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Effect of solid volume fraction and tilt angle in a quarter circular solar thermal collectors filled with CNT–water nanofluid ☆

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ABSTRACT

Solar thermal collectors have significant importance due to its wide use in solar thermal technology. Augmentation of heat transfer is a key challenge for solar thermal technology. A quarter circular solar thermal collectors is investigated throughout the paper introducing carbon nanotube (CNT)–water nanofluid in the cavity. Tilt angle of this type of collector plays a vital role and heat transfer can be maximized for a particular tilt angle and solid volume fraction of the nanofluid. Galerkin weighted residual of FEM has been applied for the numerical solution of the problem. Grid independency test and code validation have been assessed for the accuracy of numerical solution. In this paper a wide range of solid volume fraction ($\delta = 0$ to $\delta = 0.12$) and tilt angle ($\phi = 0$ to $\phi = 60°$) has been investigated for Rayleigh number ($Ra = 10^5$–10^8) with varying dimensionless times. It has been found that both solid volume fraction and tilt angle play vital roles for the augmentation of heat transfer and a good heat transfer characteristic can be obtained by compromising between these two parameters. The results are shown using streamline, isotherm contour and related graph and chart.

1. Introduction

For the past few decades solar thermal collector has been given a vigilant attention due to its importance in using solar energy which is a major source of renewable energy. Solar thermal collector has a wide range of application as it is used in solar water heating system, solar cooling system, solar dryer, solar desalination, solar home system and so on [1–10]. Different types of solar thermal collector are available commercially nowadays and different studies have been carried out to understand the heat transfer which is the major aspects of solar thermal technology. Basically convection and radiation heat transfer are responsible for the heat transfer in solar thermal technology.

Natural convection heat transfer has been studied to a great extent which has a certain limitation of using conventional fluid such as air and water for the heat transferring medium. To augment the heat transfer use of nanofluid is justified in recent years [11–15]. Solid suspension of metal, metal oxide and carbon based material which have a very high thermal conductivity are suspended in the base fluid with a view to increasing the thermal conductivity of the base fluid. Here base fluid works as the carrier medium. Various nanofluids are used to enhance heat transfer rate in practical applications. Among them CuO–water, TiO_2–water, and Al_2O_3–water nanofluid are very common and have been used commercially. Besides conventional nanofluids, AgO-water, diamond-water and nanodiamon-mineral oil nanofluids have gained much attention. However, CuO-water nanofluid has shown a tremendous potential to be the best of the lot due to its better performance and availability. Related literatures can be found in [16–20]. In recent years carbon nanotube (CNT), and graphene are being studied to investigate the heat transfer having the suspension of CNT and graphene in the base fluid. Godsona et al. [21] reviewed the enhancement of heat transfer using different nanofluids and they reported that nanofluid has a great potential for further research in heat transfer enhancement. Kumaresan et al. [22] studied convective heat transfer characteristics of CNT nanofluids in a tubular heat exchanger of various lengths for energy efficient cooling/heating system. Kamali and Binesh [23] numerically investigated heat transfer enhancement using carbon nanotube-based non-Newtonian nanofluids. Xu et al. [24] studied the energy dissipation behavior of multiwalled carbon nanotube (MWCNT) based nanofluid and reported the optimum length of the carbon nanotube. Ettefaghi et al. [25] investigated on the thermal properties of engine oil (SAE 20) based MWCNT nanofluid and reported that 0.1 wt.% improved

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Nomenclature

c_p	specific heat (J kg^{-1} k^{-1})
g	gravitational acceleration (ms^{-2})
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
Ra	Rayleigh number
S_δ	source term in Eq. (1)
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})
δ	solid volume fraction
Γ_φ	diffusion term in Eq. (1)
ϕ	tilt angle
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
Γ	general dependent variable

