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Steps optimization and productivity enhancement in a nanofluid cascade solar still

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A B S T R A C T

In this paper, a numerical study is performed to investigate the effects of nanofluid on the productivity of a stepped solar still. Moreover, a sensitivity analysis is arranged to determine the sensitivity of the hourly productivity to the height and length of steps. Finally, an optimization analysis is performed by using response surface method to optimize the geometry of stepped inside the still. Obtained results indicate that 22% enhancement in the hourly productivity is observed by increasing the nanoparticle concentration from 0% to 5%. Moreover, there is only 2.1% difference between the estimated results by RSM and calculated results by CFD.

1. Introduction

Only about 0.014% of available water sources can be utilized directly as potable water for domestic usages. Accordingly, the production of the potable water has become a vital challenge for researchers. Different technologies are used for water distillation. Among them, solar water distillation is a famous technology that can be utilized for water purification in arid remote area. Recently, some researchers introduced some active and passive techniques to enhance the performance of solar stills [1,2]. Active methods need external energies. Some active techniques used in solar stills are using heatpipe and thermoelectric module [3], using flat-plate solar collector and cooling glass cover [4], using heater [5], and so on. Moreover, the passive methods are related to amendments of the system configuration which do not require any input energy during process. Some passive techniques used in solar stills are incorporating fins [6], inserting porous materials [7], using wick materials [8], etc.

Nafey et al. [9] used various gravels and rubbers as a passive technique to improve the output production of a solar still. Their results revealed that the daily production improved up to 20% for larger gravel size and rubber thickness. As a passive technique, some researchers used nanoparticles in solar stills to enhance the productivity of this device [10]. Elango et al. [11] applied different nanoparticles containing Al, SnO_2, ZnO, and Fe_2O_3 in a single slope solar still. They observed a higher production by using nanofluids in the still. Rashidi et al. [12] performed a numerical simulation to investigate the potential of nanofluid for enhancing the productivity of a single slope solar still. They concluded that the average Nusselt number inside the still enhances about 18% by increasing the solid volume fraction from 0% to 5%. As an active-passive technique, Kabeel et al. [13] used the nanofluid and provided vacuum by fan inside the solar still to improve the performance of this device. They used different types of nanoparticles with different values of solid volume fraction. They observed 133.64% and 93.87% enhancements in the distilled productivity by applying the Cu_2O nanoparticles for with and without providing the vacuum, respectively.

Some researchers provided step inside solar stills to achieve a higher evaporation rate and enhance the water production. Note that step could maintain minimum depth in the basin of a solar still. Velmurugan et al. [14] performed a performance analysis for the stepped solar still. They used fin, sponge, pebble, and combination of them inside this still to enhance the productivity. They reported that the maximum enhancement of productivity about 98% in the

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Nomenclature

A	symbol/number of factor (–)
B	symbol/number of center points (–)
Cp	specific heat (J kg^{-1} K^{-1})
d_l	molecular diameter of base fluid (nm)
dp	nanoparticle diameter (nm)
h_{fg}	latent heat of vaporization (J kg^{-1})
H	height of steps (m)
k	thermal conductivity (W m^{-1} K^{-1})
K_B	Boltzmann constant (J K^{-1})
l_{BF}	mean free path of water (–)
L	length of steps (m)
Pr	Prandtl number (–)
$\dot{m}$	productivity (kg h^{-1} m^{-3})
Re	Reynolds number (–)
T	temperature (K)

Subscripts/superscripts

b	bottom (–)
B	Brownian (–)
eff	effective (–)
g	glass cover (–)
l	liquid phase (–)
p	particle (–)
sat	saturation (–)
v	vapor phase (–)
w	water (–)

Greek symbols

α	thermal diffusivity (m^2 s^{-1})
α	volume fraction (–)
δ	distance between particles (nm)
α_0	average of the results of the replicated center point (–)
α_1, α_2	main half-effects of the coded variables A and B (–)
α_{11}, α_{22}	squared effects (–)
α_{12}	two factor interaction half-effects (–)
μ	dynamic viscosity (kg $m^{-1}s^{-1}$)
ρ	density of the fluid (kg m^{-3})
φ	solid volume fraction of nanoparticles (–)

