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A developed solar-powered desalination system for enhancing fresh water productivity

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A B S T R A C T

A solar-powered desalination system using condenser integrated with flat-plate solar collector and vacuum pump was developed for producing fresh water and compared its performance with the ordinary solar desalination system without vacuum pump under different operational conditions. Systems temperatures added to ambient temperature were measured with hour intervals, under all experimental conditions for both solar desalination systems. Heat and mass transfer regimes were conducted for the used parallel condenser. Performance of the two systems was studied as a function of change in water salinity level and water tank flow rate and evaluated in terms of recorded temperatures, condenser efficiency, water productivity and cost. The experimental results reveal that the developed system increases water productivity for all water salinities compared with the ordinary system due to the presence of vacuum pump. The same results also reveal that water productivity increased and cost decreased by increasing water flow rate using the developed system while the vice versa was noticed using the ordinary system. Maximum fresh water productivity values of 10.94 and 7.27 L/d corresponding to cost values of 0.031 and 0.030 US $/L were recorded at ground water tank flow rates of 0.80 and 0.40 L/h using developed and ordinary systems, respectively.

1. Introduction

Water is an essential for the maintenance of life and also the key to human's prosperity. There is a significant need to increase the supply of drinking water in developing countries. Common sources estimate that one milliard people in the developing world drink unsafe water. When all viable sources of water have been utilized, extracting drinkable water from salt water can help to solve this problem. As natural fresh water resources are limited, seawater plays an important part as a source for drinking water as well. In order to use this water, it has to be desalinated. Desalination method is a process of obtaining pure water from waste /brackish or saline water using solar energy. According to World Health Organization (2004), the permissible limit of salinity in water is 500 ppm and for special cases up to 1000 ppm while most of the water available on earth has the salinity up to 10,000 ppm whereas seawater normally has salinity in the range of 35,000–45,000 ppm in the form of total dissolved salts. Bilal et al. (2000) studied the effect of the salinity of water on solar distillation. The results show that as the salt concentration increases in the water, the production rate decreases due to the increase in partial pressure of the salt in the water solution. Ghandour (2001) studied the effect of salinity level of raw water on the productivity. The experimental result for different concentrations of saline feed water were 5500 ppm, 10,500 ppm, 15,500 ppm and 35,000 ppm producing distilled water 500 ppm, 750 ppm, 1200 ppm and 1890 ppm respectively. The saline feed water curve and the distilled water curve tacks the same trends of increase the salinity feed water with increase the salinity-distilled water. Talaat et al. (2002) found that using high salt concentration brackish feed water increasing the energy consumption of desalination. Low salinity brackish water (TDS 1000 ppm) consumes 0.40–0.60 kW·h/m^3, medium salinity brackish water (TDS 1000–3000 ppm) consumes 0.80 –2 kW·h/m^3 and high salinity brackish water (TDS 3000–5000 ppm) consumes 2.2 –3.3 kW·h/m^3.

Desalination processes fall into two main categories, thermal processes or membrane processes. Thermal processes are generally used in the following applications: to treat highly saline waters (predominantly seawater), where large volumes of product water are required. In locations where energy costs are low or where a waste heat source is available. On the other hand, membrane processes are more favorable for treating brackish waters (under most conditions) or highly saline wastes where energy costs are high or the flow rates are low.

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Many researches were carried out dealing with the different types of solar desalination systems such as active and passive solar stills. Kumar et al. (2000) showed that the solar distillation systems are mainly classified as passive solar still and active solar still. In a passive solar still, the solar radiation is received directly by the basin water and is the only source of energy for raising the water temperature and consequently, the evaporation leading to a lower productivity. Later, many active solar stills have been developed. Hence, an extra thermal energy is supplied to the basin through an external mode to increase the evaporation rate and in turn improve its productivity. Sethi and Dwivedi (2013) designed and fabricated a basin type double slope active solar still under forced circulation mode and a performance evaluation were carried out for different water depths of 0.03 m, 0.04 m and 0.05 m. The distillate output is maximum 4.82 kg for water depth 0.03 m and minimum 4.36 kg for water depth 0.05 m. The maximum instantaneous thermal efficiency is 46.96 at water depth of 0.04 m.

