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Performance study on a passive solar seawater desalination system using multi-effect heat recovery

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HIGHLIGHTS

- A solar seawater desalination system with multi-effect heat recovery processes.
- System uses all-glass evacuated tube absorber as heat collector with a simplified CPC.
- Mechanism of its operation are multi-stage distillation and heat recovery.
- The system operated under barotropic or atmospheric pressure without power consumption.

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ABSTRACT

A novel small-sized solar seawater desalination system with multi-effect heat recovery processes using all-glass evacuated tube absorber as heat collector, in which there is no power pump and the steam and freshwater flow are driven only by pressure drop, was designed and tested. The whole system consists of 7 heat collecting/heat recovery integration units, which were divided into 7 temperature/pressure states. Each unit has a heat collector which consists of a simplified CPC panel, an all-glass evacuated tube absorber, a seawater tank and a bar heat pipe that connects the absorber and seawater tank to transfer heat from the absorber to the seawater tank. Every unit operated under barotropic or atmospheric pressure. Meanwhile, a stepwise heat recovery method was adopted to recycle the sensible heat and latent heat of the steam generated. In order to investigate the effects of operating parameters on system performance, including freshwater yield, solar collecting performance and heat recovery performance, a series of experiments were conducted under different weather condition. It can be found that the all-day freshwater yield of unit area can reach 4.23 kg/m^2 on the sunny day and 3.03 kg/m^2 on the cloudy day. Meanwhile the collecting efficiency and comprehensive thermal coefficient can reach 0.41 and 1.39 respectively. The experiment results confirm that the designed system has a superior performance in seawater desalination without power consumption.

1. Introduction

Water is the most active and influential factor in the ecological environment and it is also one of the most valuable resources in the world. However, about 97% of the Earth's water is salt water in the ocean, and a tiny 3% is fresh water [1]. At present, about 1.5 billion people in more than 80 countries around the world face the shortage of fresh water. By 2025, it is projected that there will be 3 billion people lack of water, involving more than 40 countries and regions. Water resource is becoming a valuable resource in the twenty-first Century; as a result, the problem of water resource is not only a resource problem, but also a major strategic issue related to the national economy, social sustainable development and long term stability. Therefore, it is very urgent to solve the problem of water shortage. Desalinating salt water from the ocean, river, lakes is the best way to supply fresh water to growing population.

Seawater desalination techniques are mainly divided into two categories on the basis of different elements of fresh water production, namely, the membrane processes, for which reverse osmosis (RO) and electrodialysis (ED) were utilized [2,3] and the thermal processes whose thermal energy may be obtained from a conventional fossil-fuel source, nuclear energy or from a non-conventional solar energy, etc. [4–6]. Moreover, the thermal processes are broadly classified into two major categories, direct and indirect systems. The indirect method of

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Nomenclature

A_{cpc}	horizontal projection area of CPC panel (m^2)
G_m	freshwater yield (kg/h)
$G_{m,all}$	all-day freshwater yield of the system (kg)
G'_m	freshwater yield of unit collecting area (kg/(h m^2))
Δh	enthalpy difference (J/kg)
n	number of collecting units in the system
PR	performance ratio of desalination
q_r	irradiance (W/m^2)
Q	power (W)
$\dot{Q}$	useful power extracted from collector (W)
η_{re}	heat recovery efficiency
η_t	heat collecting efficiency
ε	comprehensive thermal coefficient

Subscripts

1	Unit 1
2	Unit 2
3	Unit 3
4	Unit 4
5	Unit 5
6	Unit 6
7	Unit 7
Sys	system
Ac	actual
Th	theoretical

Acronyms and abbreviations

CPC	compound parabolic concentrator
MED	multi-effect distillation
MEH/D	multi-effect humidification/dehumidification

solar desalination plant consists of two subsystems, solar collector and desalination unit. The different types of solar collector such as evacuated tube, flat plate and heat pipe can be used along with the thermal desalination processes such as multiple effect evaporation (MEV), vapor compression (VC) and multi-stage distillation (MSD) [7]. In addition, the solar distillation systems can be 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. However, in an active solar still, an extra thermal energy is supplied to the basin through an external mode to increase the evaporation or a vacuum pump is used to maintain the vacuum working condition.

