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Theoretical simulation of small scale psychometric solar water desalination system in semi-arid region

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HIGHLIGHTS

- An affordable small scale desalination system is proposed.
- A mathematical model of the desalination system is developed and programmed using Matlab Simulink.
- The model describes the psychometric process based on humidification and dehumidification.
- The model is used in optimal selection of elements and operating conditions for solar desalination system.
- The use of solar water desalination contributes significantly to reducing global warming.

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ABSTRACT

Many countries around the world suffer from water scarcity. This is especially true in remote and semi-arid regions in the Middle East and North Africa (MENA) where per capita water supplies decline as populations increase. This paper presents the results of a theoretical simulation of an affordable small scale solar water desalination plant using the psychometric humidification and dehumidification process coupled with an evacuated tube solar collector with an area of about 2 m^2. A mathematical model was developed to describe the system's operation. Then a computer program using Simulink Matlab software was developed to provide the governing equations for the theoretical calculations of the humidification and dehumidification processes. The experimental and theoretical values for the total daily distillate output were found to be closely correlated. After the experimental calibration of the mathematical model, a model simulating solar radiation under the climatic conditions in the Middle East region proved that the performance of the system could be improved to produce a considerably higher amount of fresh water, namely up to 17.5 kg/m^2 day. This work suggests that utilizing the concept of humidification and dehumidification, a compact water desalination unit coupled with solar collectors would significantly increase the potable water supply in remote area. It could be a unique solution of water shortages in such areas.

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1. Introduction

Fresh water of acceptable quality has become a scarce commodity in many parts of the world. Water scarcity is expected to affect one out of three people in every continent of the globe, and almost one fifth of the world's population live in areas where water is physically scarce. It is projected that by the year 2025 water demand will exceed supply by 56%, due to persistent regional droughts causing population shifts to urban coastal cities [1].Currently, about three billion people have no access to potable water and another 1.76 billion people live in areas facing severe water shortage [2]. This situation will get worse with population growth, more urbanization, climate change impacts and increases in household and industrial uses of water [3]. The total global water reserves are about 1.4 billion cubic kilometers, of which around 97.5% is in the oceans and the remaining 2.5% is fresh water present in the atmosphere, ice mountains and ground water. Of the total, only about 0.014% is directly available for human beings and other organisms [4].

Currently, large commercial desalination plants using fossil fuel are in use in most countries that have water shortages and particularly in oil-rich countries. In contrast, people in many other parts of the world have neither the financial nor oil resources to

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Nomenclature

$\dot{Q}_{hum}$	the supplied energy at the humidifier chamber (KJ)
$\dot{Q}_{aux}$	the auxiliary energy (KW)
$\dot{Q}_{col}$	solar collector input energy (KW)
$\dot{Q}_{heater}$	electrical heater input energy (KW)
C_p	specific heat capacity of water (J/kg K)
$T_{h,i}$	temperature of water at inlet humidifier (°C).
$T_{h,o}$	temperature of water at outlet humidifier (°C)
T_a	ambient air temperature (°C)
T_m	mean collector temperature, (°C)
T_{SCi}	solar collector inlet temperature (°C)
T_{SCo}	solar collector outlet temperature (°C))
$\dot{m}_{w,h}$	mass flow rate of hot water sprayed into the humidifier (kg/hr)
$\dot{m}_a$	mass flow rate of air (kg/hr)
$\dot{m}_{cooling}$	mass flow rate of cooling water (kg/min)
h_a	specific enthalpy of air (KJ/kg)
ω	humidity ratio
W_p	distillate output (kg)
A_{col}	solar collector area (m^2)
$\overline{G}$	daily average insolation (W/m^2)
h_{fg}	latent heat of vaporization of water (J/kg)
η_i	solar collector efficiency

Abbreviations

COP	coefficient of performance
TDS	total dissolved solids (mg/L)
EC	electrical conductivity (μS/cm)
WHO	World Health Organization
HDD	humidification and dehumidification process
MEH	multi effect humidification
MED	multi effect distillation

install such technologies [5]. Most of the current desalination technologies are not economically viable in remote areas, even those near a coast, or in areas that experience an intermittent electricity supply. In addition, they cause massive environmental pollution. The development of alternative, compact, small scale water desalination systems is imperative for the populations of such areas [6]. Thermal solar energy water desalination is known to be a viable method of producing fresh water from saline water in remote areas [4]. Humidification and dehumidification solar water desalinations units and conventional basin solar stills with a relatively large footprint are examples of such simple technologies.

