Water Desalination for Environment-Friendly Cities Using Clean and Green Renewable Energy-Based Processes

Aref Maalej and Hatem Ben Taher

Abstract

Given the continuous scarcity of drinkable water and the exceptional rise of the planet temperature, environment-friendly solutions for potable water production are searched for within the concept of green cities which resolve the need without aggravation of the impact on the environment. Drinking water consumption rises increasingly in our planet given the dense use in industrial and agricultural sector and increase of the world population. A review of the vast literature available on solar distillation systems has revealed the main efficiency challenge in terms of low freshwater production of units. Current research work is focusing on improving the productivity and the thermal efficiency of the distillation process. The proposed new design of solar desalination units allowed an optimization technique to the conventional solar still design by the coupling and the integration of a condenser, a solar air, water collector, and a humidifier. The developed design for the proposed desalination technique produced a patented process called solar multiple condensation and evaporation cycle (SMCEC) which showed better performance than the classical solar still techniques. Optimization of the system performance is boosted with a mathematical modeling of the process and system components validated with experimental measurements on prototype and pilot units.

Keywords

Solar energy • Desalination • Green house • SMCEC

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1 Introduction

The availability of safe drcxsinking water is becoming an increasingly important issue. Expanding populations, enhanced living standards, and decreased availability of freshwater have catalyzed much research in the area of obtaining potable water. Since a large majority of the earth's water supply is salt water, desalination methods such as reverse osmosis and electrodialysis have been developed (Ben Bacha et al. 1999a). In addition to the practical limitation of small-scale usage, these methods are energy demanding, costly for small amounts of freshwater, require high maintenance, due to the practical difficulties associated with the high operating temperature like corrosion and scale formation, and are generally coupled to fossil fuel sources which have a negative impact on the environment. A potentially feasible alternative is solar powered desalination with a humidification–dehumidification principle. Solar energy is free, abundant, and an environmentally friendly energy source. Combining the principle of humidification–dehumidification (HD) with solar desalination leads to an increase in the overall efficiency of the desalination system and therefore appears to be the best method of water desalination.

2 Design of the SMCEC Desalination Process

The LASEM laboratory at the Engineering School of Sfax, Tunisia, worked on the development of a novice design of a new generation of water desalination installation by solar energy based on the SMCEC principle (Ben Bacha et al. 1999b) (Solar Multiple Condensation Evaporation Cycle). The desalination unit consists of three main parts (Fig. 1): 7.2 m^2 of flat plate water solar collector, condensation tower, and evaporation tower. Thorn trees were used for evaporator, and a condenser was constructed using polypropylene plates. The thermal insulation of chambers was achieved by the

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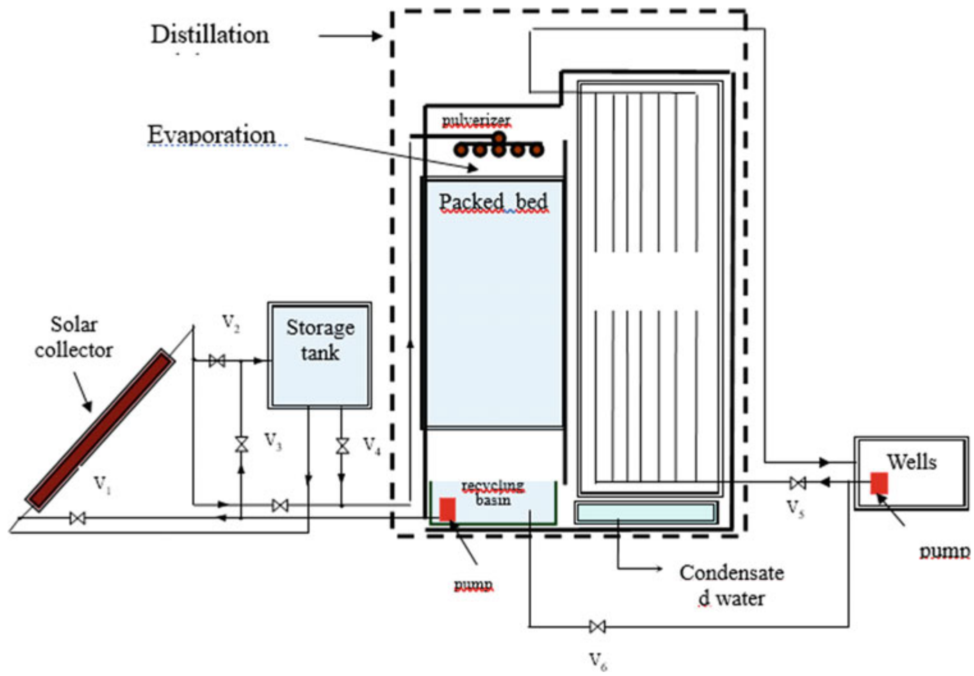


