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Augmentation of natural convection heat transfer in triangular shape solar collector by utilizing water based nanofluids having a corrugated bottom wall ☆

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ABSTRACT

Nanofluids have been introduced for the enhancement in the heat transfer phenomena in the last few years. In this paper a corrugated bottom triangular solar collector has been studied introducing water based nanofluids inside the enclosure. The corrugated bottom is kept at a constant high temperature whereas the side walls of the triangular enclosure are kept at a low temperature. Three types of nanoparticles are taken into consideration: Cu, Al_2O_3, and TiO_2. The effect of solid volume fraction (ϕ) of the nanoparticle of nanofluid has been studied numerically by Galerkin weighted residual method of finite element for a wide range of Grashof number (Gr) 10^4–10^6. Calculations are carried out for $\phi = 0, 0.05, 0.08$, and 0.1 and dimensionless time, $\tau = 0.1, 0.5$, and 1. For the specified conditions streamlines and isotherm contours are obtained and detailed results of the interaction between different parameters are studied using overall Nusselt number. It has been found that both Grashof number and solid volume fraction have significant influence on streamlines and isotherms in the enclosure. It is also found that heat transfer increased by 24.28% from the heated surface as volume fraction ϕ increases from 0% to 10% at $Gr = 10^6$ and $\tau = 1$ for copper water nanofluid.

1. Introduction

A prodigious importance has been given to the natural convection heat transfer phenomena as it has a very wide range of application in heat exchangers, solar collector, electronics cooling, desalination process and so on [1–4]. However the conventional fluid used such as air, water, ethylene glycol etc. for the natural convection has a very low thermal conductivity and cannot fulfill the demand of high thermal conductivity of fluid which is a desired property of fluid nowadays. To enhance the thermal conductivity in addition to the heat transfer rate for the last few years a new advanced technique has been deployed by mixing nanosized (less than 100 nm) particles such as metal, metal oxide and carbon materials etc. in the base fluid. And this fluid is called nanofluid which has a very good characteristic of thermal conductivity which can meet the challenge of higher heat transfer rate in modern engineering application. Basically nanosized particle suspension in the base fluid enhances the heat transfer rate but still there are controversies over whether heat transfer is increased due to the nanoparticle or not. Numerous research works have been carried out on this regard which show both positive and negative results.

Khanafer et al. [5] have investigated numerically the effect of nanofluid assuming that the nanofluid is in single phase and reported that heat transfer rate has been improved due to the increase of nanoparticle. Similar work has been carried out by Ozotop and Abu-Nada [6], Tiwari and Das [7], Aminossadati and Ghasemi [8], Ghasemi and Aminossadati [9] and they concluded that heat transfer rate increases with an increase of the nanoparticle. Kim et al. [10] found that with an increase of density and heat capacity of nanoparticle thermal conductivity and the shape factor decrease. Xuan and Li [11] experimentally witnessed that copper water based nanofluid enhances the heat transfer rate.

Hwang et al. [12] investigated Benard convection and found the adverse effect of using nanofluid. Santra et al. [13] also reported that nanoparticle decreases the heat transfer rate. Details review on the nanofluid can be found in Wang and Mujumdar [14]. Shape of the enclosure plays a vital role in convection, though the shape depends on practical application. Different types of enclosure filled with nanofluid are studied in recent years. Most of them are rectangular, square, triangular and trapezoidal enclosures. Square and rectangular shape enclosures are mostly studied. Related studies are presented in these literatures [15–28].

Triangular cavities are not studied in a great extent yet. Zi-Tao et al. [29] inspected the effect of nanofluids in a bottom heated isosceles triangular enclosure in transient buoyancy driven condition. Rahman et al. [30,31] studied the convection which was laminar mixed in an

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Nomenclature

c_p	specific heat (J kg^{-1} k^{-1})
g	gravitational acceleration (ms^{-2})
Gr	Grashof number
H	enclosure height (m)
k	thermal conductivity (Wm^{-1} k^{-1})
L	length of the enclosure (m)
Nu	Nusselt number
p	dimensional pressure (kg m^{-1} s^{-2})
P	dimensionless pressure
Pr	Prandtl number
T	fluid temperature (K)
t	dimensional time (s)
u	horizontal velocity component (ms^{-1})
U	dimensionless horizontal velocity component
v	vertical velocity component (ms^{-1})
V	dimensionless vertical velocity component
x	horizontal coordinate (m)
X	dimensionless horizontal coordinate
y	vertical coordinate (m)
Y	dimensionless vertical coordinate

