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Enhancement of heat transfer by nanofluids and orientations of the equilateral triangular obstacle

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ABSTRACT

This paper simulates the forced convective heat transfer of Al_2O_3–water nanofluid over an equilateral triangular obstacle. Computations are performed for different orientations of the triangular obstacle (side, vertex and diagonal facing flows). The ranges of Reynolds number (Re) and solid volume fractions of nanoparticles (φ) are $1 \leqslant Re \leqslant 200$ and $0 \leqslant \varphi \leqslant 0.05$, respectively. Two-dimensional unsteady conservation laws of mass, momentum, and energy equations have been solved using finite volume method. The effects of Reynolds number, solid volume fractions of nanoparticles and different orientations of the triangular obstacle on the flow and heat transfer characteristics are investigated in detail. Detailed results are presented for wake length, streamline, vorticity, temperature contours and time averaged Nusselt number. Finally, the value of time averaged Nusselt number has been investigated in three equations using least square method which the effects of solid volume fraction of nanoparticles and Reynolds numbers are taken into account. The calculated results revealed that the maximum effect of nanoparticles on heat transfer rate augmentation is for the side facing flow and the minimum is related to the vertex facing flow. Also, the required Reynolds numbers for wake formation decrease with increase in solid volume fraction.

1. Introduction

The study of the flow and heat transfer past a bluff body has been a subject of interest for the past decades due to their different practical applications such as flow meters, agricultural products, cooling of electronic components, cooling towers, oil and gas pipelines, sedimentation, melting, combustion, vaporization and heat exchangers [1]. In most of above applications, enhancing the heat transfer rate has become a critical challenge for researchers. The previous studies show that using triangular obstacle increases the heat transfer compared with that in other obstacles [2]. Therefore, this special body is selected to investigate the problems that their goal is heat transfer enhancement. As we know, the heat transfer capacity of the most conventional fluids is not suitable for many actual processes due to the low thermal conductivity of such fluids. Adding nanoparticle to the base fluid is a new way of improving the heat transfer in theses fluids [3–6]. A review of previous published works in this field is necessary to classify them.

Different aspects of the heat transfer and flow over bluff bodies have been studied in last two decades [7–13]. For example, Srikanth et al. [14] investigated the fluid flow and heat transfer across an equilateral triangular obstacle placed in a horizontal channel. They found that the maximum crowding of the temperature are for the bottom and top surfaces of the triangular obstacle. The influence of power-law index on the fluid flow and heat transfer over a triangular obstacle is reported by Prhashanna et al. [15]. Their results revealed that the thickness of thermal boundary increases with decrease in Prandtl number. Experimental investigation for forced convection heat transfer past a triangular obstacle in cross flow is presented by Ali et al. [2]. A mixed convective flow and heat transfer characteristic over a square obstacle for different angles of incidence is studied by Dulhani et al. [1]. Their results indicated that the rate of heat transfer from the obstacle increases with increase in angle of incidence. There are some researches that subjected obstacle has a different cross sections. Fluid dynamics and forced convective heat transfer over a semi-circular obstacle have been studied numerically by Bhinder et al. [16]. They observed that the streamline curvature increases by increase in angle of incidence.

The flow and heat transfer past a confined square obstacle studied by Dhiman et al. [17]. They employed both constant temperature and constant heat flux boundary conditions for the obstacle. In previous literatures, the clear fluid without nano particles has been assessed. Also, some researches studied the effects of nanofluid on heat transfer rate. For example, flow-field and heat transfer of a copper–water nanofluid around a circular obstacle is studied numerically by Valipour and Zare Ghadi [18]. Their results revealed that the magnitude of the maximum negative velocity in recirculation

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Nomenclature

A	surface of obstacle (m^2)
B_c	Boltzmann constant (–)
C	specific heat (J/kg K)
C_D	drag coefficient ($=F_D/0.5\rho U^2_\infty S$) (–)
d_f	molecular diameter of base fluid (nm)
dp	nanoparticle diameter (nm)
h	heat transfer coefficient (W/m^2 K)
k	thermal conductivity of fluid (W/m K)
l_{BF}	mean free path of water (–)
L_R	wake length (m)
Nu	Nusselt number (–), $= h\,D/k$
$\overline{Nu}$	surface-averaged Nusselt number (–)
$\langle\overline{Nu}\rangle$	time-averaged Nusselt number (–)
p	pressure (Pa)
Pe	Peclet number, ($=Re \times Pr$) (–)
Pr	Prandtl number, ($=\upsilon_f/\alpha$) (–)
Re	flow Reynolds number ($=\rho_f U\infty S/\mu_f$) (–)
S	obstacle size (m)
St	Strouhal number (–), $=f\,S/U_\infty$
t	time (s)
t_p	period of time integration (s)
T	temperature (K)
x,y	rectangular coordinates components (m)
u, v	velocity component in x and y directions (ms^{-1})