Fig. 1 SMCEC-based desalination station

plates of polypropylene which covered the whole internal surface of chambers and protected the external insulating Styrofoam layer against corrosion.

A prototype and pilot units were constructed to conduct and analyze the performance of the system and to perform the experimental validation of the mathematical models developed for the various components of the desalination process (Fig. 2). These models permit the sizing of the solar collectors, the evaporation tower, and the condensation tower. A suitable software totally modular in nature and providing adequate computational facilities for simulating, sizing, designing, and optimizing this kind of desalination unit was developed.

Fig. 2 Prototype unit and the pilot unit constructed based on the SMCEC principle

The desalination unit can function according to four different modes (Fig. 3):

- Mode 1: Brackish water is preheated in the condenser by exchange of heat with the vapor
- Mode 2 (Recycle Mode): The recycling is needed to recover the heat stored in the water which did not evaporate
- Mode 3: Collected non-evaporated water is collected in a basin at the tower and then injected in the solar collector.
- Mode 4: Proposed to be used in sunny days (high insulation)

The system distillate water production obtained from the laboratory unit for the first two modes of functioning is shown in Fig. 4.

The developed curves from the system performance showed that production of the unit at evaporator inlet water temperature of 70 °C is 7.2 kg/h. The low production requires the hot water recycling by injection at the top of the evaporation chamber and a storage tank to store the hot water excess that would extend water desalination beyond sunset.

