inlet; 2-over flow tube; 3-control valve; 4-the horizontal rubber perforated tube; 5-water film; 6-insulation layer; 7-the 1st effect feed water pipe; 8-the 2nd effect feed water pipe; 9-the 3rd effect feed water pipe; 10-electric heater; 11-hot water tube; 12-outer shell; 13-the water absorption materials; 14-water linerboard; 15-silicone rubber rings; 16-cold water tube; 17-pressure gages; 18-valve; 19- pressure buffer balloon; 20-brine collection tank; 21-freshwater tank.

Fig. 1 illustrates a schematic layout of the multi-effect vertical concentric tubular brackish water desalination system, Fig. 2 shows a 3D diagram of the system coupled with vacuum tube solar collector, and Fig. 3 shows a photograph of the experimental set-up.

The multi-effect vertical concentric tubular solar brackish water desalination system is compounded of brackish water tank, vacuum tube solar collector, two water collection tanks and four circular stainless steel pipes, which form three annulus sealed spaces that are used as the first-, second-, and third-effect distillation chambers respectively, while the innermost pipe is filled with hot fresh water as a heat source. For the convenience of description, three pipes within the corresponding outer shell may be numbered as 1st, 2nd and 3rd effect from the innermost to the outer. The outer surface of the 1st, 2nd and 3rd pipes were covered with water absorption materials (wicking material) knitted with wool, which was adhered tightly by the feed brackish water and exhausting air between the pipe outer surface and the water absorption materials. Three horizontal rubber perforated tubes with some holes of 2 mm diameter which surround across the 1st, 2nd and 3rd pipes round, were placed at the top bordering edge of the corresponding pipe outside. Brackish water storage tank, which was placed higher than the pipes and contained a constant water level, supplied the brackish water via the 1st, 2nd and 3rd effect feed brackish water pipe, which entered in the corresponding distillation chamber at the bottom of the device and were coiled on the outside surface of the 1st, 2nd and 3rd effect pipe form bottom to top as shown in Fig. 2, respectively. It is important to emphasize that the feed water was preheated by the hot brackish water film before entering the horizontal rubber perforated tube, which is beneficial to enhance the fresh water productivity. In order to overcome the weakness of the non-uniform wetting or dry patches along the water absorption materials surface, which lead to decrease the effective evaporation area and hence reducing the distillated yield, several silicone rubber rings were pasted to the water absorption materials and cotton thread was stitched into the water absorption materials and form lengthwise horizontal lines and crosswise lines, which means larger evaporation area than conventional wick.

The operational principle of the multi-effect vertical tubular solar brackish water desalination system is shown in Figs. 1 and 2. The water in the hot water container is heated by the vacuum tube solar collector, by which the brackish water falling film (5), preheated and drained down the out surface of the 1st, 2nd and 3rd pipes, is heated up. As the temperature of container water rises, the brackish water in the water absorption materials (13) will evaporate and the gas in the distillate