Abbreviations

CCD	central composite design
CFD	computational fluid dynamics
Res	response
RSM	response surface methodology

stepped solar still can be achieved when fin, sponge, and pebbles are utilized in the basin. El-Samadony et al. [15] performed an experimental work on a modified stepped solar still. They considered the internal and external reflectors along with an external condenser for this still. They reported that the water production of stepped solar still with a condenser increases up to 66% in comparison with the conventional still.

As mentioned earlier, providing step inside solar still and using nanofluid can lead to a higher water production and evaporation rate. Many experimental and mathematical studies have been performed on this topic but a numerical simulation and an optimization analysis are missed in these works. Accordingly, this paper employs a numerical model to investigate the effects of nanofluid on productivity of a weir type cascade solar still. Moreover, the response surface methodology is used to determine the optimized height and length of the steps inside the still for achieving the maximum hourly productivity.

2. Problem statement and physical description

A schematic view of the solar still with coordinate system is shown in Fig. 1. It can be seen that the solar still with height of right side 0.285 m, height of left side 0.06 m, and length 0.57 m is considered. The still has a glass cover at top and two completely insulated sidewalls. It is assumed that a layer of water is placed on the bottom surface of the still at the initial time and there are no materials above this layer. The vapor is generated by evaporating the water during the time. A number of steps with length L and height H are used at the bottom surface of the still. The glass cover and bottom surface have constant temperatures of $T_g = 30\ °C$ and $T_b = 40\ °C$, respectively. The 2D laminar and unsteady Al_2O_3-water nanofluid flow is considered. The vapor phase flow is assumed as an incompressible ideal gas flow.

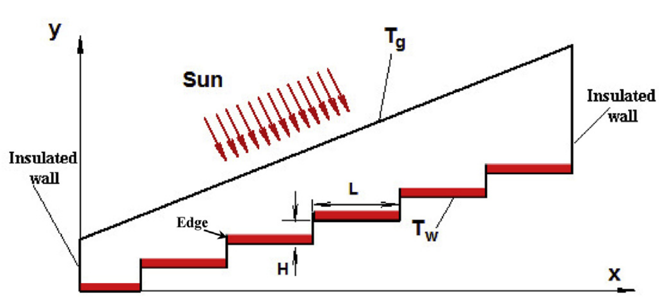

Fig. 1. Schematic view of the stepped solar still.

For a cascade solar still (stepped solar still), there are no inlet and outlet sections. Moreover, water is fixed without flowing in each step by creating an edge on each step. Accordingly, there is no flow in the cascade unit. This edge is shown in Fig. 1. It should be stated that a cascade solar still is designed to decrease the distance between water (evaporating surface) and glass (condensing surface) surfaces. The required time for transferring vapor from water zone to glass surface decreases as this distance reduces and this causes an enhancement in the productivity of the still.

3. Simulation

All simulations in this paper are developed employing the Ansys-Fluent. In the Fluent, two zones are considered for this problem. Zone 1 is placed in the region between above water surface and glass cover. This zone is defined as the vapor zone. This means that only vapor can be placed in this zone. The major part of the solar still is covered by this zone. Moreover, zone 2 is placed in the region between water surface and bottom surface of the solar still. This zone is defined as the mixture zone. This means that both water and vapor phases can be placed in this zone. In an actual solar still, water is only placed on the bottom surface of the still as a thin layer but vapor can be placed in both zones. In zone 2, liquid water can be evaporated during time and accordingly, replaces with vapor. Vapor arises from the water surface and circulates inside the solar still due to the natural convection. The vapor phase flow as an incompressible ideal gas flow. The Boussinesq model is used to simulate the natural-convection flow. No slip boundary condition