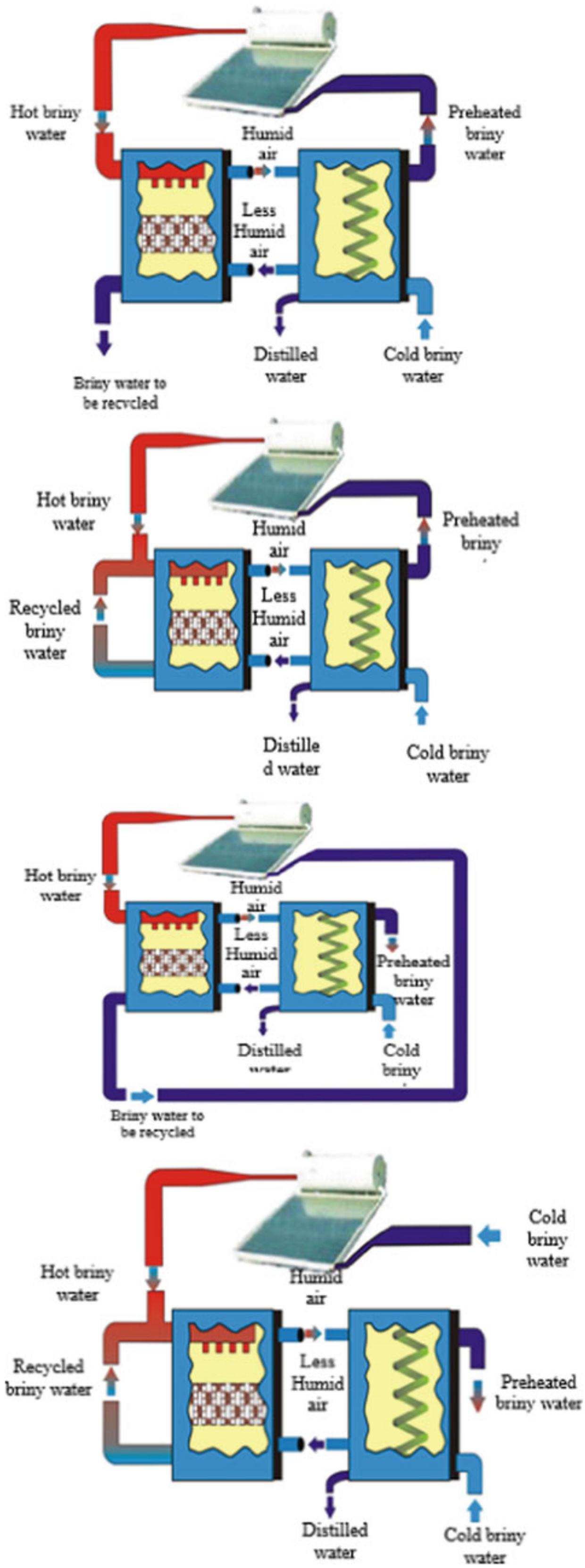
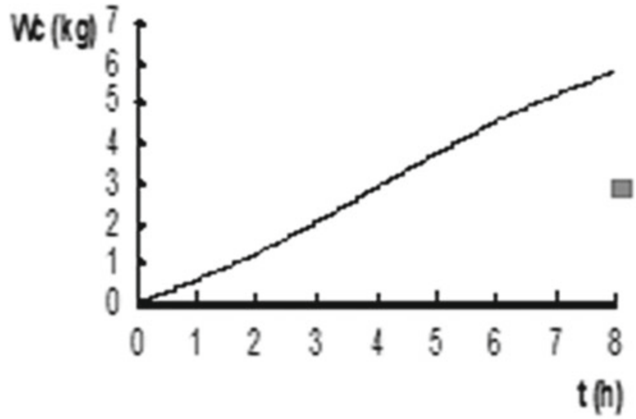


Fig. 3 System configuration for the four modes of functioning of the unit



(a) mode 1 (nominal mode)

(b) mode 2 (recycle mode)

Fig. 4 Variation of the condensation rate for mode a and b

3 Optimization of the Designed Desalination Unit

The major drawback of standalone solar desalination unit based on humidification/dehumidification principle is their limited freshwater production which in some cases cannot compete with solar distiller fresh water production. So, to overcome the shortcomings of the developed SMCEC solar desalination unit and to ameliorate its freshwater production, the system design is modified to integrate, with the main modules, a flat plate air solar collector for heating air and a humidifier for subsequent humidification. The integration of both air solar collector and humidifier into the SMCEC unit is motivated with 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 670 kcal when its temperature increases from 30 to 80 °C (Zhani et al. 2009; Zhani and Ben Bacha 2010a, 2010b).

The third-generation design of the solar desalination system is characterized with the following improvements (Fig. 5):

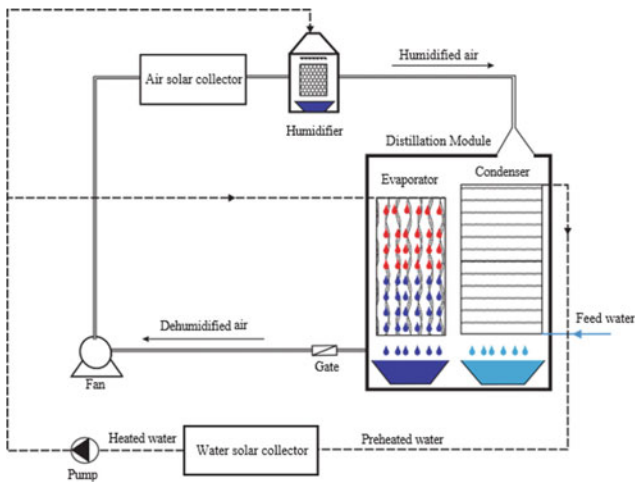


Fig. 5 Third-generation SMCEC desalination unit with air solar collector and humidifier