Extensive research and development (R&D) using renewable energy technologies have been carried out by many researchers aiming to create an affordable and feasible method to produce drinking water [7]. A significant number of publications have focused on improving the design and performance of small scale solar water desalination. For example the conventional basin solar still without additional concentration of solar energy produces an average water output capacity of about 2.5–3.0 L/m^2/day at a thermal efficiency of around 25% due to large heat losses [8,9].

The effect of coupling a flat plate solar collector with humidification and dehumidification processes and a basin solar still have been investigated in a series of R&D projects. For example, Zhang and Yuan (2007) [10] studied a closed circulation solar desalination unit and focused on analysis of water production and system performance by investigating the effect of the cooling water flow rate, the feed water rate and the structural dimensions. Similarly, Mohamed and El-Minshawy (2011) [11], and Eames et al. (2007) [12] described the theoretical and experimental investigation of a small scale solar powered barometric desalination system. The results showed that the production rate of fresh water depended on three main factors, namely, the heat exchange effectiveness of the condenser, solar insolation and pressure. Mohamed and El-Minshawy (2009) studied the same concept but with the use of geothermal energy [13]. Gude et al. (2012) studied low temperature desalination using solar collectors of area 18 m^2 augmented by thermal energy storage of 3 m^3 volume; their work included theoretical and experimental investigation with water production of 100 L/day [14].

Hou and Zhang (2008) [15] proposed a hybrid desalination process in a multi-effect humidification–dehumidification system heated by solar collectors and they showed that the distilled water output increased by a factor of 2–3 when the rejected water was reused. In their study, they maximized condenser heat recovery through composite curves and found that there is an optimum value for the water to air flow rate ratio, but they did not take the effect of the humidifier inlet temperature and the solar collector efficiency into account. Garg and Adhikari et al. (2003) tested a multi effect humidification (MEH) solar system to provide continuous hot water to a desalination unit over a 24 h period by system modeling based on solving heat and mass transfer equations. The results showed that the rate of distilled water production varied linearly as a function of water temperature at the humidifier [16]. Similarly, Muller-Holst et al. (1999) studied the same concept on a small scale thermal seawater desalination apparatus and showed that the water productivity depended on the magnitude of the thermal energy used in the evaporation process [17]. Soufari et al. (2009) [18] studied parametric effects on the performance of an HDD system and optimized the operating parameters. These studies show that an HDD system may operate at a temperature as low as 50 °C, and therefore could be suitable for incorporation with a Rankine cycle power generation system. However, water quality needs attention here because biological contamination can occur at low operating temperatures.

This paper presents an affordable novel desalination system that requires a very small energy input using hybrid psychometric energy either by electric heater or solar energy supply. This system was built on the humidification and dehumidification principle with two specially designed humidifiers. It was also coupled with an evacuated solar collector panel. Unlike most previous experimental and simulation work that was restricted to the steady state operation at a fixed value of insolation as in Refs. [14,15], this work validated a mathematical model of the psychometric process with evaporation and condensation for transient numerical simulations of daylight insolation variations for daylight under Middle East climate conditions. Furthermore, the development of such a mathematical model means that carrying out the experimental investigations is no longer restricted to a specific solar insolation region; it is possible to simulate solar insolation conditions anywhere in the world. This simulation was extended to the night-time period utilizing the heat stored during the day using the developed Simulink matlab model.

2. System description

The system employs the concept of humidification and dehumidification based on the pyschrometric energy process using a specially designed heat recovery system converting the saline

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