As the water productivity with the use of passive solar stills is low, researchers tried to couple flat-plate solar collector with the passive solar stills to improve their performance. Badran and Al-Tahaineh (2005) studied the effect of coupling flat-plate solar collector on solar stills productivity. They found that coupling solar collector with solar still increased its productivity by 36%. Badran et al. (2005) performed the tests in solar still augmented with flat-plate collector using tap water and saline water. They found that the mass of distilled water production using augmentation increased by 231% in case of tap water as a feed and by 52% in case of salt water as a feed. Tabrizi et al. (2010) studied the influence of water flow rate on the internal heat and mass transfer and daily productivity of a cascade solar still (CSS) for water purification with a view of enhancing the daily productivity. 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. Morad et al. (2015) carried out thermal analysis for double slope solar still based on internal and external heat transfer and energy balance equations to predict its performance. Depending on the thermal analysis, they installed passive and active solar stills (solar still and solar still integrated with flat-plate solar collector) to use solar desalination technology for producing freshwater. Performance of both solar stills was studied as a function of change in basin brine depth and glass cover thickness under conditions of applying glass cover cooling (flash tactic) or without cover cooling and evaluated in terms of recorded temperatures, instantaneous and internal thermal efficiencies and system productivity. The experimental results revealed that active solar still maximizes fresh water productivity (10.06 L/m^2·day) and internal thermal efficiency (80.6%) compared with passive solar still (7.8 L/m^2·day productivity and 57.1% internal efficiency) under conditions of 1 cm basin brine depth and 3 mm glass cover thickness and by applying flash tactic cover cooling with 5 min on and 5 min off.

Other researchers tried to attach condenser with the passive solar stills to improve fresh water output. Malek (2014) studied the effect of condenser unit attached to the passive solar still on the daily productivity and carried out a comparative study for passive solar still and condenser attached to the solar still. It has been observed that condenser attachment gives the higher productivity as compared to the passive solar still. Kabeel et al. (2014) investigated the design modification of a single basin solar still to improve the solar still performance through increasing the productivity of distilled water. The results show that integrating the solar still with external condenser increases the distillate water yield by about 53.2%. Eltawil and Omara (2014) enhanced the productivity of a single slope solar still for remote communities facing a shortage of good quality water. The single slope solar still was equipped with a flat plate solar collector, spraying unit, perforated tubes, external condenser and solar air collector. The developed solar still (DSS) was evaluated in passive and active modes and compared with the conventional solar still (CSS). The CSS productivity ranged from 3 to 4 L/m^2. The DSS productivity was more than the CSS by 51–148% depending on the type of amendment. The use of external condenser with solar still increased the productivity by 51%.

Evacuated solar distillation systems were also designed to increase the productivity and improve the efficiency of the simple solar stills. Ahmed et al. (2009) proposed a new multistage evacuated solar distillation system that was designed to increase the productivity and improve the efficiency of the simple solar still. The solar still works by virtue of the higher evaporation rate under vacuum conditions. The preliminary results showed a significant improvement of the overall productivity. Indeed, the total productivity of the solar still is affected very much by changing the internal pressure. The productivity decreased as the pressure increased due to the lower evaporation rates at the higher pressure values. Abutayeh and Goswami (2010) developed a model depicting a sustainable desalination process. The simulated process consists of pumping seawater through a solar heater before flashing it under vacuum in an elevated chamber. The vacuum enhances evaporation and is maintained by the balance between the pressure inside the elevated flash chamber and the outdoor atmospheric pressure. Saad et al. (2011) proposed and designed a new desalination system for converting sea water into fresh water utilizing the waste heat of internal combustion engines. The desalination process is based on the evaporation of sea water under a very low pressure (vacuum). The low pressure is achieved by using the suction side of a compressor rather than a commonly used vacuum pump. The evaporated water is then condensed to obtain fresh water. The effects of operational variables such as evaporator temperature, condenser temperature, vacuum pressure, and flow rate of both evaporator and condenser on the yield of fresh water are experimentally investigated. It is found that decreasing the vacuum pressure causes a significant increase in the yield of fresh water. Moreover, increasing the condenser flow rate tends to increase the yield of fresh water. Takahisa and Kaoru (2012) developed a simple vacuum distillation system for the desalination of the seawater and for the purification of contaminated well water. This simple system had the thermal efficiency of 70%, which is equivalent to the generation of 10 kg/m^2 of water per day. Lin and Jwo (2014) proposed a process utilizing the wind transmission vacuum pump and freezing system for seawater desalination. The wind drives the vacuum pump pressure to near absolute vacuum stage and creates evaporation of seawater at low temperature. Then the compressor of the freezing system evaporates water and condenses the vaporized water into ice at low temperature using the circulating system via wind transmission.

As to Reverse Osmosis systems, Karagiannis and Soldatos (2008) stated that for conventional desalination systems the cost for seawater ranges from 0.4 \$/m^3 to more than 3 \$/m^3, while for brackish water desalination the cost is almost half. When renewable energy sources are used the cost is much higher, and in some cases can reach even 15 \$/m^3, due to most expensive energy supply systems. However, this cost is counterbalanced by the environmental benefits. The choice of desalination method affects significantly the water desalination cost. Thermal methods are used mainly in medium and large size systems, while membrane methods, mainly RO, are used by medium and low capacity systems. Yet, during the last years, RO is the optimal choice in even larger units. RO methods, which are dominant in the desalination of brackish water, have the lowest cost, mainly due to much lower energy consumption and the recent technological advances that have been achieved in membranes. Lauren et al. (2009) stated that membrane technology has improved, allowing significant increases in product