Energy Conversion and Management 98 (2015) 151–160

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Experimental and numerical investigation on a novel solar still with vertical ripple surface

Guo Xie [a,b], Jianyin Xiong [b], Hongtao Liu [a], Baoping Xu [c], Hongfei Zheng [b,*], Yingjun Yang [b]

[a] State Key Laboratory of Hydraulics and Mountain River Engineering, College of Water Resource & Hydropower, Sichuan University, Chengdu 610065, China
[b] School of Mechanical Engineering, Beijing Institute of Technology, Beijing 100081, China
[c] School of Energy Power and Mechanical Engineering, North China Electric Power University, Beijing 102206, China

ARTICLE INFO

Article history:
Received 14 November 2014
Accepted 26 March 2015
Available online 10 April 2015

Keywords:
Solar still
Solar desalination
Solar distillation
Multi-effect diffusion solar still

ABSTRACT

Since the great potential of Solar desalination in providing access to freshwater for arid areas, a novel solar still with better performance was designed in the paper. Compared with the other vertical multi-effect diffusion-type solar still (VMEDS), the proposed one owns the following merits: (1) better reliability and anti-scale security due to that the saline-soaked wicks (porous) were replaced by water troughs on the vertical plate; (2) more compact structure, decreasing the heat loss and facilitating the operation. Before the test under environment conditions, steady-state experiments with electricity as heating power were carried out to obtain several basic parameters, including the temperature distribution and freshwater yield of the novel solar still. Results indicated that the accumulated freshwater yield decreased from the first to the third stage during the test, with the maximum performance ratio of 1.81. An empirical correlation in terms of *Nu* and *Ra* number was given against the steady-state data, based on which a model was developed for predicting the heat transfer performance of the still under environment conditions. Following that experiment under environment conditions was performed, by which the new model was validated. Further analysis by the model indicated that inadequate heat insulation caused significant heat loss and reduction of the freshwater yield. And the highest distillation efficiency (performance ratio) of the four sample days in a year was up to 2.0 for the optimized still.

1. Introduction

The steadily increasing demand of freshwater in industry, agriculture and daily-life is an extensive issue which human beings have to face today. It is anticipated that almost 70% of the world population will run into the freshwater shortage by 2025 [1–3]. Provision of freshwater is still being the most serious problem in many regions [4,5].

Solar desalination is driven by solar energy and regarded as a sustainable and promising methodology to partially solve the problem of freshwater shortage, particularly suitable for those arid areas where sunshine is abundant. Various kinds of solar stills have been studied previously, including the multi-effect solar distillation, the dew point solar distillation and the reverse osmosis solar distillation [6–9]. The first one received more attention due to its less maintenance, simple technologies in fabrication and installation. The effect of adding dye in water on the performance of a double basin still was investigated by Dutt et al. [10], a 10% increase in the efficiency compared with traditional system was confirmed. Tiwari et al. [11–13], Al-Karaghoulia and Alnaserb [14,15] optimized the structure of a double slope solar distiller and developed a mathematical model based on the experiments on the system. They confirmed the importance of a perfect insulation in the productivity of the basin-type solar still. Ahmed et al. [16], Tanaka et al. [17], Xiong et al. [18] experimentally studied the multi-effect solar still under indoor and environment conditions, and developed a numerical model for predicting the heat transfer characteristics of the system.

Nowadays, a key issue in the development of the multi-effect solar desalination is how to increase its stability without scarifying its high efficiency in heat transfer [19]. Rajaseenivasan and Kalidasa [20] reviewed the technology involving vertical multi-effect diffusion solar still (VMEDS) and confirmed its potential in application. VMEDS was firstly studied by Dunkle [21] in 1961. He constructed a solar distillation system, consisting of solar stills and a storage tank connected to a solar collector, and found that narrowing the gaps between plates or replacing the air in the gaps with hydrogen could increase the productivity of freshwater. A simplified VMEDS was developed by Cooper and Appleyard [22],

* Corresponding author. Tel.: +86 10 68912510; fax: +86 10 68412865.
E-mail address: hongfeizh@bit.edu.cn (H. Zheng).

