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# Volume of fluid model to simulate the nanofluid flow and entropy generation in a single slope solar still

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ABSTRACT

This paper proposes volume of fluid (VOF) model to investigate the potential of $Al_2O_3$-water nanofluid to improve the productivity of a single slope solar still. Accordingly, VOF model is utilized to simulate the evaporation and condensation phenomena in the solar still. An entropy generation analysis is used to evaluate the system from the second law of thermodynamics viewpoint. The effects of solid volume fraction of nanofluid on the productivity and entropy generation in the solar still have been examined. The numerical results are compared with the experimental data available in the literature to benchmark the accuracy of VOF model. The numerical results showed that the productivity of solar still increases with an increase in the solid volume fraction of nanoparticles. The productivity increases about 25% as the solid volume fraction increases in the range of 0%–5%. There is about 18% enhancement in the average Nusselt number as the solid volume fraction increases in the range of 0%–5%. Moreover, the maximum values of viscous and thermal entropy generations are happened at the regions around the bottom and top surfaces of the solar still. Both types of entropy generation increase by increasing the solid volume fraction of nanoparticles. The viscous and thermal entropy generations increase about 95% and 25%, respectively as the solid volume fraction increases in the range of 0%–5%.


## 1. Introduction

Solar stills are recognized as the most efficient desalination technology, which utilize solar radiation to desalinate water and generate drinking water. These devices are usually cheap and have a simple structure with insignificant maintenance cost. As a matter of fact the solar energy is used as a free, stable, and trusty source of energy. However, these devices have a low performance. Consequently, there is a necessity to recover the performance of solar stills by using active and passive methods. The active methods need external source of energy such as applying heat pipe and thermoelectric module [1,2], put on flat-plate solar collector and cooling glass cover [3], using parabolic concentrator [4], by means of water sprinkler [5] and via heater [6] are a number of active techniques used to improve the efficiency of solar stills. Aside from active method, some researchers used passive methods to enhance the efficiency of solar stills. Most common of these methods are installing fins [7], blade in solar still [8,9], porous materials [10,11], PCM [12], baffles [13] and applying vapor adsorbent pipe network [14] and so on.

Common liquids such as water have almost small value of thermal conductivity and thus cannot achieve acceptable heat transfer rates in thermal systems. A method to overcome this defect is adding nanoparticles in such liquids in order to enhance their thermal conductivity. Some researchers used this technique in different solar systems, for instance Mahian et al. [15] evaluated the applications of them in solar systems in a review paper. They reported that applying nanofluids in solar collectors has some economic and environmental advantages as they cause a decrease in $CO_2$ pollution and fuel savings.

Some investigators have used nanoparticles inside the solar still as a passive technique to improve the performance of this device. Kabeel et al. [16] used the nanofluid in a solar still integrated with external condenser. The productivity of their solar still was increased about 116% and 53.2% by using the nanofluids and external condenser, respectively. Kabeel et al. [17] applied nanofluids and vacuum simultaneously in an experimental work to enhance the efficiency of a solar still. Their results showed that

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**Nomenclature**

| | |
|---|---|
| $A$ | surface ($m^2$) |
| $B_c$ | Boltzmann constant (−) |
| $C$ | specific heat ($J/kg\ ^\circ C$) |
| $d_f$ | molecular diameter of base fluid ($nm$) |
| $dp$ | nanoparticle diameter ($nm$) |
| $E$ | energy ($J/kg$) |
| $F$ | force ($N$) |
| $g$ | gravitational acceleration ($m/s^2$) |
| $H$ | height of solar still ($m$) |
| $k$ | thermal conductivity ($W/m.^\circ C$) |
| $l_{BF}$ | mean free path of water (−) |
| $L$ | length of solar still ($m$) |
| $\dot{m}$ | productivity ($Kg/m^2$) |
| $N_g$ | non-dimensional local entropy generation (−) |
| $N_t$ | mean entropy generation rate (−) |
| $Nu$ | Nusselt number (−) |
| $P$ | Pressure ($Pa$) |
| $Pr$ | Prandtl number (−) |
| $Re$ | Reynolds number (−) |
| $S'''_g$ | entropy generation rate ($W/m^3.^\circ C$) |
| $S_h$ | energy source term ($Kg/m.s$) |
| $S_\alpha$ | mass source term ($Kg/m^3.s$) |
| $T$ | time ($s$) |
| $T$ | temperature ($^\circ C$) |
| $u,v$ | velocity components in horizontal and vertical directions ($m/s$) |
| V | velocity ($m/s$) |
| $x,y$ | rectangular coordinates components ($m$) |

