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Mixed convection nanofluid flows through a grooved channel with internal heat generating solid cylinders in the presence of an applied magnetic field

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ABSTRACT

In this paper, we investigate the unsteady MHD mixed convection flows of SWCNT-water and Au-water nanofluids within a horizontal grooved channel with two heat generating solid cylinders. These flows may be used to model a wide range of engineering problems such as the flow of fluid in tubular heat exchangers and the cooling of nuclear fuel rods. The fluid is initially at rest and the initial temperature throughout the channel is constant. The flow velocity at the inlet is suddenly raised to a constant value and the inlet of the channel is maintained at the initial temperature. The mixed finite element method with polynomial pressure projection stabilization is used to solve the governing equations with the corresponding initial and boundary conditions. The effects of time t, groove geometry, cylinder radius r_c, groove area A_g, Reynolds number Re, Grashof number Gr, Hartmann number Ha and solid volume fraction ϕ on the fluid flow and heat transfer are examined.

1. Introduction

The study of mixed convection is important in understanding the heat transfer processes involved in industry. Applications of mixed convection fluid flows may be found in the operation of heat exchangers and the cooling of electronic devices. The efficiency of these devices may be improved using grooved or corrugated surface geometries. This improvement in heat transfer efficiency occurs as a result of enhanced mixing of fluid near the grooved or corrugated surface. Another method of heat transfer enhancement is the addition of nanoparticles to commonly used heat transfer liquids such as water, ethylene glycol and oil. The resulting liquid, which is referred to as a nanofluid, improves the efficiency of heat transfer systems via an enhancement in the thermal conductivity of the fluid.

The mixed convective flow around a heated cylinder within a channel has been studied by many researchers. Bijjam et al. [1] considered an unsteady fluid flow over a heated cylinder within a channel. The rate of heat transfer at the surface of the cylinder was shown to increase with increased Reynolds number. Nasrin and Parvin [2,3] examined the effects of the Prandtl, Richardson and Reynolds numbers on the fluid flow and heat transfer in an octagonal channel with a heat-generating cylinder. It was found that an increase in these parameters causes an increase in the rate of heat transfer at the surface of the cylinder and a decrease in fluid temperature. Nasrin and Alim [4] considered the effect of an applied transverse magnetic field on the mixed convection flow through an octagonal channel with heat generating hollow cylinder. The penalty finite element method was used to solve the governing non-linear partial differential equations. The results showed that an increase in the magnetic field strength decreases the average fluid temperature and rate of heat transfer at the surface of the cylinder. Cheraghi [5] studied the effect of flow of fluid through a channel with heated walls and an internal adiabatic cylinder. The effect of gap spacing between the cylinder and the bottom wall on the heat transfer along the channel was investigated. It was observed that the rate of heat transfer is greatest when the cylinder is in the middle of the channel. Etminan-Farooji et al. [6] investigated the flow of Al_2O_3 and CuO nanofluids around a heated square cylinder within a straight channel. The results showed that the rate of heat transfer is enhanced with the addition of Al_2O_3 and CuO nanoparticles to the base fluids (water and ethylene glycol). Furthermore, CuO nanofluids exhibit greater heat transfer enhancement than the Al_2O_3 nanofluids.

The enhancement of heat transfer within a channel by introducing grooves or corrugations in the channel walls has been investigated in numerous studies. An experimental study was conducted by Selvaraj et al. [7] on the flow and heat transfer characteristics of

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Nomenclature

A_g	groove area, m^2
c_p	specific heat capacity, Jkg^{-1} K^{-1}
h_1	distance between cylinders, m
Ha	Hartmann number
Nu	Nusselt number
p	pressure, kgm^{-1} s^{-2}
q_1, q_2	heat generation rates, Wm^{-3}
Pr	Prandtl number
Ra	Rayleigh number
r_c	cylinder radius, m
t	time, s
T	temperature, K
u,v	velocity components, ms^{-1}
x,y	space coordinates, m
β	coefficient of thermal expansion, K^{-1}
κ	thermal conductivity, Wm^{-1} K^{-1}
μ	viscosity, kgm^{-1} s^{-1}
ρ	density, kgm^{-3}
σ	electrical conductivity, $\Omega^{-1}m^{-1}$
ϕ	solid volume fraction
ψ	stream function

