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Unsteady hydromagnetic mixed convection nanofluid flows through an L-shaped channel with a porous inner layer and heat-generating components

Victor M. Job, Sreedhara Rao Gunakala *

Department of Mathematics and Statistics, The University of the West Indies, St. Augustine, Trinidad and Tobago

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ABSTRACT

In this paper, we consider the MHD mixed convection flows of copper (Cu)-water and silver (Ag)-water nanofluids through an L-shaped channel with a porous inner layer. Four heat-generating components are located on the channel wall opposite to the porous layer. A numerical solution of the governing equations with the given initial and boundary conditions is obtained using the polynomial pressure projection stabilized (PPPS) mixed finite element method. The effects of time, Darcy number, porosity, Reynolds number, Grashof number, Hartmann number, magnetic field orientation and solid volume fraction on the convective heat transfer within the channel are investigated.

1. Introduction

The flow of fluids in channels with heated obstacles is the most widely used model for the study of electronic cooling. As the design of modern electronic devices become more refined and compact, the associated increase in surface heat flux raises concerns about their reliability and durability. In this view, a significant amount of research has been conducted towards the development of more effective cooling techniques for electronic systems [1,2]. The mixed convective cooling of an electronic circuit board with heat generating rectangular blocks was investigated by Kim et al. [3]. In their investigation, cross-streamwise periodic boundary conditions were used to model the temperature on the surface of the board. It was observed that the fluid temperature and heat transfer rate on the circuit board decrease with increased Reynolds number. The removal of heat from a series of heat generating components via unsteady mixed convection in a shallow enclosure was studied by Bhoite et al. [4]. The results showed that the temperature at the surface of each component decreases with increased Reynolds number when the Grashof number is less than 5×10^5. For higher Grashof numbers, the temperature increases at low Reynolds number, then decreases as the Reynolds number becomes large.

Although many studies have been done on the mixed convective cooling of heated obstacles in channels, there are very few existing studies on the cooling of heated obstacles using nanofluids. Among these is the work of Saedodin et al. [5], which considered the mixed convective heat transfer performance of Al_2O_3-water nanofluids in an inclined ventilated cavity containing isothermally heated blocks. The results showed that the heat transfer on the surface of the heated blocks is enhanced by increased Reynolds number and nanoparticle concentration. Esfe et al. [6] investigated the mixed convective flow of an Al_2O_3-water nanofluid in a ventilated square cavity that contains two heated blocks. This study revealed that heat transfer within this enclosure is enhanced by increased nanoparticle concentration, Richardson number and Reynolds number. The mixed convective heat transfer in a nanofluid-filled horizontal channel with two surface-mounted isothermally heated obstacles was studied by Esfe et al. [7]. It was observed that the heat transfer rate increases with an increase in Reynolds number, Rayleigh number and nanoparticle volume fraction. However, an increase in the Richardson number and the size of the obstacles causes a reduction in the average Nusselt number at the surface of the obstacles. Job and Gunakala [8] examined MHD mixed convection flows of SWCNT-water and Au-water nanofluids through a grooved channel that contains two heat-generating solid cylinders. The authors found that heat transfer is enhanced by an increase in Reynolds number and Hartmann number. When the nanoparticle concentration increases, the heat transfer performance is reduced for low Reynolds number and increased for high Reynolds number. It was also observed that heat transfer

* Corresponding author.
E-mail address: sreedhara.rao@sta.uwi.edu (S.R. Gunakala).

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Nomenclature

A_d	area of components, m^2
c_F	form drag coefficient
Da	Darcy number
c_p	specific heat capacity, $J\,kg^{-1}\,K^{-1}$
Gr	Grashof number
h	channel width, m
h_1	porous layer thickness, m
Ha	Hartmann number
K	permeability, m^2
Nu	Nusselt number
p	pressure, $kg\,m^{-1}\,s^{-2}$
Pr	Prandtl number
q	heat flux density, $W\,m^{-3}$
Q	heat generation parameter
Re	Reynolds number
t	time, s
T	temperature, K
u, v	velocity components, ms^{-1}
U	inlet velocity, ms^{-1}
x, y	space coordinates, m
β	coefficient of thermal expansion, K^{-1}
ε	porosity
θ	magnetic field inclination angle, K^{-1}
κ	thermal conductivity, $W\,m^{-1}\,K^{-1}$
μ	viscosity, $kg\,m^{-1}\,s^{-1}$
ρ	density, $kg\,m^{-3}$
σ	electrical conductivity, $\Omega^{-1}\,m^{-1}$
ϕ	solid volume fraction

Subscripts

c	components
ck	component k ($k = 1,\ 2,\ 3,\ 4$)
eff	effective
f	fluid
m	nanofluid in porous layer
nf	nanofluid in free-fluid region
ps	porous solid
s	solid
av	average

performance is greater for the Au-water nanofluid at low Reynolds number, and greater for the SWCNT-water nanofluid when the Reynolds number is high.