*Subscripts/superscripts*

| | |
|---|---|
| Ave | average |
| b | bottom |
| B | Brownian |
| Eff | effective |
| f | base fluid |
| g | glass cover |
| i | $i^{th}$ phase |
| l | left |
| p | particle |
| r | right |
| th | thermal |
| v | vapor |
| v | viscous |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | volume/void fraction (−) |
| $\delta$ | distance between particles ($nm$) |
| $\theta$ | slope of the glass cover ($^o$) |
| $\mu$ | dynamic viscosity ($kg/m.s$) |
| $\rho$ | density of the fluid ($kg/m^3$) |
| $\varphi$ | solid volume fraction of nanoparticles (−) |

*Abbreviations*

| | |
|---|---|
| CFD | Computational fluid dynamics |
| VOF | Volume of fluid |

these techniques enhance considerably the evaporation and condensation rates and accordingly, cause a more productivity. Sahota and Tiwari [18] examined the influence of nanofluids on the efficiency of a double slope solar still. They observed the higher thermal energy efficiency and thermal exergy for nanofluids in comparison with the case of pure water. Elango et al. [19] inspected experimentally the effects of various water nanofluids containing $Al_2O_3$, ZnO, $Fe_2O_3$, and $SnO_2$ on the efficiency of a single slope solar still. They concluded that $Al_2O_3$-water nanofluid, with 29.95% higher productivity in comparison to the water, has the maximum productivity among all nanoparticles considered in this research. Sahota and Tiwari [20] studied the influence of $Al_2O_3$ nanoparticles on the efficiency of a passive double slope solar still. They observed about 12.2% enhancement of yield for 35 kg basefluid by adding $Al_2O_3$ nanoparticles with 0.12% concentration. Sahota and Tiwari [21] used $Al_2O_3$, CuO, and $TiO_2$-water nanofluids in a double slope solar still. They concluded that the optimization of concentration of nanoparticles depends on the climatic conditions containing the ambient temperature and solar intensity. El-Said et al. [22] coupled a hybrid desalination system with $Al_2O_3$-water nanofluids solar heater. They reported that the solar water heater efficiency is about 49.4%. Sharshir et al. [23] used nanofluids and glass cover cooling simultaneously in an experimental research to improve the efficiency of a solar still. They used copper oxide and graphite as the nanoparticles. They reported a daily efficiency of 30% for the non-modified still. They recorded 46% and 49% for the daily efficiencies of the still by applying copper oxide and graphite particles with glass cooling, respectively. Kabeel et al. [24] reported both theoretically and experimentally the effects of nanofluids and external condenser on the performance of a solar still. They used aluminium oxide and cuprous oxide as the nanoparticles. They concluded that the daily efficiency of the modified still is 84.16% and 73.85% when applying cuprous oxide and aluminium oxide nanoparticles, respectively, with operating the fan. Additionally, the daily efficiency of their conventional still was about 34%. Sahota et al. [25] analytically investigated the influences of $Al_2O_3$, CuO, and $TiO_2$-water nanofluids on the efficiencies of the active solar distillation systems. They coupled the double slope solar still with photovoltaic thermal flat plate collectors and helical heat exchanger. They observed a higher productivity by using CuO-water nanofluid in comparison with $Al_2O_3$ and $TiO_2$-water nanofluids. Sahota et al. [26] presented the influences of $Al_2O_3$, CuO, and $TiO_2$-water nanofluids on the exergy of a double slope solar still. They found that the exergy of the solar still increases by using the nanofluid. Mahian et al. [27] investigated the influences of nanofluids on the evaporation rate in a solar still equipped with a heat exchanger. They used Cu and $SiO_2$-water nanofluids. They reported that at high temperatures, employing $SiO_2$-water nanofluid, which has a lower effective thermal conductivity in comparison with Cu-water nanofluid, causes the higher performance. Sahota and Tiwari [28] performed exergoeconomic and enviroeconomic analyses for a hybrid double slope solar still. Their analyses were performed for three cases containing hybrid solar still operating without heat exchanger (case A), hybrid solar still operating with helically coiled heat exchanger (case B), and conventional solar still (case C). They used $Al_2O_3$ and CuO-water nanofluids. They observed that CuO-water nanofluid has better annual performance and exergoeconomic and enviroeconomic for the cases A and B, while, $Al_2O_3$-water nanofluid has better results for the case C. Chen et al. [29] studied stability, optical characteristics, and thermal conductivity of SiC-saline water nanofluids used in a solar distillation system. Their results showed that enhancing the salt concentration