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Solar desalination system using spray evaporation

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This paper evaluates a one-stage technique to improve fresh water production from salty water by enhancing the evaporation and condensation. A pilot plant is designed and constructed in an arid area with 1 m^2 solar water collector area to evaluate the one-stage process. The effect of main parameters on fresh water production of the unit is studied. The results show that, the productivity, efficiency, productivity rate, and Gained Output Ratio of the desalination unit are strongly affected by the inlet hot water temperature and flow rate. Within the studied ranges, the maximum daily productivity reached to 9 l/m^2. According to these results, fresher water production of the present system is higher than that solar humidification–dehumidification desalination system in the previous studies. The maximum daily efficiency in the desalination system is about 87%. A TDS (total dissolved solids) of fresher water is 40 ppm. Finally, the cost of distilled water per liter is $0.029.

1. Introduction

Desalination based on renewable energy such as solar energy, presents a sustainable and a zero-polluting alternative to fossil fuel based desalination, which aggravates environmental pollution problems. It is cheap, allows energy diversification, available for predictable periods of time, and helps avoid dependence on external energy supplies (Garcia-Rodriguez [1]). Solar still desalination uses a sustainable and pollution-free source to produce high-quality water.

Fresh water could be obtained from salty water through the solar HDH (humidification–dehumidification) cycle. In this process, hot air supplied from a solar collector was circulated either by a natural or a forced convection process over the water where it becomes humid. The humid air was then passed through a condenser or de-humidifier system where the desalinated water was obtained. Multi-effect humidification plants were the most effective units among solar desalination plants (Farid et al. [2]). Many researchers have conducted studies on process and the equipment's related to the (HDH) systems for water desalination. Abdelkader [3] studied the solar desalination system with multi-effect humidification–dehumidification cycles with couples central solar receiver. In this system, saline water was warmed through the solar central receiver and it was then entered into a desalination chamber. The air circulation in the humidification chamber was provided by natural convection.

The amount of distillate water produced by the unit depends on the solar collector size. The performance of the collector depends mainly on the weather conditions, design and operating parameters. However, to estimate the optimum values of these parameters in different weather conditions using full experiment was costly and time-consuming. Therefore, the development of a simulation model offers a better alternative and has proven to be a powerful tool in the evaluation of the performance of the system. Both air and water, solar collectors were the main components of a solar desalination unit and any improvement in their efficiency will have a direct bearing on the water production rate and the product cost (Al-Hallaj and Selman [4]). The solar collectors that were used to heat water and/or air were expensive and can reach in some cases from 25 to 30% of the total desalination unit cost by Ben Bacha et al. [5]. The best known thermal processes for the desalination of seawater, namely MED (multi-effect desalination) and MSF (multistage flash), make an efficient use of energy because the heat released in each stage or effect was used in the next one, making multiple use of energy. However, these processes require a very precise control of temperature and pressure in each stage, which must be constant in time in order to keep the conditions needed for the boiling process (El-Dessouky and Ettouney [6]). This poses a problem when coupling desalination with solar energy, due to the intrinsic variability of insolation, thus requiring a thermal storage

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Nomenclature

A	Area, m^2
h	Enthalpy, (kJ/kg)
H	Solar radiation, (W/m^2)
L	Latent heat of water, (J/kg)
m	Flow rate, (l/h)
M	Productivity, (l/h)
P_p	Pump power, (W)
T	Temperature, °C

Greek letters

η	Efficiency

Subscripts

Av	Average
ci	Cold inlet
co	Cold outlet
d	Daily
h	Hourly
hi	Hot Inlet
ho	Hot outlet
S	Solar water collector
w	Water

Abbreviations

CC	Cooling coil
CV	Control value
EC	Condensation tower
ET	Evaporation tower
FM	Flow meter
FWR	Fresh water reservoir
GOR	Gain output ratio
HDH	Humidification–dehumidification
HEX	Heat exchanger
MED	Multiple effect distillation
MSF	Multi stage flash
PR	Productivity rate
SWC	Solar water collector
TC	Thermocouples
TDS	Total dissolved solids
TES	Thermal Energy Storage

tank and/or a supplementary heat source from fossil fuels (Blanco and Alarcon [7]).