Greek symbols

α	thermal diffusivity (m^2 s^{-1})
β	thermal expansion coefficient (K^{-1})
ϕ	solid volume fraction
μ	dynamic viscosity (kg m^{-1} s^{-1})
ν	kinematic viscosity (m^2 s^{-1})
τ	dimensionless time
θ	non-dimensional temperature
ρ	density (kg m^{-3})
ψ	stream function
λ	wave length
Γ	general dependent variable

Subscripts

av	overall
h	hot
c	cold
f	fluid
nf	nanofluid
s	solid nanoparticle
max	maximum
min	minimum

inclined triangular enclosure filled with water based Cu nanofluid and found that the angle of inclination plays a significant role along with the nanofluid in the heat transfer. Billah et al. [32] studied unsteady buoyancy-driven heat transfer enhancement of nanofluids in an inclined triangular enclosure. Corrugated bottom walls are also available in different physical phenomena and play a significant role in the heat transfer. Rahman et al. [33] show the effect of corrugated bottom on a triangular cavity for a double diffusive buoyancy induced flow.

In the previous work triangular enclosure gets a very little attention along with the corrugated bottom surface. In this paper a numerical study has been performed for a triangular shape solar collector with a corrugated bottom and the enclosure is filled with the copper–water nanofluid. As in solar thermal collector higher heat transfer rate is required, introducing nanofluid can be a possible solution of this problem. Different nanofluids such as TiO_2–water, Al_2O_3–water, Cu–water etc. are available nowadays. This paper also shows that Cu–water nanofluid is the best nanofluid for the augmentation of heat transfer due to its thermophysical properties. Enhancements of heat transfer with the increase of solid volume fraction are also shown.

2. Problem formulation

2.1. Physical model

The detail of the physical model is presented in Fig. 1(a) along with its specified co-ordinate system and boundary conditions. In this model a triangular type solar collector with a corrugated bottom is shown in Fig. 1(b). The enclosure is filled with the nanofluids which are Cu–water, Al_2O_3–water and TiO_2–water. The height of the cavity is H and the length of the cavity is L. The effect of the gravity is shown in the negative Y axis. Here the cavity is formed by the two inclined glass covers where the horizontal base plate is corrugated and acts as an absorber plate. The absorber plate has a constant higher temperature than the inclined glass cover.

2.2. Thermophysical property of nanofluid

For this numerical study Cu, Al_2O_3 and TiO_2 are taken as the nanoparticle and water is taken as the base fluid. Different experiments have been carried out by different researchers. Different nanofluids such as TiO_2–water, Al_2O_3–water, and Cu–water are recently available. The data used for the numerical simulation [23] is given in Table 1.

2.3. Mathematical modeling

The governing equations which define the system behavior are conservation of mass, energy and momentum. The thermophysical properties of the nanofluid are presumed to be constant excluding the density variation in the buoyancy force, which is established on the Boussinesq approximation. Cu–water, Al_2O_3–water and TiO_2–water nanofluids filled the free space of the enclosure and which are modeled as a Newtonian fluid. The flow is assumed to be unsteady, laminar and incompressible. Thermal equilibrium between the base fluid and nanoparticles is considered, and no slip arises between the two media. In the light of these suppositions stated above, the continuity, momentum and energy equations in two-dimensional form can be written as [15]:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho_{nf}}\frac{\partial p}{\partial x}+\frac{\mu_{nf}}{\rho_{nf}}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \tag{2}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho_{nf}}\frac{\partial p}{\partial y}+\frac{\mu_{nf}}{\rho_{nf}}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+\frac{(\rho\beta)_{nf}}{\rho_{nf}}g(T-T_c) \tag{3}$$

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha_{nf}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \tag{4}$$

where, the effective density ρ_{nf} of the nanofluid is described by

$$\rho_{nf}=(1-\phi)\rho_f+\phi\rho_s \tag{5}$$

and ϕ is the solid volume fraction of nanoparticles. Furthermore, the thermal diffusivity α_{nf} of the nanofluid is specified by:

$$\alpha_{nf}=\frac{k_{nf}}{\left(\rho c_p\right)_{nf}}. \tag{6}$$