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Small-scale low pressure 'single effect distillation' and 'single stage flash' solar driven barometric desalination units: A comparative analysis

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ABSTRACT

Worldwide water scarcity signifies an urgent need to develop sustainable, simple to operate, low-cost, small-scale desalination units especially suitable for remote communities. The single effect distillation (SED) and the single stage flash (SSF) type low-pressure barometric desalination units satisfying the above requirements have attracted great interest in academic circles, but a comparison of the two has never been attempted. Thus, analytical models have been developed to identify and evaluate common performance indication parameters. The main results of the analysis show that the SSF unit's heat input rate is ~30% greater than that of the SED unit, with a resulting decrease in its performance ratio of ~24%, in comparison. Consequently, the brine heater area of the SSF is ~3.25 times the evaporator area of the SED. Furthermore, the seawater feed rate in the SSF is also about 20 times greater, leading to a 20 times larger release of non-condensable gases into its condenser. This additionally results in the SSF unit's 'recovery factor' of only 3.3%, as compared to ~67% in the SED unit. These results reveal that the solar-driven barometric SED type units have a considerably better performance in all comparison aspects over the SSF type units.

1. Introduction

As the world's population is ever increasing, so is the demand for fresh water. In many areas of the world, fresh water resources are already very scarce, thus aggravating the situation even more, necessitating the need to explore other means of obtaining fresh water like desalination.

The main limitation of all seawater desalination technologies is the high energy input requirement as pointed out by Kalogirou [1], who reported that production of 1000 m^3 of potable water per day requires 10,000 tons of oil per year. It is, however, a fortunate coincidence that all over the world, most arid regions with lack of freshwater resources are also blessed with a significant abundance of solar insolation potential. In some of these regions, direct solar radiation exceeds 6 kW-h/m^2 per day with statistically many sun hours per year. Therefore, with the impending depletion of fossil fuels and their many negative environmental impacts, we can rationally conclude that these areas are ideally suited for a solar-powered sustainable desalination option. According to Fath et al. [2], for large-scale water production, all main conventional desalination technologies have been proven to be technically and economically suitable, however, for small communities living in areas far from the sources of fresh water and energy with little technical capabilities, only requiring limited fresh water (up to 10 m^3/d); solar desalination is more applicable. It is also to be noted that it is difficult to integrate solar energy with most of high capacity industrial-scale desalination systems because of its low energy density and variation in a day [1], but for small capacity units, this is not a serious concern.

Solar energy can be used to power small-scale desalination units in two ways. One way is to first transform solar energy into electric current using photovoltaic (PV) panels which can then be used to operate a reverse osmosis (RO), or an electrodialysis (ED) unit, although the high cost of PV panels is a major hurdle for an economically viable application these technologies. According to Garg and Joshi [3], even after incorporating cost reduction measures like energy recovery units, hybrid pretreatment, and battery-less operation, the PV-RO capital cost is still quite prohibitive. Moreover, for high salinity coastal areas, the RO desalination system cost may prove to be even more excessive. The PV driven ED is most cost-effective for brackish waters of low concentrations of < 2500 ppm, but only a few low capacity mostly R&D pilot

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plants of this type have been tested so far [4].

The other way is to directly use solar thermal energy collected by means of flat plate solar collectors or small solar ponds to distill the saline water directly for obtaining fresh water. According to Saidur et al. [5], distillation is the most cost-effective and one of the best methods for small-scale fresh water production from seawater. Therefore, it is logically appropriate to devise small scale, easy to operate, self-sustainable solar-powered water desalination systems like the barometric SED & SSF distillation units for easy water accessibility in remote areas at a low cost. Granted that these units have lower efficiencies compared to their respective small-scale multi-unit counterparts, but as ease of maintenance and the simplicity of plant control and operation are a major requirement for the intended application, they should be considered appropriate for water deficient small isolated communities. Shattat et al. [6] rightly point out that alternative development of small-scale desalination units is of vital importance if people living in isolated areas are to gain access to fresh and safe water supplies.