- It requires a low level of maintenance from unskilled operators by using dismantled components.
- The simultaneous heating of air and water, respectively, by air and water solar collectors increases the thermal performance of the system.
- The simultaneous use of evaporation chamber and a humidifier increases the quantity of evaporated water and consequently the freshwater production.
- The integration of the evaporation chamber and the condensation chamber in one module, called distillation module, enhances the thermal and mass transfers of produced steam quantity toward the condensation chamber, thus improves the rate of condensed water.
- It allows the optimization of the energy recovery of the heating system.

The main components of the new designed unit are the air and water solar collectors, the humidifier, and the distillation module. The water solar collector uses a sheet-and-tube (in copper material) absorber with the tubes as an integral part of the sheet. The air solar collector is a flat plate one and is formed by a single glass cover and an absorber. The humidifier, also called cooling tower, is used in many chemical processes. In the desalination process, the humidifier is used to separate clean water from the salt water. This is essentially an extraction process. The humidifier used in the desalination unit is a pad one. The distillation module consists of air humidifier (evaporator) and dehumidifier (condenser). The functioning principle of this desalination process is as follows: Sea or brackish water which is preheated in the condensation tower, by the latent heat of condensation, and heated in the water solar collectors is pulverized into the humidifier and the evaporation tower. Due to heat and mass transfers between the hot water and the heated air stream in the humidifier in case of working in open air loop and between the hot water and the dehumidified air stream, coming from the condensation tower, in the evaporation tower in case of working in closed air loop, the latter is loaded by moisture. In order to increase the surface of contact between air and water, and therefore rise the rate of air humidification, packed bed is implanted in the tower of evaporation and the humidifier. The saturated moist air is then transported toward the tower of condensation where it contacts a surface whose temperature is lower than the dew point of the moist air. The condensed water is collected from the bottom of the condensation tower, while the brine (the salty water exiting the evaporator and the humidifier) at the bottom of both the humidifier and evaporation tower will be either recycled and combined with the feed solution at the entry point or rejected in case of increase of saltiness rates.

A global mathematical model expressing the heat and mass transfers and the enthalpy balances in each component of the unit is formulated. The developed model is simulated numerically to study the following behavior of key output parameters of the system (Figs. 6, 7, 8, 9, 10, and 11).

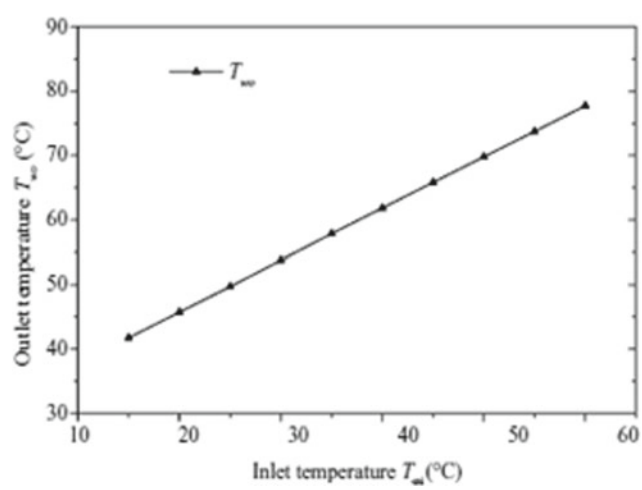


Fig. 6 Influence of the inlet water temperature on the outlet one at the water solar collector

