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Numerical analysis of the performance of a tiltable multi-effect solar distiller

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ABSTRACT

This paper proposes a tiltable multiple-effect solar distiller and presents a numerical analysis on its performance. The distiller consists of a glass cover, a number of parallel plates, and seawater-soaked wicks placed in contact with the plates. The wick of the glass cover is designed to be black color to increase the solar energy absorption. A 2-dimensional numerical model of heat and mass transfer was developed to analyze the distiller's optimal operating and design conditions, and a numerical analysis was conducted in each of the four seasons at N30° and E127°. The results show that the TMED can produce the fresh water of 16.6 kg/m^2 by optimal operation and the performance ratio is 1.44, which is 2.8 times more than that of a basin-type still. The wind reduced the productivity of the distiller due to heat loss from the glass. Although the productivity increased with decrease of inclination angle of the distiller, the optimum value was 40–50° considering deformation of plate and contamination of fresh water. Feeding the same flowrate of 6 ccm to all effects was recommended for convenient and reliable operation. The optimal number of effects was 11 based on annual productivity and manufacturing cost.

1. Introduction

Whereas the world population stood at about 2.5 billion people in 1950, it surpassed 6.0 billion people in 1999 and is expected to exceed 8.3 billion people in 2025 and 10.0 billion people in 2060 [1]. According to a recent OECD report, some 340 million people in 28 countries around the world currently have difficulty obtaining sufficient water, and that figure is forecast to increase tenfold to about 3 billion people in 52 countries by 2025. As the global population increases, the shortage of water resources is becoming increasingly acute, with the water shortage caused by the irregular distribution of water resources in underdeveloped countries becoming a particularly intractable problem. Many desalination processes have been developed to solve such problems, and the solar distiller in particular is attracting attention as a useful technology in island areas, remote areas and underdeveloped countries due to its simple structure and the fact that it does not need a separate energy source.

Solar desalination technology is classified into direct and indirect desalination. A direct desalination utilizes solar radiant energy directly transferred to the seawater inside a distiller for production of fresh water without separated heat exchanger. With indirect desalination, the radiant energy is generally transferred to the heating medium of a solar collector, and fresh water is produced by the heat exchange of the heating medium to the seawater. Although the productivity of the direct desalination is low due to its low supply energy density, it is easy to operate and relatively inexpensive to maintain due to its simple architecture [2]. Conversely, the indirect desalination plants can be mass-produced due to its relatively high energy density, but it has the disadvantages of complexity and being costly to install and maintain due to the need for additional devices such as a solar thermal collector, heat storage device, heat exchanger, and circulation pump. In the indirect type solar desalination, Xiong et al. [3] developed a dual-effect solar still using a vacuum tube collector, and obtained a maximum of 43 kg of distilled water in a solar radiation area of only 1.28 m^2. They applied a corrugated stacked tray for the distiller to increase the condensation surface and thereby increase its production efficiency. The system had the additional advantage to produce fresh water using the sensible heat of seawater not only during the daytime but also at night by processing a greater amount of seawater (about 200 kg) than other solar water distillers [4]. The distiller applied the vertical ripple surface with water troughs instead of wicks. It is considered as a capacity of 10.3 kg/(m^2·d) of water production in summer.

Many studies have been carried out with the aim of increasing the productivity per unit area using various direct solar desalination technologies. Of these, the vertical or inclined multi-effect distillation (MED) technology has attracted attention since it can increase the

