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A new desalination system using a combination of heat pipe, evacuated tube and parabolic trough collector

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ABSTRACT

The solar collectors have been commonly used in desalination systems. Recent investigations show that the use of a linear parabolic trough collector in solar stills can improve the efficiency of a desalination system. In this work, a combination of a heat pipe and a twin-glass evacuated tube collector is utilized with a parabolic trough collector. Results show that the rate of production and efficiency can reach to 0.27 kg/(m^2 h) and 22.1% when aluminum conducting foils are used in the space between the heat pipe and the twin-glass evacuated tube collector to transfer heat from the tube collector to the heat pipe. When oil is used as a medium for the transfer of heat, filling the space between heat pipe and twin-glass evacuated tube collector, the production and efficiency can increase to 0.933 kg/(m^2 h) and 65.2%, respectively.

1. Introduction

Human survival depends on natural drinking water resources like rivers, lakes, and underground water reservoirs. However, industrialization and growth in the world's population have increased the demand for fresh water. Although the number of desalination plants has been growing in recent years, conventional plants with fossil fuel feeding will provoke the crisis of air pollution. Furthermore, rising fuel prices has highlighted the importance of renewable energy sources as clean and sustainable alternatives of fossil fuels. Among different types of renewable energies, the solar energy can play a significant role in arid areas, albeit without any pollution [1]. However, manufacturing and establishment costs, low efficiency, and compatibility issues are still big obstacles ahead, even though considerable progresses have been achieved during the last decades. In this regard, Price et al. [2] reviewed the ongoing R&D efforts to enhance parabolic trough solar power technology. Mills [3] assessed the market prospects of the available solar thermal technologies. The author described the funding systems in Europe, Australia, and the USA, and made suggestions for more effective programs of support. Thirugnanasambandam et al. [4] reviewed the solar thermal technologies. Also they discussed on the performance analyses and mathematical simulations of existing designs.

Industrial desalination technologies are divided into two categories: 1 – phase change or thermal processes, 2 – membrane or single-phase processes. All processes require a chemical pre-treatment of raw seawater to avoid scaling, foaming, corrosion, biological growth, and fouling and also require a chemical post-treatment [1]. One of the evolving desalination methods is solar distillation. Solar stills are divided into two main categories: passive and active. In active solar stills, additional thermal energy can be given to the passive solar still using an external source to increase the evaporation rate. In contrast, passive systems use no other external source. A detailed review of different types of solar stills, including passive and active systems was discussed by Kaushal [5]. Many different types of solar stills have been developed. Badran and Al-Tahaineh [6] experimentally investigated a solar still coupled with a flat plate solar collector. They reported that the coupling increase the productivity by 36%. Kabeel and El-Aghouz [7] reviewed the single-effect solar stills and also solar stills coupled with different devices such as sun-tracking and phase change materials. They demonstrated that using the sun tracking is more effective than the fixed system in enhancing the still productivity. Sanjeev and Tiwari [8] theoretically studied on a double effect active solar still. It was observed that an active double effect solar still is more effective in production of distillate output in comparison to a passive distillate system. Singh and Tiwari [9] evaluated the thermal performance of a regenerative active solar still under the thermosyphon mode of operation for a Delhi climate condition. They concluded that there is a significant improvement in overall performance due to water flow over the

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Nomenclature

A	area
F	focal length
h	enthalpy
I	solar Intensity
m	mass
r	radius
T	temperature (°C)

Greek symbols

α	altitude angle
η	efficiency
θ	rotational angle
δ	declination angle
β	title angle from the horizon
λ	local altitude

Subscripts

dw	desalinated water
f	fluid
g	gas
i	inlet
o	outlet
s	surface

Abbreviations

CPL	cost per liter
CRF	capital recovery factor
ED	electro-dialysis
ETC	evacuated tube collector
HP	heat pipe
PTC	parabolic trough collector
SFF	sink fund factor
TETC	twin-glass evacuated tube collector