The study of convective fluid flows at the interface between a porous medium and a free fluid is useful in a wide range of engineering applications such as micro-porous heat exchangers and the cooling of electronic devices [9,10]. Consequently, a substantial amount of research has been conducted on convective heat transfer through channels containing porous media. A numerical and experimental study was conducted by Boomsma [11] on the heat transfer performance of metal foam heat exchangers for the cooling of electronic devices. It was determined that the heat transfer is increased as the porosity of the metal foam decreases. Kiwan and Khodier [12] examined convective heat transfer in an inclined channel which is partially filled with a porous medium. It was found that an increase in the Darcy number results in an increased Nusselt number. The authors also determined that the Nusselt number is minimum when the porous thickness ratio is 0.5. Servati et al. [10] examined the influence of a magnetic field on the forced convective flow of Al_2O_3-water nanofluid through a channel that is partially filled with a non-ordered porous medium. It was observed that the average temperature within the channel increases with increased nanoparticle concentration and decreased magnetic field strength. Moreover, an increase in nanoparticle concentration and the magnetic field strength causes an enhancement in the rate of heat transfer.

The vast majority of the literature on the mixed convective cooling of heated obstacles pertain to straight channel flows. However, bent channels must be used in typical high heat flux electronic cooling applications due to the limited size of the cooling systems [13]. As seen in the works of Haller et al. [14] and Zhang [2], bent channels yield significant enhancements in heat transfer due to the enhanced mixing within the fluid. Moreover, nanofluid heat transfer in bent channels have been reported to increase when the concentration of nanoparticles is increased [15,16]. To the best of the author's knowledge, there is no existing study on the mixed convective nanofluid cooling of heat-generating obstacles within a bent channel containing a porous layer. Hence, in this paper, we study the mixed convective cooling of four heat generating components within an L-shaped channel with a porous inner layer using copper (Cu)-water and silver (Ag)-water nanofluids. This work is useful for improvement of heat transfer efficiency in numerous applications such as electronics, automobiles and the petrochemical industry.

2. Problem formulation

We consider the mixed convective flow of nanofluid through an L-shaped channel. The width of this channel is h, whereas the length of the inlet section and outlet section are both equal to $3h$. The porous layer within the channel has thickness h_1, porosity ε and permeability K. Four heat-generating components are located on the opposite side of the porous layer, each having area A_d. The channel inlet has velocity U and temperature T_0, and the channel walls are thermally insulated. The four heat-generating components have heat flux densities q_1, q_2, q_3 and q_4 respectively. The heat absorbed from these devices by the nanofluid gives rise to free convection within the channel. Furthermore, the flow velocity is influenced by a magnetic field with strength B_0 which is applied at angle θ to the x-axis. The L-shaped domain Ω is comprised of the free-fluid region Ω_1, the saturated porous layer Ω_2 and the four components which are located at Ω_3, Ω_4, Ω_5 and Ω_6. A schematic diagram of the problem and a diagram of the domain as outlined above are given in Figs. 1 and 2 respectively.

Based on the geometry of the problem domain, the potential applications of the study and the nature of the nanofluids considered in the analysis of the present problem, we identify the following limitations of the study:

1. Turbulent and compressible flows are not considered.
2. The flow phenomena and heat transfer is not influenced by radiation.
3. The convective nanofluid flow is not affected by any external electric fields.
4. Thermal dissipations due to viscous or magnetic forces within the nanofluid are not considered.
5. The spatial and temporal variation of nanoparticle solid volume fraction is not taken into consideration.
6. Large temperature differences within the domain of the problem are not considered.
7. The heat-generating components are rectangular, have identical size and generate heat with identical heat flux. Components with non-rectangular geometries and non-identical heat fluxes were not considered.