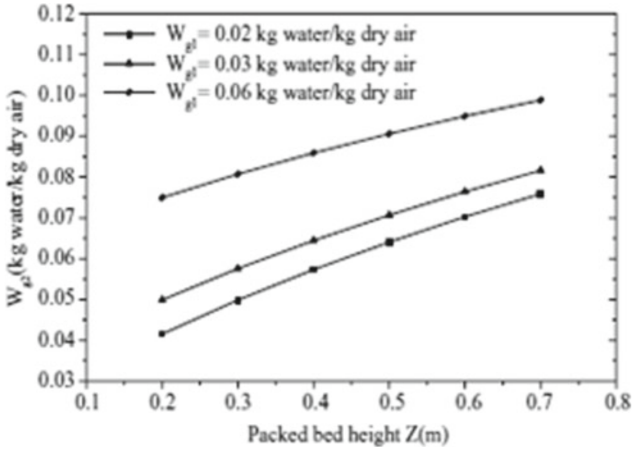


Fig. 7 Impact of the humidifier packed bed height on outlet air humidity

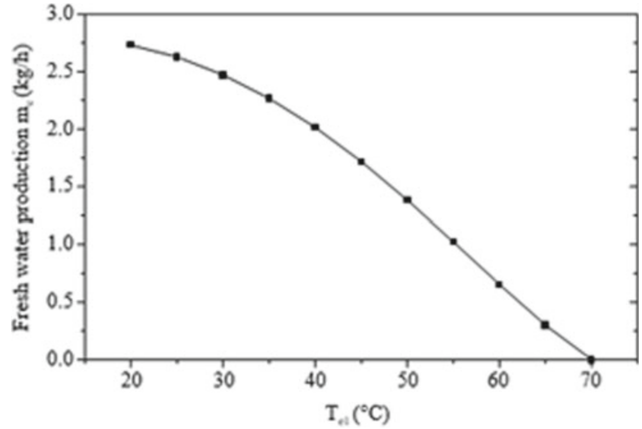


Fig. 10 Influence of the inlet cooling water temperature on the freshwater production

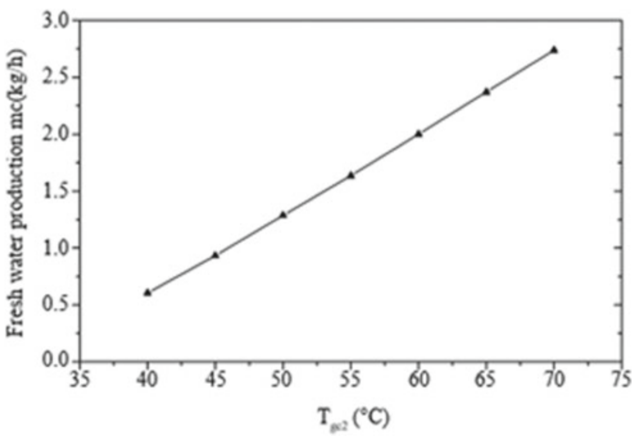


Fig. 8 Influence of the inlet moist air temperature on the freshwater production

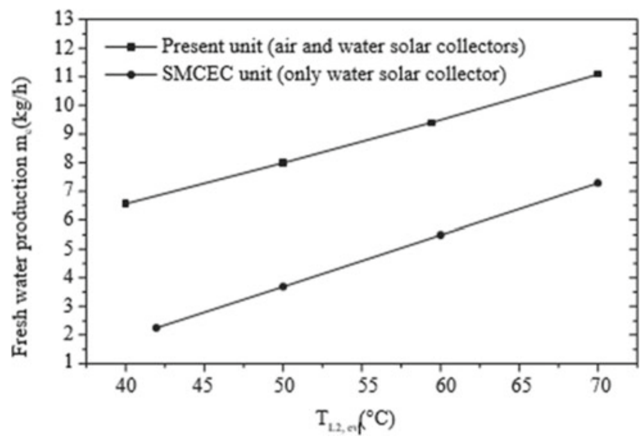


Fig. 11 Effect of inlet water temperature at the evaporation tower on freshwater production