glass cover. Kumar and Tiwari [10] designed and fabricated a solar still coupled with a photovoltaic system. They showed the efficiency of their system is 20% higher than their passive solar still. Dev and Tiwari [11] experimentally investigated the annual performance of a solar still coupled with an evacuated tube collector (ETC) and the annual average thermal efficiency of the system was found to be 21.3%. In 2007, Nandi and De [12] used a parabolic trough collector (PTC) solar still in which temperature increased up to 200 °C. They concluded that the system is not economical, but reduction of greenhouse gas emissions is its main advantage. In 2014, Yacine Marif et al. [13] studied on the performance of a solar PTC using finite difference numerical simulation. According to their findings, the one axis polar East–West and horizontal East–West tracking systems were most desirable for a parabolic trough collector throughout the whole year in Algerian Saharan. Canavarro et al. [14] studied on Linear Fresnel concentrators (LFR) for tabular receivers and compared them with PTCs. It was observed that a substantially higher concentration will result into smaller thermal losses, thus providing higher conversion efficiency at high operating temperatures. Gorjian et al. [15] experimentally evaluated the performance of a stand-alone point-focus parabolic solar still, and reached up to a maximum productivity of 5.12 kg/day. However, they observed no significant effect of air temperature, wind speed, and water salinity on the productivity. Alvarado-Juárez et al. [16] numerically investigated on the heat and mass transfer in a solar still and showed that the heat conduction in the glass cover of the basin and the absorbed and transmitted energy through the glass cover had a strong influence in the fluid flow pattern in basin. Elango et al. [17] studied on the performance of a single slope solar still with and without nanofluids. They concluded that the still with Aluminum Oxide (Al_2O_3) nanofluid has almost 30% higher production rate than the still with water.

The concept of conventional thermosyphons and thermosyphon heat pipe (HP) have been widely used in flat plate solar systems. Some experiments, theoretical analyses and simulations on characteristics of thermosyphonic flow were carried. For instance, Shitzer et al. [18] tested a water heating system in thermosyphonic-flow. The system consisted of two flat plate collectors painted matt black connected in parallel and a storage tank. The water flow rate was found to essentially follow solar radiation, but the value was found to be about 33 percent smaller than the one predicted by an analytical model developed by the authors. Morrison and Ranatunga [19] theoretically predicted the flow rate in thermosyphon solar collectors and compared it with experimental measurements obtained using a laser doppler anemometer. The measurements showed that the generally accepted method of calculating flow rate in thermosyphon circuits underestimates the flow rate for Reynolds numbers less than 300 and overestimates the flow for high Reynolds numbers. Gupta and Garg [20] presented a computer model for predicting the thermal performance of domestic solar water heaters, employing thermosyphon circulation between the collector and the insulated storage tank. They compared different geometries such as different pipe diameters, and different distances between collector and tank. Sodha and Tiwari [21] presented an analysis of the performance of a solar water heating system with natural thermosyphon circulation between the collector and the storage tank. They concluded that the system efficiency increases by a small amount for considerable change in the capacity of storage tank.

A heat pipe is a two-phase heat transfer device which conducts a high rate of heat transfer with the minimum temperature difference between a heat source (evaporator) and a heat sink (condenser) [22]. The device is an evacuated pipe, partially filled with a working fluid. Hence the boiling point temperature decreases compared to atmospheric condition, due to the lower pressure of the fluid. A heat pipe is consisted of three sections: Evaporator, Adiabatic section and Condenser. Most of the commonly used heat pipes have no adiabatic section (i.e. length of adiabatic section is zero). In the evaporator region of a heat pipe, the working fluid absorbs heat from a heat source, then evaporates and flows to the other side of the heat pipe (i.e. condenser). In the condenser, the fluid releases the absorbed heat to a heat sink and the vapor changes to liquid. Then the liquid flows back to the evaporator section, by use of a wick or gravity forces. This process continues as long as the heat source is available in the system.

Compared to forced-circulation or natural convection solar systems, use of solar heat pipes has many advantages such as a higher rate of heat transfer with a low temperature difference, simple construction and wide adjustability. Esen and Esen [23] used different refrigerants as the working fluid in heat pipes of a solar water heater and concluded that R410A has the highest performance compared to R-134a and R407C. In addition, Esen [24] designed a solar cooking system using a vacuum-tube collector and heat pipes and they could heat edible oil up to 175 °C. Also they concluded that compared to conventional concentrators and box cookers, the system shown was more expensive and complex. Many other investigations on the thermal performance of the