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Influence of inclination angle of magnetic field on mixed convection of nanofluid flow over a backward facing step and entropy generation

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ABSTRACT

In this paper, numerical study of laminar forced convection of nanofluid flow over a backward facing step for different inclination angles of magnetic field is performed. The bottom wall of the channel downstream of the step is isothermally heated and the other walls of the channel are assumed to be adiabatic. Finite element method was used to solve the governing equations. The influence of the Reynolds number (between 20 and 200), Hartmann number (between 0 and 50) and solid volume fraction of the nanoparticle (between 0 and 0.04) on the fluid flow and heat transfer are numerically investigated for different orientation angles of the magnetic field. It is observed the averaged heat transfer increases as the Reynolds number increases and this effect is more pronounced with higher values of inclination angle of the magnetic field. As the value of the Hartmann number decreases for horizontally aligned magnetic field and volume fraction of the nanoparticles increases averaged and local enhancement of heat transfer are observed. For the inclined and vertical magnetic field, suppression of the recirculation zone behind the step is observed as the value of Ha increases which results in heat transfer enhancement. The total entropy generation ratio increases with increasing values of Reynolds number, solid volume fraction of nanoparticles and decreasing values of Hartmann number for horizontally oriented magnetic field.

1. Introduction

Due to its importance in many engineering applications such as flow around buildings, electronic devices, combustors, airfoils and collectors of power systems a vast amount of literature is devoted to the studies related to backward/forward facing step flow [1–7]. Laminar mixed convection over vertical, horizontal and inclined backward- and forward-facing steps was investigated by Abu-Mulaweh [8]. The effects of Reynolds number, Prandtl number and expansion ratio on the fluid flow and thermal characteristics are presented. The linear stability of backward-facing step flow for Reynolds numbers between 450 and 1050 were studied by Barkley et al. [9]. Experimental studies have been conducted for the flow over a backward facing or forward facing step [10–12]. Armaly et al. [12] have reported the velocity distribution and reattachment length using Laser-Doppler measurement for flow downstream of a backward facing step in a two-dimensional channel. Their results showed separation length varies with Reynolds number and various flow regimes are characterized by variations of the separation length. Sherry et al. [13] have made an experimental investigation for the recirculation zone formed downstream of a forward facing step immersed in a turbulent boundary layer. In their study, the mechanisms effecting the reattachment distance is discussed.

In heat transfer applications, nano-sized particles (average particle size less than 100 nm) are added in the base fluid such as water or ethylene glycol to obtain better thermal properties compared to base flow. Nanofluids improve the heat transfer characteristics with little pressure drop as compared to base fluids [14–18]. The study of nanofluids for the backward facing step problem has been conducted by many researchers [19–22]. Abu-Nada [21] numerically investigated the heat transfer characteristics over a backward facing step using different nanofluid types. He observed that the nanoparticles with low thermal conductivity have better heat transfer characteristic within the recirculation zone and as the volume fraction of nanoparticles increases averaged heat transfer increases. Laminar mixed convection for a three dimensional horizontal micro-scale backward facing step with nanofluids was numerically investigated by Kherbeet et al. [23]. The working fluid was EG-SiO2 nanofluid with 25 nm nanoparticle size, and 0.04

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Nomenclature

$\mathbf{B}_0$	magnetic field strength
Gr	Grashof number, $\frac{g\beta_f(T_h-T_c)H^3}{\nu_f^2}$
h	local heat transfer coefficient (W/m^2 K)
Ha	Hartmann number, $B_0 H\sqrt{\frac{\sigma_{nf}}{\rho_{nf}\nu_f}}$
k	thermal conductivity (W/m K)
H	step size (m)
n	unit normal vector
Nu_x	local Nusselt number
Nu_m	averaged Nusselt number
p	pressure (Pa)
P	non-dimensional pressure
Pr	Prandtl number $\frac{\nu_f}{\alpha_f}$
Re	Reynolds number $\frac{u_0 H}{\nu_f}$
S_{nd}	nondimensional entropy generation
S^*	entropy generation ratio
T	temperature (K)
u, v	x–y velocity components (m/s)
U, V	dimensionless velocity components
x, y	Cartesian coordinates (m)
X, Y	dimensionless coordinates

