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Original Research Paper

Convection of heat and thermodynamic irreversibilities in two-phase, turbulent nanofluid flows in solar heaters by corrugated absorber plates

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ABSTRACT

The effects of simultaneous implementation of corrugated walls and nanoparticles upon the performance of solar heaters are investigated. Triangular and sinusoidal wall profiles along with varying concentration of nanoparticles are analyzed. The multi-phase mixture and the SST κ-ω models are used to simulate turbulent nanofluid flows inside the corrugated channels. The staggered computational grid is employed for storing the velocity and pressure terms at cell faces and cell center, respectively. The governing equations are first discretized by employing a second-order upwind differencing technique and are then solved by means of pressure-based finite volume approach. The convergence criterion is also presented for the validation of obtained results. The effects of wall profiles and nanoparticle concentration on the pertinent parameters including Nusselt number, pressure drop, performance evaluation criterion (PEC), and thermal and frictional irreversibilities are studied. This reveals that, in general, the triangular duct features superior heat transfer and inferior hydraulic characteristics in comparison with the sinusoidal duct. It is demonstrated that as long as the base fluid (water) is used the highest value of PEC corresponds to the straight duct. Yet, by introducing nanofluids the PEC values of the corrugated ducts exceed those of the straight duct. The analysis further shows that on the basis of the performance evaluation criterion, the sinusoidal duct appears to be a better choice in comparison with the triangular duct. However, the situation is reversed when thermodynamic irreversibilities are considered. It is argued that vortex formation in the two investigated wavy walls and shear layer developed in the triangular case are the essential physical reasons for the observed thermal, hydraulic and entropic behaviors.

1. Introduction

Solar heaters are widely employed in low temperature applications wherein temperature gradients are relatively small and hence heat transfer potentials are limited. Example can be found in domestic sector for cloth laundering and bathing goals. Solar heaters devices are potentially inexpensive due to the simplicity of their configuration and ease of manufacturing. Further, they can utilize both direct and diffuse solar radiation to heat up a fluid flow. Nonetheless, the low heat transfer coefficient and the resultant requirement of high surface area remains as a major challenge for the design of solar heaters. As a result, currently there is a strong demand for the development of effective techniques to achieve ultra-performance in heat transfer rate of these devices. This problem has already attracted attention of the researchers from heat transfer and solar energy engineering communities. They have reported the development of various passive techniques to improve the performance of different solar systems. Some of these passive techniques are addition of rough surfaces [1], inserting porous materials [2], mixing nanoparticles with the working fluid [3], adding swirl flow devices to enhance flow mixing [4] and implementing corrugated plates [5] for heat transfer improvement in solar systems. These have demonstrated varying levels of heat transfer enhancement with the expense of high pressure drop and sometimes higher levels of exergy destruction. As a result, the search for finding the optimal configurations and techniques of performance improvement remains ongoing.

It is now well demonstrated that nanofluids have substantial heat transfer capabilities due to their enhanced thermal conductivity in comparison with base fluids. This makes the use of nanofluids in thermal systems, including solar systems, most attractive.

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Nomenclature

a	amplitude of wave (m)
$\vec{a}$	nanoparticles acceleration ($\mathrm{m\,s^{-2}}$)
Be	Bejan number
C	specific heat capacity ($\mathrm{J\,kg^{-1}\,K^{-1}}$)
d_f	base liquid molecular size (nm)
d_p	size of particles (nm)
D_ω^+	positive segment of cross diffusion term
f_{drag}	drag function
G_k	creation of turbulent kinetic energy
G_ω	creation of ω
h	heat transfer factor ($\mathrm{W\,m^{-2}\,K^{-1}}$)
H	channel height (m)
L_w	wavelength of the wavy wall (m)
N_g	non-dimensional positional volumetric entropy generation rate (Eqs. (34) and (35))
Nu_{ave}	average Nusselt number (Eq. (29))
p	pressure (Pa)
Pr	Prandtl number
PEC	performance evaluation criteria (Eq. (31))
q''	heat flux ($\mathrm{W\,m^{-2}}$)
Re	Reynolds number (Eq. (28))
S_g'''	entropy generation rate ($\mathrm{W\,m^{-3}\,K^{-1}}$)
T	temperature (K)
$\underset{\rightarrow}{u}$, v	velocities in x and y axes ($\mathrm{m\,s^{-1}}$)
$V_{dr,s}$	drift velocity ($\mathrm{m\,s^{-1}}$)
x, y	rectangular axes (m)

