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Theoretical with experimental validation of modified solar still using nanofluids and external condenser

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ABSTRACT

The effects of using nanofluids and integrating the solar still with external condenser have been studied numerically. The performance of the modified desalination system is evaluated and compared with that of the conventional one under the same meteorological conditions. Theoretical analysis of heat and mass transfer mechanisms for the solar stills has been developed. Numerical calculations had been performed on the solar stills in Kafrelsheikh city, Egypt (31.07°N latitude and 30.57°E longitude) for different nano-material concentrations and providing low pressure to study the effects of these parameters on the daily productivity of the system. The analyses are conducted in the weight concentrations range from 0.02 to 0.3% for aluminum oxide (Al_2O_3) and cuprous oxide (Cu_2O) nanoparticles. Thermo-physical properties of the nanofluid are considered by assuming nanofluid is a single-phase fluid. The simulation results are in a good agreement with the published experimental data. The daily efficiency of the modified still is 84.16% and 73.85% when using Cu_2O and Al_2O_3 nanoparticles, respectively, with operating the fan. And the daily efficiency when providing low pressure only is 46.23%. In addition, the conventional stills' daily efficiency was 34%.

1. Introduction

Solar radiation is free, never lasting and available on site. Moreover, using the solar energy reduces fossil fuels consumption and pollutants. Solar stills use the solar radiation for producing freshwater. Solar stills are simple, cheap and need low maintenance, but they suffer from low productivity. Because of their advantages, scientists have conducted studies, which can be classified into two main categories: experimental and theoretical, to enhance the solar still performance.

A review of various designs of solar stills was made by Xiao et al. [1] and Ganapathy Sivakumar and Sundaram [2]. Different methods have been carried out in the literature to improve the productivity of solar stills. These methods include adding dyes [3] and charcoal pieces [4] to the basin water, using reflectors [5], external condensers [6] or internal condensers [7], connecting the stills to solar collectors [8] or concentrators [9], etc. Recently, other methods have been carried out to enhance the daily productivity of single effect solar stills.

Several researchers have suggested improvements to the passive solar still with separate condenser and natural circulation of water vapor. Fath and Elsherbiny [10] investigated a single sloped basin solar still integrated with an external condenser. The condenser was located in the shadow zone of the still. They found that the still efficiency was increased. El-Bahi and Inan [11,12] developed a solar still integrated with a separate condenser with double glazing and another solar still integrated with a separate condenser with one glass cover. The condenser was located on the shaded side of the evaporator. A vertical steel reflector was fitted in the top part of the evaporator cast a shadow over the condenser system. It was found that the performance of the solar still with a condenser was better than the one which had no condenser. Gnanadason et al. [13] reported that using nanofluid in a solar still increases its productivity. They examined the effects of adding carbon nanotubes (CNTs) to the water inside a single basin solar still. Their results obtained that adding nanofluid increased the efficiency by 50%.

In our recent study, Kabeel et al. [14] conducted the experimental attempts to improve the solar still productivity by providing vacuum fan with integrating an external condenser to the basin and also by using the aluminum oxide–water nanofluid. The results revealed that providing vacuum increased the distillate water productivity by about 53.2%. In addition, using the aluminum oxide–water nanofluid improved the solar still water yield by about 116%,

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Nomenclatures

English symbols

A	area, m^2
C_p	specific heat, J/kg K
F	fan
Fs	fan speed, rpm
FP	fan power, W
Gr	Grashof number
h	heat transfer coefficient, W/m^2 K
h_{fg}	enthalpy of evaporation at T_w, J/kg
K	thermal conductivity, W/m.K
$I(t)$	solar radiation on inclined surface, W/m^2
L	perimeter, m
m	mass, kg
M	molecular mass, g/mol
P	partial pressure, N/m^2
Pr	Prandtl number
Ra	Rayleigh number
St	sticking coefficient
t	time, S
T	temperature, °C
U	heat loss coefficient from basin and sides to ambient, W/m^2 K
V	wind velocity
X	insulation thickness, m

Greek Symbols

α	absorptivity
β	volumetric thermal expansion
ε	emissivity
ρ	density, kg/m^3
σ	Stefan–Boltzmann constant, 5.6697×10^{-8} W/m^{2}K^4
δ	characteristic length, m
η_d	the daily efficiency of the still
μ	dynamic viscosity, N/m^2.s
φ	nanomaterial concentration
τ	transmissivity