Subscripts

ave	average (–)
B	Brownian (–)
eff	effective (–)
f	base fluid (–)
p	particle-pressure (–)
s	solid (–)
v	viscous (–)
w	wall (–)

Greek symbols

∞	free stream (–)
φ	volume fraction (–)
μ	fluid dynamic viscosity (kg m^{-1} s^{-1})
υ	fluid kinematic viscosity ($=\mu/\rho$) (m^2 s^{-1})
ρ	fluid density (kg m^{-3})
α	thermal diffusivity of fluid (m^2 s^{-1})
δ	distance between particles (nm)

zone increases with increase in solid volume fraction and Reynolds number. Nanofluid flow and heat transfer over a square obstacle has been investigated by Etminan-Farooji et al. [19]. It was found that the heat transfer rate decreases with increase in nanoparticle diameter. Also, Valipour et al. [20] investigated the fluid flow and forced convective heat transfer around a square obstacle utilizing AL_2O_3–H_2O nanofluid at low Reynolds numbers. Their results revealed that the pressure coefficient increases by adding nanoparticles to the base fluid on sides where pressure gradient is inverse.

Mixed convective flow and heat transfer of nanofluid past a circular obstacle has been studied by Sarkar et al. [21]. Their results indicated that for both aiding and opposing buoyant fields, Strouhal number increases with increase in solid volume fraction.

In another study, the above mentioned topic is repeated for square obstacle in vertical upward flow by Sarkar et al. [22]. They found that the averaged Nusselt number is higher for copper–water nanofluid, as compared to alumina–water nanofluid at a fixed solid volume fraction. Recently, a numerical study on MHD natural convection for alumina–water nanofluid within the circular cylindrical enclosure with an inner triangular has been performed by Sheikholeslami et al. [23].

Our literature review shows that this subject of study has received many attentions due to its importance in different applications. Most of these researches are related to circular and square obstacles and triangular obstacle did not get much attention. The previous results show that the use of triangular obstacle increases the heat transfer compared with that in the circular and square obstacles. Therefore, we have made an attempt to improve the heat transfer by nanofluids and orientations of the triangular obstacle. However, this is for the first time that the nanofluid past a triangular obstacle is investigated. Moreover, detailed results discuss for three cases of side, vertex and diagonal facing flows.

2. Mathematical formulation

2.1. Problem statement

The fluid flow past an equilateral triangular obstacle with a uniform velocity (U_∞) and a temperature (T_∞) is considered. The obstacle has a constant temperature (T_w) that is higher than the flow temperature (T_∞). The schematic of the computational domain is available in Fig. 1. As shown in this figure, the triangular obstacle is placed against the flow by vertical side (side facing flow), apex (vertex facing flow) and diagonal side (diagonal facing flow).

Also, following assumptions are considered:

- The flow is assumed to be unsteady, two-dimensional and laminar.
- The width and inflow length of the computational domain were set to 60S and 20S, respectively (for minimizing the effects of outer boundary). Also, S is the side of the triangular obstacle.
- Ultrafine solid particles are used which the particle sizes are less than 100 nm.

2.2. Governing equation

Single-phase model is applied for nanofluid modeling in the cases that the dissipation is neglected [24]. Under previous assumptions, the governing equations for two dimensional unsteady state flow are as below:

Continuity equation:

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

Momentum equations in x and y directions:

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

$$\rho_{eff}\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{\partial p}{\partial y}+\mu_{eff}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right) \tag{3}$$

Energy equation:

$$\rho_{eff}C_{eff}\left(\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=k_{eff}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \tag{4}$$

In above equations, ρ_{eff}, μ_{eff}, C_{eff} and k_{eff} are effective density, viscosity, specific heat, and conductivity, respectively.