Greek symbols

α	thermal diffusivity (m^2/s)
β	expansion coefficient (1/K)
γ	inclination angle
θ	non-dimensional temperature $\frac{T-T_c}{T_h-T_c}$
ν	kinematic viscosity (m^2/s)
ρ	density of the fluid (kg/m^3)
σ	electrical conductivity (S/m)
ϕ	solid volume fraction
χ	irreversibility factor

Subscripts

c	cold
h	hot
m	average
nd	nondimensional
nf	nanofluid
p	solid particle

volume fraction and the effect of step height was investigated. Aswadi et al. [22] numerically studied the laminar forced convection flow of nanofluids over a backward facing step using finite volume method with different types of nanofluids and solid volume fractions. They observed that nanofluid with SiO2 nanoparticles has highest velocity among other nanofluids types while nanofluid with Au nanoparticles has the lowest velocity. Other related studies can be found in references [24,25].

Magnetic field effect of electrically conducting fluid (MHD) on the heat transfer and fluid flow can be encountered in many engineering applications such as purification of molten metals, coolers of nuclear reactors, MEMs and many systems [26]. Convection heat transfer can be controlled by using an external magnetic field as studied by many researchers [27–32]. Oztop et al. [33] studied the mixed convection with a magnetic field in a top sided lid-driven cavity heated by a corner heater. They showed that heat transfer decreases with increasing the Hartmann number and magnetic field plays an important role to control heat transfer and fluid flow. Sheikholeslami and Ganji [34] numerically studied the effects of an external magnetic field on ferrofluid flow and heat transfer in a semi-annulus enclosure with sinusoidal hot wall by using Control Volume based Finite Element Method. They showed that for low Rayleigh number, as the Hartmann number increases and Magnetic number decreases, heat transfer enhances while opposite trend was observed for high Rayleigh number. Abbassi and Nassrallah [35] numerically studied the MHD laminar flow of a viscous incompressible electrically conducting fluid for a backward-facing step geometry for Reynolds number less than 380 and for a range of Stuart number and Prandtl numbers. They observed thatthe heat transfer is significantly augmented with the magnetic field for high Prandtl number case.

MHD with nanofluids offers a good possibility to control the convection as it has been studied by many researchers [36–46]. Mahmoudi et al. [36] numerically simulated the MHD natural convection in a triangular enclosure filled with nanofluid. The impact of the Rayleigh number, Hartmann number and nanoparticle volume fraction on the heat transfer and fluid flow are numerically investigated. Ghasemi et al. [37] studied the MHD natural convection in an enclosure filled with water - Al_2O_3 nanofluid. Their results showed that an enhancement or deterioration of the heat transfer may be obtained with an increase of the nanoparticle volume fraction depending on the value of Hartmann and Rayleigh numbers. Sheikholeslami et al. [41] studied the magnetic field effect on natural convection heat transfer in cavity filled with CuO-water nanofluid using Lattice Boltzmann method. The effect of Brownian motion on the effective thermal conductivity was considered. Hatami et al. [42] analytically investigated the MHD Jeffery-Hamel nanofluid flow in non-parallel walls by using different base fluids and nanoparticles. They observed that the skin friction coefficient is an increasing function of nanoparticle volume fraction but a decreasing function of Hartmann number.

Second law analysis with entropy generation is important for system performance and several studies have been conducted to investigate the entropy generation within cavities [47–51]. The available energy destruction can be quantified by the measurement of irreversibly during a process which is called entropy generation rate. The performance of the system can be optimized by using the entropy generation minimization concept. The fundamentals of entropy generation was presented by [52]. A review of entropy generation in natural and mixed convection for energy systems may be found in [53]. Some of the relevant entropy generation studies with nanofluids or MHD effect can be found in Refs. [54–57].

Based on the literature survey above and to the best of authors' knowledge, laminar forced convection of nanofluid flow over a backward facing step under the influence of an inclined magnetic field has never been studied in the literature even its importance in many engineering applications is apparent as outlined above. The present numerical study aims at investigating the effects of Reynolds number, Hartmann number, orientation angle of the magnetic field and solid volume fraction of the nanofluid on the fluid flow and heat transfer in a backward facing step geometry. Second law analysis of the system for various parameters is also performed.

2. Mathematical formulation

A schematic description of the physical problem of channel with a backward facing step is depicted in Fig. 1. The step size of

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