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A novel integrated solar desalination system with multi-stage evaporation/heat recovery processes

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ABSTRACT

A novel small-sized integrated solar desalination system with multi-stage evaporation/heat recovery processes is designed and tested in this study. The system consists of four linked collecting units and operates under barotropic and atmospheric pressure. Each of the four units contains a seawater tank and at least one solar collecting/desalination panel mainly comprising a simplified CPC (Compound Parabolic Concentrator) and an all-glass evacuated tube collector. In the last three units, heat exchangers made of copper tubes are inserted concentrically into the all-glass evacuated tubes to recover heat. In each unit, an independent desalination process including solar collecting, heat recovery (no heat recovered in the first unit) and seawater evaporation can be carried out completely. The experimental results show that the freshwater field of the designed system can reach as high as 1.25 kg/(h m^2) in the autumn and the system total efficiency is close to 0.9. Both experimental results provide a striking demonstration that the designed solar desalination system has outstanding performance in solar collecting, heat recovery and seawater evaporation.

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1. Introduction

Water has always been mankind's most precious resource. There are no substitutes and the struggle to control water resources has shaped human political and economic history. The amount of water deemed necessary to satisfy basic human needs is 1000 cubic meters per capita annually. By 2050, it is projected that the availability of potable water will fall below this level for 1.7 billion people in 39 countries [1]. On the other hand, about 97% of the earth's water is salt water in the oceans, and a tiny 3% is freshwater. It would be feasible to address the water-shortage problem through seawater desalination [2].

Seawater desalination techniques are mainly divided into two categories, namely, the thermal processes, for which either multi-stage flash (MSF), multiple-effect boiling (MEB), vapor compression (VC), freezing or solar distillation are used [3–14] and the membrane processes, for which reverse osmosis (RO) or electrodialysis (ED) is applied [15,16]. In the thermal processes, the distillation of seawater is achieved by utilizing a thermal energy source. The thermal energy may be obtained from a conventional fossil-fuel source, nuclear energy or from a non-conventional solar thermal energy, geothermal energy, etc. [2,17,18].

In terms of energy consumption, desalination of seawater is an energy intensive process. The installed capacity of desalinated water systems in the year 2000 is about 22 million m^3/day and the production of this water requires about 203 million tons of oil per year [2,19,20]. With the total installed capacity expected to increase drastically in the coming decades, the energy consumption for desalination will continue to rise and hence the required amount of conventional hydrocarbon fuels required will go up substantially [21]. Meanwhile, the world's production of conventional hydrocarbons will soon decline. Hydrocarbon shortages are inevitable unless radical changes occur in demand, or in the supply of non-conventional hydrocarbons [22]. Renewable energy is the alternative solution to the decreasing reserves of fossil fuels [23]. At present, there are already several kinds of renewable energy applied to water desalination. Garcıa-Rodriguez presented an economic analysis of wind-powered RO desalination technology [15]. Marcos S. Miranda and David Infield used a 2.2 kW wind turbine generator powering a variable-flow RO desalination unit which was considered suitable for the application in remote areas [16]. Karim Bourouni et al. experimentally investigated a desalination plant functioning by aero-evapo-condensation. The work was carried out on a geothermal desalination plant installed in the south of Tunisia [24]. The use of solar energy in thermal desalination processes is one of the most promising applications of the renewable energies. In terms of solar thermal energy usage, solar desalination can either be direct; using solar energy to distillate directly in the solar

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Nomenclature

A_{CPC}	lighting area of a CPC plate (m^2)
h	enthalpy (J/g)
I_r	solar radiation intensity (W/mP^2)
G_m	freshwater yield per second (kg/s),
n	number of the CPC plates in the system
PR	performance ratio
P	net energy absorbed by the collector (W)
Q	power used to evaporate seawater in one unit (W)
Φ	heat collecting power of one panel (W)
η_{tol}	system total efficiency
η_t	system collecting efficiency
Subscripts	
I	UnitI
II	UnitII
III	UnitIII
IV	UnitIV

collector, or indirect; combining conventional thermal processes desalination techniques with solar collectors for heat generation [25]. Many different systems of direct and indirect solar desalination have been proposed and implemented.