Greek symbols

α	thermal diffusivity of liquid ($\mathrm{m^2\,s^{-1}}$)
λ	thermal conductivity ($\mathrm{W\,m^{-1}\,K^{-1}}$)
μ	dynamic viscosity ($\mathrm{kg\,m^{-1}\,s^{-1}}$)
$\mu_{t,m}$	turbulent molecular viscosity
κ	turbulent kinetic energy ($\mathrm{m^2\,s^{-2}}$)
ω	specific dissipation rate of turbulence kinetic energy ($\mathrm{m^2\,s^{-3}}$)
ν	kinematic viscosity ($\mathrm{m^2\,s^{-1}}$)
ρ	density of the fluid ($\mathrm{kg\,m^{-3}}$)
ΔP	pressure drop (Pa)
ΔP^*	dimensionless pressure drop (Eq. (30))
φ	solid volume fraction
σ_k	effective Prandtl number for turbulent kinetic
σ_ω	effective Prandtl number for rate of dissipation

Subscripts/superscripts

f	fluid
m	mixture
in	inlet
P	particle
w	wall
x	local value

Mahian et al. [6] have reviewed the usages of nanofluids in solar systems. They introduced high production expenses, instability, augmentations of pressure drop and erosion as the critical challenges before the wide use of nanofluids in solar systems. Michael and Iniyan [7] evaluated the efficacy of CuO-water nanofluid in a solar water heater. They concluded that the thermal efficiency of the solar water heater enhanced by about 6.3% through using nanofluid with solid volume fraction of 0.05%. Kabeel et al. [8] studied experimentally the thermal performance of a solar water heater with Aluminum Oxide-water nanofluid. They observed that the outlet water temperature in the solar water heater enhanced by about 5.46% through using nanofluid with solid volume fraction of 2%. Chaw Sint et al. [9] evaluated theoretically the performance of a Copper Oxide/water nanofluid in a solar collector used for water heating. They reported that the influence of nanoparticle size on the efficiency of the system is marginal. Ebrahiminia-Bajestan et al. [10] performed both experimental and numerical works for nanofluid heat transfer characteristics for applications in solar heat exchangers. They concluded that the convective heat transfer coefficient increases with an increase in the nanoparticle concentration and flow Reynolds number.

Some researchers have used other techniques to improve the thermal performance of solar heaters. Acir and Ata [11] improved the heat transfer in a new solar air heater by using circular type turbulators. They reported that the heat transfer and friction factor were improved by 416% and 511%, respectively in comparison with the conventional heater. Skullong et al. [12] used simultaneously corrugated groove and drilled-delta wing vortex generators inside a solar air heater. They concluded that simultaneous usage of the two techniques improved the thermal efficiency of the system between 37.7% and 46.3% larger than that obtained by the groove alone. Kumar et al. [13] investigated numerically the effects of roughened walls on the thermal performance of triangular duct solar air heater. They found that the heat transfer rate decreased through reducing the relative roughness, while it enhanced by increasing the relative roughness height on the internal surface of the duct. Sawhney et al. [14] used experimentally wavy delta winglets in a solar air heater. Their results indicated that heat transfer rate enhanced as the longitudinal pitch of the wavy delta winglets decreased. Bopche et al. [15] experimentally investigated the heat transfer and frictional specifications of a turbulator solar air heater duct with rough walls. They found that this duct improved the heat transfer and friction factor about 2.82 and 3.72 times, respectively comparing to the corresponding smooth duct.

A common feature of most of the cited literature is their sole focus on thermos-hydraulic aspects of the problem. However, the second law analysis is essential for each thermal system as the first law is only considered the conservation of energy and provides no data about destruction of the system exergy. Indeed, it has been shown that the second law analysis is a potent facility for the design, optimization and efficiency assessment of a wide range of thermal systems. Some researchers have conducted this analysis on different solar and thermal systems. Rashidi et al. [16] carried out the second law study on a solar heat exchanger with a porous insert in laminar regime. They concluded that the entropy generation rate enhanced by reducing the Darcy numbers. Rashidi and Abolfazli Esfahani [17] conducted the second law analysis for a single slope solar still in laminar regime. These authors found that the still with larger aspect ratio has larger values of irreversibility. In their study, the aspect ratio was measured as the ratio of the still length and the still height. Bahaidarah and Sahin [18] investigated the second law characteristics of the fluid flow in a wavy duct. They showed that the height ratio of the duct has a great effect on the distribution of the irreversibility. Rashidi et al. [19] carried out an entropy generation study on the flow through a wavy duct. Their results indicated that the viscous entropy generation enhances by increasing the wave amplitude of the wavy wall. To get more understanding on the said topic, readers are referred to the studies [19–29].

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