http://dx.doi.org/10.1016/j.enconman.2015.03.099
0196-8904/

Nomenclature

a	thermal diffusivity (m^2/s)
A	area (m^2)
A_c	equivalent heat convective section area = $\pi(d_2 - d_1)h/(\ln d_2 - \ln d_1)$ (m^2)
A_e	evaporative area (m^2)
A_{ud}	top and bottom surface area for every stage cavity and central water tank (m^2)
A_{w1}	heating area of water tank to the first stage troughs (0.81 m^2)
c_l	length correction factor of the central water tank, 1.5
c_p	specific heat at constant pressure (J/(kg K))
d_1	average diameter of annular evaporation trough (m)
d_2	average diameter of annular ripple condensation surface (m)
d_{41}	inner diameters of the polyethylene–aluminum, 12 mm
d_{42}	out diameters of the polyethylene–aluminum, 16 mm
d_{43}	out diameter of the sponge insulation layer, 56 mm
g	gravity acceleration (m/s^2)
G	solar irradiance (W/m^2)
G_{max}	the maximum solar irradiance on the test day (W/m^2)
h	equivalent height of the vertical solar still, 1.04 m
h_c	convective heat transfer coefficient ($W/(m^2 K)$)
h_{fg}	latent heat of water vaporization (2.3×10^6 J/kg)
H	accumulated solar irradiance of the collector on the test day (J/m^2)
l_c	average distance between the evaporation and condensation surface (m)
l_p	length of the connection pipeline (2 m)
m_i	accumulated freshwater yield of every stage (kg/s)
m_0	accumulated freshwater yield of solar still in whole day (kg/s)
M	residual seawater mass in evaporation troughs (kg)
M_a	the molar mass of air (28.96 kg/k mol)
M_v	the molar mass of water vapor (18 kg/k mol)
p	vapor pressure (Pa)
p_T	total pressure of the humid air (1.01×10^5 Pa)
PR	performance ratio of the solar still
Q_c	convective heat transfer rate (W)
Q_{cc}	convective heat transfer rate between the wall and ambient environment (W)
Q_e	evaporative heat transfer rate (W)
Q_h	effective heating rate of the concentrated solar collector (W)
Q_{h2}	heating rate absorbed by the out stainless steel wall (W)
Q_{hu}	heating rate of the first stage cavity (W)
Q_k	heat loss rate to ambient environment (W)
Q_r	radiant heat transfer rate (W)
Q_{rc}	radiant heat transfer rate between the wall and ambient environment (W)
ΔQ	water sensible heat change after one day operating (J)
R_b	modified factor of the solar irradiance between two different surfaces
t_a	time of sunrise
t_b	time of sunset
T	temperature (K)
T_a	temperature of the ambient environment (K)
T_i^*	normalized temperature difference = $(T_0 - T_a)/G$ (K m^2/W)
T_{sky}	the sky temperature (K)
T_v	average temperature for central water tank and each stage cavity (K)
u	air velocity of test field (m/s)

Creek

α	absorptivity
β	thermal expansivity (K^{-1})
ρ	density (kg/m^3)
μ	dynamic viscosity (kg/(m s))
λ	thermal conductivity (W/(m K);
ε	emissivity of the surfaces
η	efficiency
δ	thickness (m)

Subscripts

i = 1,2,3	first, second and third distillation cavity
0	central water tank
4	connection pipelines
ha	humid air in the distillation cavity
co	concentrated solar collector
w	evaporation surface
g	condensation surface
wall	out stainless steel wall
rp	rubber plate
ep	engineering plastic
pa	polyethylene–aluminum
sp	sponge

which integrated the solar collector and the still. Benefited from their pioneering work, many researchers subsequently have been kept trying to optimize structures and parameters of the VMEDS. Elsayed and Fathalah [23,24] tested a three-effect diffusion solar still with the same structure as Dunkle's and studied the relation between the distillation rate of the VMEDS and feed rate of the saline water. Toyama and Aragaki [25] studied the dynamic characteristics of a VMEDS and gave the operation conditions required to maximize the distillation productivity on four sample days through a year. Tanaka et al. [26–28] experimentally studied the VMEDS which combined a basin-type absorber, a flat plate reflector and a heat-pipe solar collector. They pointed out that narrowing diffusion gaps between the partitions, increasing the number of partitions, sandwiching small spacers between partitions and insulating the frame, can greatly improve the productivity of the VMEDS. In their experiments, 9% and 17% increase in productivity in winter and summer, respectively, were realized compared with that of the multi-effect tray basin solar still. Huang and Chong [29] developed a multiple-effect bended-plate solar still and obtained a productivity as much as 23.9 kg m^{-2} d^{-1}.

In the designs of references [20–29], a thin wick (porous) material was attached on the vertical plate, with which the freshwater productivity of the VMEDS can be significantly increased by narrowing the diffusion gap between the parallel partitions. However, the wick material may gradually peel off from the vertical plate after operating for a certain time, probably leading to the blockage of the gap and the contamination of the freshwater. In addition, controlling the evaporation temperature and feeding rate of the system have to be much more careful to prevent the deposit and bubble formation of the wick material.

The objectives of this paper are to: (1) design a novel VMEDS to overcome the peel-off problem and improve the stability; (2) test and analyze the temperature and freshwater yield under steady-state and environment conditions of the new VMEDS; (3) establish a numerical model to describe the heat and mass transfer process in the new VMEDS and validate the model with experiments.