ArefY. Maalej studied the performance ratio and efficiency of a solar still operating under different conditions [3]. Fath reviewed the various designs of solar stills and studied the suitability of solar stills for providing potable water [4]. Xiao et al. categorized the solar stills into six sorts based on the design guidelines used in each device. The properties of these design guidelines were detailed and evaluated in terms of enhancing the productivity of solar stills [5]. Arunkumar et al. designed a tubular solar still with a rectangular basin for water desalination and studied the effect of cooling air and water flowing over the cover [6]. Nematollahi et al. conducted an experimental and theoretical energy and exergy analysis for a solar desalination system consisting of a solar collector and a humidification tower, the results showed that the overall exergy efficiency increased by a decrease in humidification tower length, a decrease in inlet air temperature, and an increase in tower diameter [7]. Reddy et al. developed a novel multi-stage evacuated solar desalination system utilizing latent heat recovery. The effect of various design and operating parameters on the system performance were studied to optimize the configuration and suggested that the designed multi-stage evacuated solar desalination system was a viable option to meet the needs of rural and urban communities [8]. Mohamed and El-Minshawy theoretically investigate the principal operating parameters of a proposed desalination system based on air humidification–dehumidification principles [9]. Rajvanshi proposed a scheme to desalinate seawater using solar energy. The seawater heated by solar energy was flash evaporated in a multi-stage flash evaporator (MSF) unit to yield freshwater. Economic analysis of the scheme showed that it compared favorably with the existing fossil fuel fired desalination plants of the equivalent capacity [10]. Zejli et al. designed a multi-effect desalination system operating with an adsorption heat pump with an open cycle and using zeolite as the solid vapor adsorbent. A theoretical model was used to study the water production and energy consumption of the system [11]. Hawlader et al. designed a single effect desalination unit connected to an existing solar assisted heat pump and conducted a series of experiments on the system under different operating and meteorological conditions of Singapore [12]. Abdalla Hanafi analyzed the design and performance of the solar MSF desalination systems and carried out a stage-to-stage design of the MSF chamber and the system transient performance [13]. Joseph et al. carried out an experimental study of a single stage solar desalination system. The input parameters such as solar irradiance and vacuum pressure in the flash evaporator were varied to find its influence on the system efficiency and yield of potable water per day [14]. Mahmoud Shatat et al. presented an economic and comparative evaluation study for a small scale solar powered water desalination system [26]. A. Eslamimanesh and M.S. Hatamipour made an economical study of humidification–dehumidification desalination (HDD) pilot plant in order to estimate the economic benefits of the process in comparison with a small-scale reverse osmosis (RO) system [27]. A.E. Kabeel and Emad M.S. El-Said presented a hybrid solar desalination system consisting of a humidification–dehumidification unit and single stage flashing evaporation unit and numerically studied the system [28]. Kyaw Thu et al. have made a detailed study on an adsorption desalination cycle with evaporator–condenser heat recovery circuit [29–32].

In this paper, we put forward a novel small-sized solar desalination system which incorporates the solar collecting, seawater evaporation, heat recovery and freshwater condensation processes within the common evacuated tubular solar collector to produce freshwater directly. The system operates under barotropic and atmospheric pressure and adopts a stepwise heat recovery method to recycle the latent heat of the steam generated. It consists of four linked collecting units. Each of the four units contains a seawater tank and at least one solar collecting/desalination panel mainly comprising a simplified CPC (Compound Parabolic Concentrator) and an all-glass evacuated tube collector. In the last three units, heat exchangers made of copper tubes are inserted concentrically into the all-glass evacuated tubes for heat recovery. In each collecting unit, an independent desalination process including solar heat collecting, heat recovery (no heat recovered in the first unit) and seawater evaporation can be carried out completely. This novel solar desalination system is easy to assemble just like building blocks and can work with the absorption refrigerator to carry out the combined cycle of desalination and air-conditioning. The cost of manufacturing and running the designed system is low and its footprint is also small.

Unlike the common multiple-effect boiling (MEB) process where the steam from one effect acts the role of heat source in the following effect, the majority of the heat used in each unit (effect) of the present system to evaporate the seawater comes directly from the solar energy collected by the all-glass evacuated tube, while the rest from the latent heat of the steam passing through the unit. Instead of using a vacuum pump to provide pressure gradient between each unit, the present system simply adopts several pressure regulating valves to control the working pressure which ranges from the atmospheric pressure to barotropic and neither vacuum pump nor delivery pump is needed. In the Multiple Effect Stack (MES) evaporator which is considered to be the most appropriate type for solar energy application, the thin seawater film evaporates or boils simultaneously on the outside of the tube bundles, the steam generated is likely to carry the seawater, while in the present system, the heat transfer mode is mainly the natural convection of the seawater immerged in the glass tube and the evaporation only occurs on the surface of the vapor–liquid, therefore the possibility of seawater carried by steam is smaller than that in MES system. Due to the temperature differences between the four units, the method of multi-stage heat recovery is applied to the system to fully utilize the sensible and latent heat of the steam generated. All these designs aim at simplifying the structure of solar desalination system, improving the thermal performance and increasing the freshwater yield. Though some manual operations such as brine draining are needed to run the system, this new type of solar desalination

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