The water demand is increasing rapidly than the sustainable level and desalination is the best method to provide the shortfall of water. From the perspective of energy consumption, most of the desalination systems [8–11] are energy intensive, which consume high grade energy like gas, electricity, oil and fossil fuels accelerating the global warming that is the burning topic and becomes threat to life sustainability. Renewable energy is the alternative solution to decreasing consumption of fossil fuels [12]. So far, there are already several kinds of renewable energy applied to seawater desalination such as wind energy [13,14] and solar energy. Considering that the solar energy can be efficiently harvested for solar to implement the heat application for green and environmental sustainability, it is one of the most promising applications of renewable energies in thermal desalination processes. So far, there have been many solar desalination researches carried out as follows.

Many researchers have carried out research on solar humidification/dehumidification desalination system (HDDS) [15,16]. However, the performance of HDDS seriously depends on the thermal properties of working medium and the humidification/dehumidification ability is weak at low temperature difference. Besides the HDDS, Khamid Mahkamov et al. [17] developed and tested an innovative small dynamic water desalination plant that is a combination of a heat pipe evacuated tube solar collector, conventional condenser and novel fluid piston converter. Young-Deuk Kim et al. [18] proposed a hybrid desalination system consisting of vacuum membrane distillation (VMD) and absorption desalination (AD) units, designated as VMD-AD cycle. Nematollahi et al. [19] carried out an experimental and theoretical energy and exergy analysis for a solar desalination system consisting of a solar collector and a humidification tower. In addition, the multi-effect desalination system attracts many researchers due to its high-energy efficiency. Zhili Chen et al. [20] designed a multi-stage stacked-tray solar seawater desalination still and test water production performance in both transient and steady states. Meanwhile, a mathematical model of heat and mass transfer was developed. Patricia Palenzuela et al. [21] conducted work to analyze whether the integration of Multi-Effect Distillation (MED) process into Concentrating Solar Power (CSP) plants can be more competitive, under certain conditions, than the independent freshwater and power production by connecting a Reverse Osmosis (RO) system to a CSP plant. Guo Xie et al. [22] presented a novel conceptual design of a low temperature multi-effect desalination (LT-MED) system and is composed of several modules of tubular solar still (TSS) cells. Reddy et al. [23] developed a novel multi-effect evacuated solar desalination system utilizing latent heat recovery and investigated the effect of various design and operating parameters on the system performance to optimize the configuration. Estahbanati et al. [24] conducted experiment to investigate the effect of the number of stages on the productivity of a multi-effect active solar still. Dayem [25] conducted work to demonstrate experimentally and numerically the performance of a simple solar distillation unit that is based on the multiple condensation-evaporation cycle. Chorak et al. [26] presented and discussed an experimental characterization of the solar MED system under off-design conditions.

So far, a lot of research relate to the MED systems have been published, however, many of them need auxiliary energy consumption during runtime. In addition, most of them have large floor space and high cost. In order to design a MED system that is suitable for the island and small fishing boats where the solar energy is rich, but electricity, fresh water and fossil fuel are rare, our research team developed a principle passive solar desalination system with multi-effect evaporation/heat recovery processes and verified the feasibility of the device [27], which is the mechanism research for the system presented in this paper. Furthermore, Liu ZH carried out some modification measures to optimize the principle system and considered more operating parameters for analyzing the system performance [28]. This system integrated solar collecting, seawater evaporation, heat recovery and condensation processes into the common evacuated tubular solar collector to produce freshwater directly. The system operated under barotropic and atmospheric pressure and adopted a stepwise heat recovery method to recycle the sensible heat and latent heat of the steam generated. However, for this principle system, it is difficult to develop a commercial product due to its especial fabrication.

In this research, based on the principle system, a small-sized solar seawater desalination system with multi-effect heat recovery processes using all-glass evacuated tube absorber as heat collector, in which there is no power pump and the steam and freshwater are driven only by pressure drop, is designed and tested. The originality of this system