The concept of a low pressure (partial vacuum) desalination process is based on the fact that as the water saturation pressure decreases; its saturation temperature also decreases. Therefore, vapor can be made to evaporate from the saline water at a much lower temperature. The partial vacuum can be created by evacuating the distillation evaporator/flash chamber employing a vacuum pump or by employing the so-called 'barometric height' (BH) concept which utilizes the Torricelli barometric water columns of nearly 10 m height to create a low-pressure region at the top of such water columns as explained in more detail in Section 2. In recent years, the research and developmental work on small-scale solar operated low-pressure BH based desalination units of either the SED or SSF type as a means for producing low-cost potable water have gained momentum. Since the initiation of Alsaad's [7] work on a sub-atmospheric solar desalination unit, a large number of analytical and experimental studies have been conducted on low-pressure small scale units to gain a better insight of their operational performance and applications. Alsaad's work dealt with the design, fabrication, and performance of an SED type desalination unit which works on the BH concept (but without a brine removal line). A flat-plate collector which also serves as the evaporator was used for solar heat input connected to a separate water cooled condenser. A maximum daily productivity of fresh water of 5.4 kg/m^2 with a maximum daily efficiency of 59% was reported. Al-Kharabsheh and Goswami [8] also present an experimental study of an SED type BH based desalination system, with an electrically heated evaporator operating at a pressure of ~4 kPa. A provision was also made to periodically flush the system to get rid of the NC gases. Based on weather data of Gainesville FL, USA, the system output was found to about twice the solar still's yield. Joseph et al. [9] conducted an experimental study of an SSF type solar vacuum desalination system with a projected daily output of 10 l of fresh water. The experimental setup consisted of a flat plate solar collector, a flash evaporator, a condenser, and a vacuum pump. The solar radiation flux and operating pressure in the flash chamber were varied to determine their effect on the unit's output. With a collector of 2 m^2 area, a maximum fresh water yield of 8.5 l/day was obtained, which according to the authors is three times greater than the output of a solar still. Eames et al. [10] performed an experimental study to confirm the technical feasibility of their proposed theoretical model for an SSF type BH based desalination system. The experimental apparatus was constructed utilizing electric resistance heaters to simulate solar heating. Validation of the theoretical model was carried out with the experimentally obtained data. The authors found that the theoretically predicted and experimentally obtained fresh water yields showed good agreement. The authors also concluded that a solar flat plate collector with an area of 4.727 m^2 used with their tested type unit would be enough to obtain a daily fresh water yield of 30 l. Nafey et al. [11] proposed and built another small size SSF saline water desalination unit run by utilizing solar energy input via a 2.39 m^2 flat plate solar collector to preheat the feed brine to the desired temperature. The theoretical analysis consisted of separate mathematical models for determining the solar flux intensity, and the performance of the flat plate collector, the condenser, and the flashing unit. Comparison between the theoretically predicted and experimental results showed good agreement. The system's average daily productivity in the summer was reported to be about 4.2 to 7 kg/m^2. Abutayeh and Goswami [12] also investigated a proposed solar heated self-sustainable SSF desalination process using a small pilot plant. They used electrical resistance wire heating and a vacuum pump to simulate solar heat and passive vacuum generation, respectively. The reported results showed that the accumulated fresh water production increases as the flashing temperature is increased. They also found that the NC gases slowly accumulate in the unit eroding the vacuum and thus decrease the vaporization rate. Gude and Nirmalakhandan, [13] studied a low-temperature SED type BH based saline water desalination system. Experimental results from a proof-of-concept setup were presented to demonstrate the feasibility of the proposed concept. Results presented show that a 6 l per day water production rate can be maintained at the lowest evaporation temperature of 40 °C. Ayhan and Al Madani [14] built and operated a solar driven low pressure (~7 kPa) BH based SED type experimental unit to demonstrate as well as to validate its working principles. The pilot plant's fresh water production rate of 0.022 L/min was obtained on the basis of Bahrain's climatic data. A cost comparison/analysis was also conducted, where a large size unit with a lifetime of 20 years was reported to be the most cost-effective incurring a production cost of only US $ 1.00 per ton of distilled water, with a payback period of just 6 months. Liu et al. [15] presented a description of a simple physical model to explain the working of a BH based SED type desalination unit. The authors also conducted a literature review on BH based SED and SSF units and discussed the technique for increasing the freshwater production. Wessley and Mathews [16] conducted thermodynamic analyses of both single and two-stage air-cooled solar assisted small-scale flash desalination systems. Simulations were carried out for various parameters which included a range of flash chamber operating pressures and feed water temperatures. The results provided showed that the two-stage system yield was about 36–40% higher than that of the single stage yield. The authors also pointed out that the ambient air temperature had a major impact on the performance of the air-cooled condenser. In a subsequent paper, Wessley et al. [17] conducted experimental studies on a low temperature air-cooled single stage flash evaporation desalination unit. It was reported that the system yield depended on the feed water temperature, its flow rate, as well as on the flash nozzle diameter. Rashid et al. [18] presented a review of the research works carried out on both SED and SSF types of the BH concept based desalination systems designed thus far and have also identified the various factors affecting the water production rate. Additionally, they point out that larger size plants need to be built and operated so that a better feasibility study can be carried out with realistic data. Bilgil and Hırlakoğlu [19] experimentally studied a solar driven SED type unit operating in batch mode simulating the hydrological cycle. The unit's efficiency was determined at an evaporation temperature of 45, 50, 55 and 60 °C with condensation temperatures of either 0, −15 and − 25 °C. A fan was additionally employed to assist vapor diffusion to the condensing chamber. The authors reported that decreasing the condensation temperature to −25 °C was unnecessary, as an identical efficiency was obtainable at 0 °C. Recently, Choi [20] theoretically investigated the effect of the variation of the barometric height on fresh water yield for an SSF type BH based desalination unit. He reported that a maximum yield of over 7% was possible by using a barometric height 9.8 m and a feed brine temperature of 80 °C.

At the outset of a small-scale solar desalination project implementation where either the SED or the SSF process can be selected, the key technical question which needs to be answered is: Which type of system to choose? Whether to employ an SSF or an SED type distillation process is not clear, as both seem to have certain advantages; but which is the better of the two will only become apparent if a comparative