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Nomenclature

A	area, m^2
AST	apparent solar time, min
c	specific heat, J/(kg·K)
D	diffusivity of vapor, m^2/s
DR	decreasing rate of feeding seawater flowrate between effects, %
d	distance or diffusion gap, m
E	energy in control volume, J
ET	equation of time, minute
F	shape factor
G	solar irradiance, W/m^2
H	enthalpy, J/kg
h	hour angle
h_a	convective heat transfer coefficient, W/m^2
I_0	extraterrestrial radiation measured on the plane normal to the radiation on the n_dth day of the year, W/m^2
I_{sc}	solar constant, W/m^2
k	thermal conductivity, W/(m·K)
L	latent heat, J/kg
LL	local longitude, °
LST	local standard time, minute
$\dot{m}$	mass flowrate, kg/s
$\dot{m}_{f1}$	feeding flowrate to the first effect, cm^3/min (ccm)
m_a	air mass
N_t	total numbers of effects
n_d	day number (1–365)
P	total pressure, Pa
p	partial pressure of saturated vapor, Pa
$\dot{Q}$	heat flow rate, W
R	thermal resistance, K/W
R_v	specific gas constant of water vapor, J/(kg·K)
S	seawater concentration, kg/kg
SL	standard longitude
t	time, s or Celsius temperature, °C
T	Kelvin temperature (t + 273.15), K
T_m	Average temperature, K
u	wind speed, m/s
V	volume, m^3

Subscripts

atm	atmosphere
c	convection
cd	cold part
d	conduction
df	diffuse radiation
dr	direct radiation
e	condensation or evaporation
g	glass or ground
ht.	hot part
in	inlet
n	horizontal surface
opt	optimum
out	outlet
p	plate
pw	pure water
r	radiation or reflection
sw	seawater
slr	solar energy
t	total
w	wick
wn	between plate and wick in same effect
wp	between wick and next-effect plate
v	vapor
(n,j)	n^{th} cell of wick and plate in j^{th} effect

Greek

α	solar altitude angle
β	tiled angle of distiller °
δ	declination, °
θ	solar incident angle, °
η	absorptance
ϵ	emittance
ρ	density, kg/m^3
∅	latitude, °
σ	Stefan-Boltzmann constant, W/(m^2·K^4)
τ	transmittance
Φ	solar zenith angle (= 90-α), °
ξ	azimuth angle, °

productivity per unit area by repeatedly using the thermal energy transformed from the solar radiant energy transferred to the distiller. In 1964, Kudret Selçuk [5] developed an inclined two-effects MED solar still with a double-glass cover and evaporator-condenser plates. The solar energy was collected by the black plate and transferred to the seawater of cascaded evaporating troughs installed with evaporating side surface of the plate, and the water vapor evaporated from the troughs was condensed in next plate surface and the latent heat was transferred to the plate. These repetitive evaporation and condensation in the MED part increased the efficiency of the still. In indoor test, the still obtained the distillate rate of 1.8 kg/(m^2·h) in constant heat input of 1.04 kW, and therefore the distillate was predicted by about 10.6 kg/m^2 in an input of 22 MJ/m^2. An inclined three-effects MED solar still was developed by Cooper and Appleyard [6] with integrating the solar collector and the multiple wicks and plates. The black plate of the still absorbed the solar energy and transferred to the seawater-soaked wick (spongy fabric) attached to the plate surface, and then the repetitive evaporation and condensation occurred. Elsayed et al. [7] experimentally studied the vertical MED solar distiller (VMED) with three effects and found that the increase of the feeding rate to the still reduced the performance ratio. Ouahes et al. [8] developed the inclined three-effects MED still. The still applied a thin fabric comprising a single, finely woven layer, which was held in contact with the overhanging plate through the interfacial tension, as seawater-soaked material. Ohshiro et al. [9] and Tanaka et al. [10] found that narrowing diffusion gap between the effects of the MED still increased the products. Nosoko et al. [11] theoretically studied the VMED using a steam heat energy and developed two dimensional numerical models to analyze temperature and concentration profiles of the seawater of wicks in vertical direction and found that the concentration of down-flowing seawater in wick increased by evaporation of the seawater and then the boiling point elevation by increased concentration had a negative effect on productivity.

The VMED had benefits to suppress the deformation of plates or wicks by gravity and to narrow the diffusion gap, but the productivity decreased compared to the inclined MED still due to a decline of solar energy absorption to the first black plate. The studies about the VMED combined with a solar collector as additional equipment were performed to increase the productivity. Dunkle [12] proposed and tested the five-effects VMED coupled with the flat plate solar collector. Kiatsiriroat et al. [13] theoretically and experimentally studied the VMED with a flat plate solar collector. They found that the productivity increased as the last condensing plate was covered with a wetted wick which had more cooling effect than an air and confirmed that the