Subscripts

c	cylinder
c1	cylinder 1
c2	cylinder 2
f	fluid
nf	nanofluid
s	solid
av	average

a mixture of water and ethylene glycol through a channel with grooved walls. In this study, the effects of three types of grooves (circular, square and trapezoidal) on the rate of heat transfer within the channel were examined. It was noted that the Nusselt number increases with increased Reynolds number. The results also showed that Nusselt number in the grooved channel is higher than that of the plain channel. The greatest enhancement in heat transfer was seen in the square grooved channel, while the circular groove was shown to be the least effective for heat transfer enhancement. Heidary and Kermani [8] conducted a numerical investigation on the forced convection flow of a Cu-water nanofluid through a channel with wavy (sinusoidal) walls. It was determined that an increase in the nanoparticle concentration, the amplitude of the wavy walls and the Reynolds number increase heat transfer in the channel. Ahmed et al. [9] used the finite difference method to investigate the unsteady flow and heat transfer of a Cu-water nanofluid within a corrugated channel. The heat transfer was shown to increase as the volume fraction of nanoparticles increases. Parvin et al. [10] examined the effect of Prandtl number and wave amplitude on the convective flow of a CuO-water nanofluid through a porous channel with wavy walls using the finite element method. It was observed that the temperature within the channel decreases as the Prandtl number is increased or as the wave amplitude is decreased. The rate of heat transfer decreases with increased wave amplitude, but increases with increased Prandtl number. Heshmati et al. [11] used the finite volume method to study the unsteady convective flow of a SiO_2-water nanofluid through a channel with square grooves in the bottom wall. The velocity and the rate of heat transfer were shown to increase as the nanoparticle concentration increases. Ahmed et al. [12] considered the flow and heat transfer of a Cu-water nanofluid through a trapezoidal-corrugated channel. The results were found to be consistent with those of Heidary and Kermani [8]. It was also determined that an increase in the wavelength of the corrugated channel causes a reduction in the rate of heat transfer. The forced convection flow of a Cu-water nanofluid in three configurations of a triangular-corrugated channel was studied by Falahat [13] using the finite volume method. The heat transfer rate was found to increase with increased nanoparticle concentration and with increased Reynolds number.

To the best of the authors' knowledge, there is no existing study on the unsteady MHD mixed convection flow of nanofluids in grooved channels with heat generating solid cylinders. The main objective of our article is to investigate the effects of magnetic field strength, groove geometry and other pertinent parameters on the rate of removal of heat from two heat generating solid cylinders using SWCNT-water and Au-water nanofluids of different concentrations.

2. Problem formulation

The domain Ω of the problem is comprised of three bounded subdomains Ω_1, Ω_2 and Ω_3, where $\Omega_i \subset \mathbb{R}^2$ for $i = 1, 2, 3$ and $\partial\Omega_1 = (\cup_{i=1}^4 \Gamma_i) \cup \partial\Omega_2 \cup \partial\Omega_3$. The geometry of the problem with circular, square and trapezoidal grooves is shown in Figs. 1–3.

We consider the unsteady two-dimensional convective flow of a nanofluid through the domain Ω_1. The width and length of the channel are h_1 and $4h_1$ respectively, while the radius of the heat

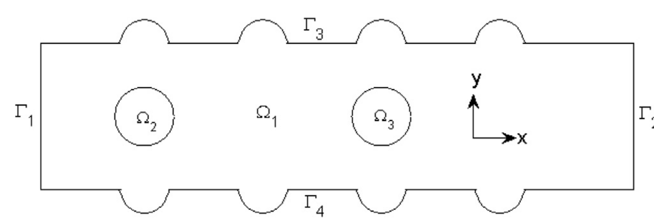

Fig. 1. Problem geometry with circular grooves.

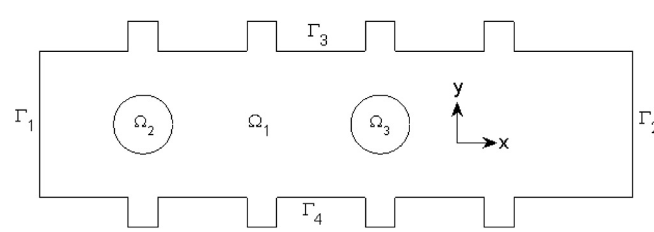

Fig. 2. Problem geometry with square grooves.

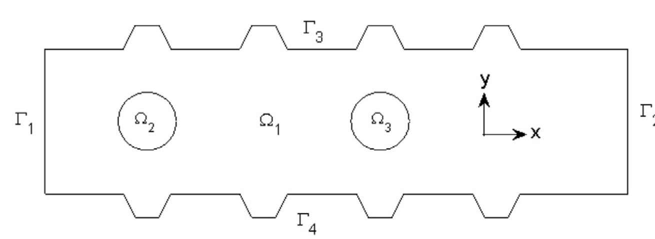

Fig. 3. Problem geometry with trapezoidal grooves.