Subscripts

av	average
h	heat source
c	cold
f	fluid
nf	nanofluid
s	solid nanoparticle
max	maximum
min	minimum

thermal conductivity of 13.2% and flash point 6.7%. Halelfadl et al. [26] recently studied the change of viscosity on the influence of temperature and concentration for carbon naotube water based nanofluids. Kumaresan et al. [27] studied the convective heat transfer characteristic of a secondary refrigerant based CNT nanofluid in a tubular heat exchanger and have reported that the effect of friction factor is very negligible for the 0.15 vol.% of the nanofluid. Harish et al. [28] studied the reason behind the enhancement of thermal conductivity of ethylene glycol based single walled carbon nanotube inclusions and observed that tri-dimensional structure of the CNT is responsible for this. Yousefi et al. [29] experimented on MWCNT–water nanofluid on the efficiency of a flat plate solar collector and reported that an increase of the weight fraction from 0.2 to 0.4% increases the efficiency significantly. Javadi et al. [30] investigated on the performance improvement of solar collector by using different nanofluids and reported that thermal conductivity has a significant effect on improving efficiency of the solar absorption collector. They also reported that there is a lack of study on the transmittance and optical property effect on efficiency analysis and showed economical consideration as a big challenge. The shape of the enclosure depends on the practical case study and a quarter circular shapes have been presented in this paper which is quite similar to a solar collector. Convection heat transfer has been analyzed for this geometry. Normally in the study of natural or forced convection square, rectangular, trapezoidal shape enclosure has been given enormous importance and a lot of numerical simulation and experimental work are available. Introducing nanofluid in this kind of enclosure also has been extensively studied. Triangular shape enclosure gets a little attention on the study of convection heat transfer though it has some very practical case. Circular shape enclosure is quite a new type of enclosure in the field of numerical and experimental heat transfer studies [31–34]. Enclosures of this sort have a mighty chance of being used in the solar thermal collectors, duct designs, heat exchangers and so on. Introduction of nanofluid to such enclosure is an idea that has never been explored before the present work. This novel idea has a very high applicability in solar collector modeling, design, analysis and optimization process.

The effect of solid volume fraction plays a very vital role in heat transfer augmentation. It is expected that an increment in the solid volume fraction of solid particles in the base fluids should enhance the heat transfer rate due to the higher thermal conductivity of the resulting nanofluids [35–37]. Tilt angle also plays a significant role. Effect of tilt angle of the enclosure is analyzed in the paper keeping in mind that the position of the sun changes with time. For both focusing and non-focusing type of collector this angle becomes one of the major parameters which govern the heat transfer rate. Handoyo and Djatmiko Ichsani [38] studied the optimal tilt angle for a solar collector and found that a tilt angle about 40° shows the best result. Jafarkazemi and Saadabadi [39] also studied the tilt angle for solar collector in Abu Dhabi, UAE and reported the optimal tilt angle as 22° which is very much close to the latitude of UAE. The authors also proposed that the tilt angle of the solar collector must be changed twice in a year as the optimum tilt angles vary significantly (−9 to 52°) with the change of the month. Bakirci [40] investigated the tilt angle of the solar collector for a case study of Turkey and reported 65° as an average tilt angle for Turkey. Yadav and Chandel [41] reviewed the tilt angle for maximizing solar irradiation and reported that this tilt angle varies from both time to time and location to location as solar irradiation is different on different parts of the world and it is also different on different months.

From the abovementioned issues it has been clear that both the use of nanofluid in solar collector and the varying tilt angles are justified. And nowadays different studies are being carried out introducing different nanofluids inside the solar thermal collector. The aim of this paper is to propose a novel model for solar thermal collector to maximize the heat transfer rate to the solar thermal collector. The effect of solid volume fraction of the CNT–water nanofluid and tilt angle has been shown throughout the paper as it has been found from the previous literature that these two parameters can augment the heat accumulation to the thermal energy collector surface. Moreover the heat transfer in a quarter circular shape geometry has been studied which is very rare in the heat transfer analysis though it has some practical application. The results are presented in the streamline, isotherm contour and related graphical analysis has been done. Since the enclosure introduced in the paper can have an inordinate use in making solar collectors, the analysis presented can help to promote the use of renewable energy especially solar energy.