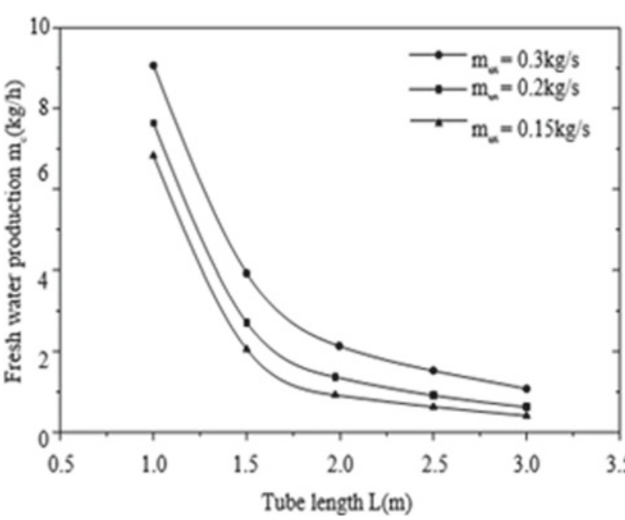


Fig. 9 Influence of the condensation tower tube length on the freshwater production

4 Discussion

According to the simulation results (Figs. 6, 7, 8, 9, 10, and 11), the optimal performance of the desalination unit is guaranteed with:

- Low values of inlet fluid temperatures at the level of both air and water solar collectors in order to obtain a better gain of heating.
- Low air humidity at the inlet of the humidifier to allow the latter to provide a better gain of humidification.
- High values of moist air flow rate at the level of the condensation tower to provide a better fresh water production.
- High values of inlet moist air temperature at the top of the condensation tower.
- High values of inlet water temperature at the evaporation tower.

- Low values of inlet cooling water temperature at the bottom of the condensation tower.

5 Conclusion

This paper presents a survey of the developments which has been brought to a novel process of water desalination using solar energy. The solar multiple condensation evaporation cycle (SMCEC) unit was first simply designed with mainly a water solar collector, an evaporation tower, and a condensation tower. Several improvements have led to the third-generation of the system design working with humidification–dehumidification (HD) technique to enhance the unit production of freshwater. This unit is made up of five components: air solar collector, water solar collector, humidifier, evaporation tower, and condensation tower. The production of freshwater using this third-generation unit with water solar collector, air solar collector, evaporation tower, humidifier, and condensation tower has improved by 65,7% for low values of water temperatures (around 45 °C) and by 34,18% for the high values of water temperatures (around 70 °C) compared to the first introduced design. Further studies were undertaken to ameliorate the performance of the various components of the system and the integration of other renewable energy functions (Fterich et al. 2018; Souissi et al. 2018).

References

H. Ben Bacha, A.Y. Maalej, H. Ben Dhia, I. Ulber, H. Uchtmann, M. Engelhardt, J. Krelle, Perspectives of solar powered desalination with “SMCEC” technique. Desalination **122,** 177–183 (1999a)

H. Ben Bacha, M. Bouzguenda, M.S. Abid, A.Y. Maalej, Modelling and simulation of a water desalination station with solar multiple condensation evaporation cycle technique. Renew. Energy **18**, 349–365 (1999b)

M. Fterich, H. Chouikhi, H. Bentaher, M. Aref, Experimental parametric study of a mixed-mode forced convection solar dryer equipped with a PV/T air collector. Solar Energy **171**, 751–760 (2018)

M. Souissi, Z. Guidara, A. Maalej, Solar concentration using flat reflectors: parametric study and experimental investigation. Int. J. Mech. Energy **6**(1) (2018)

K. Zhani, H. Ben Bacha, An approach to optimize the production of solar desalination unit using the SMCEC principle. Des. Water Treat. **13**, 96–108 (2010)

K. Zhani, H. Ben Bacha, Modeling and simulation of a new design of the SMCEC desalination unit using solar energy. Des. Water Treat. **21**, 1–11 (2010)

K. Zhani, H. Ben Bacha, T. Damak, A study of a water desalination unit using solar energy. Des. Water Treat. **3**, 261–270 (2009)