In order to enhance utilization efficiency of the latent heat of condensation, gain more fresh water output per square meter area of solar collector and reduce the energy loss of the humidification–dehumidification desalination unit, a series of designs of multi-effect solar humidification–dehumidification desalination system were presented by some researchers.

Zhani and Ben Bacha [8] presented an experimental investigation and an economic analysis on a solar desalination prototype functioning by HD (Humidification/Dehumidification) of air. The experimental results also that the outlet and the inlet temperatures at different component levels were the same trends as solar radiation and the ambient air temperature was an insignificant effect on thermal performance of the unit. The cost of distilled water per liter was $0.107.

Al-Hallaj et al. [9] studied the solar driven (HDH) desalination system and the daily fresh water production rate ranged from approximately 2.25 to 5.0 l/m^2 of solar collector area, depending on the average daily solar flux. Muller-Holst et al. [10] fabricated the solar (HDH) desalination system for operation in Munich, Germany. The system performance showed the average daily fresh water production in June was approximately 7.5 l/m^2 while that in January was approximately 1.2 l/m^2 solar collector area. Dai and Zhang [11] presented the solar desalination unit with humidification and dehumidification. They found that the performance of the system was strongly dependent on the mass flow rate of salt water, the mass flow rate of the process air, and the inlet salt water temperature to the humidifier. The results showed that the productivity achieved was around 6.2 l/m^2 of solar collector area. Yuan et al. [12] investigated a 1200 l/day (HDH) desalination unit. This system was composed of a 100 m^2 solar air heater field, a 12 m^2 solar water collector. The results showed that water production of the system can reach 10.7 l/m^2 of solar collector area, when the average solar radiation was 550 W/m^2. Zhani et al. [13] developed the modeling and the experimental solar desalination unit using air and water solar collectors. They were found that the two-temperature mathematical model describes more precisely the real behavior of the water solar collector than the one-temperature mathematical model. Gude et al. [14] designed the low temperature desalination system using solar collectors augmented by thermal energy storage. A solar collector area was 15 m^2 with 1 m^3 of TES (Thermal Energy Storage) volume or 18 m^2 with 3 m^3 of TES volume. The results show that the fresh water production can reach 6.67 l/m^2 of solar collector area. Zamen et al. [15] experimentally evaluated the two-stage technique to improve the humidification–dehumidification process in fresh water production from salty water. A two-stage pilot plant was designed and constructed in an arid area with 80 m^2 solar collectors. The results show that, fresh water production can reach 7.25 l/m^2 of solar collector area.

The main limitation of solar stills was their low productivity compared to conventional desalination processes. The operating efficiency was low due to main two limitations: (i) the rejection to the atmosphere of the latent heat of condensation and (ii) the difficulty of raising the evaporation temperature and decrease condensation temperature as heating, evaporation and condensation take place in one container (He and Yan [16]).

It has been inferred from the literatures that most of the previous works have used heated water spray during the humidification process where air used as a carrier gas to evaporate water from the saline feed and to form fresh water by subsequent condensation. On the fact that the vapor carrying capability of air increases with temperature:1 kg of dry air can carry 0.5 kg of vapor and about 2805 kJ when its temperature increases from 30 to 80 °C (Parekh et al. [17]). Therefore, the solar desalination requires efficient methods of evaporation and condensation at relatively low temperatures up to 70 °C. Initially for small quantity, as in the earlier designs the condenser is an integral part of the system. In addition, Multi-effect solar still was suggested as an efficient method for the production of desalinated water.

The present system is based on the generation of vapor from salty water when it enters an evaporator tower and condensation of vapor is accomplished by regenerative heating of the feed water. The main objectives of the present work are to describe the design for solar distillation system coupled with a solar water heater to enhance productivity and efficiency. The paper presents the results of a solar distillation system, with the water working in a closed loop. The distillation chamber consists of evaporation and condensation towers. The system is designed to improve the evaporation rate by spraying water at low temperature.

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