Subscripts

a	ambient
b	basin
bf	base fluid
c	convective
e	evaporative
eff	effective
fw	feed water
g	glass
i	insulation
nf	nanofluid
p	nanoparticle
r	radiative
s	sky
v	vapor or volume fraction
w	water or weight fraction

with operating the vacuum fan. In another study, Kabeel et al. [15] studied the effects of using the solid nanoparticles of Cu_2O and Al_2O_3 with different weight fraction concentrations on the performance of a single basin solar still with and without providing vacuum. The results showed that using the Cu_2O and Al_2O_3 nanoparticles, increased the distilled water productivity by about 133.64% and 93.87% and 125.0% and 88.97% with and without operating the vacuum fan, respectively. The performance of hybrid solar distillation system comprising of corrugated wick solar still

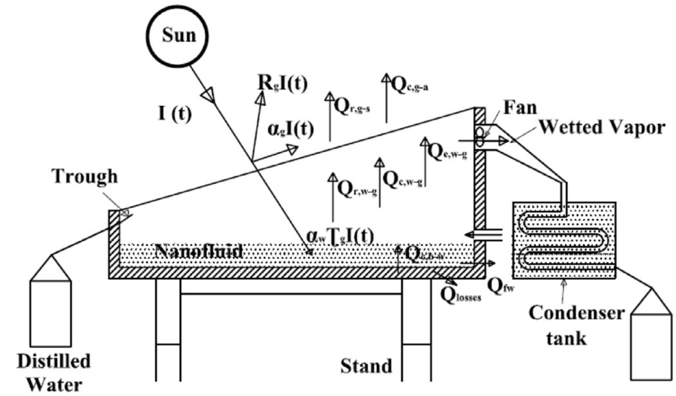

Fig. 1. Schematic diagram of the solar desalination system.

(CrWSS) with internal reflectors, integrated with external condenser and using different types of nanomaterials was investigated by Omara et al. [16]. Investigations clarified that the yield of CrWSS with reflectors when providing vacuum was about 180% higher than that of conventional solar still (CSS). In addition, using the cuprous and aluminum oxides nanoparticles increases the yield of CrWSS with reflectors when providing vacuum by about 285.10% and 254.88%, respectively.

Generally, the experimental researches are so costly and time consuming. Therefore, some researchers have focused on mathematical modeling, to find important parameters and better designs of solar stills. Kianifar and Mahian [17] investigated the effect of using low powered fan and reported an improvement in productivity. Al-hussaini and Smith [18] studied theoretically the effects of applying a vacuum inside the solar still on its productivity. Their results showed that the water yield could be increased by 100% when considering complete vacuum. In addition to mathematical modeling, some investigations have been done based on computational fluid dynamic (CFD). CFD has relatively low cost and high speed, while it can also simulate real or ideal conditions. A single sloped passive solar still with an external condenser has been studied theoretically by Madhlopa and Johnstone [19].

Because being the effect of nanomaterials and external condenser on the performance of solar still needs more theoretical research. Then, the main objective of this study is to build a numerical modelling which has the ability of expectation of the effects of nanomaterials and external condenser on the performance of solar still and also has the ability of optimizing the performance based on the considered examined parameters. The considered operating parameters of this investigation are providing low pressure (external condenser) and also using different types of nanomaterials (aluminum oxide (Al_2O_3) and cuprous oxide (Cu_2O)) with various concentrations (from 0.02 to 0.3%). The output parameters of the solar still performance are the hourly yield and the daily efficiency of the solar stills. So, they are evaluated at various operating conditions.

2. System description and operating principle

A schematic diagram of the examined solar still is shown in Fig. 1. The bottom and side walls of the basin are considered to be well insulated. Purified drinking water is collected from the distilled output collector. The solar radiation transmitted through the glass cover and basin water is absorbed by the basin liner; hence, its temperature increases. Part of thermal energy is transferred by convection to the basin water and the other will be lost by conduction to the ground. The basin water transfers heat to the inner surface of the glass cover by radiation, convection and evaporation.

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