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Natural convection and entropy generation of nanofluid filled cavity having different shaped obstacles under the influence of magnetic field and internal heat generation

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ABSTRACT

In this study, natural convection in a nano-fluid filled cavity having different shaped obstacles (circular, square and diamond) installed under the influence of a uniform magnetic field and uniform heat generation was numerically investigated. The cavity was heated from below and cooled from the vertical sides while the top wall was assumed to be adiabatic. The temperatures of the side walls vary linearly. The governing equations were solved by using Galerkin weighted residual finite element formulation. The numerical investigation was performed for a range of parameters: external Rayleigh number ($10^4 \le Ra_E \le 10^6$), internal Rayleigh number ($10^4 \le Ra_I \le 10^6$), Hartmann number ($0 \le Ha \le 50$), and solid volume fraction of the nanofluid ($0 \le \phi \le 0.05$). It is observed that the presence of the obstacles deteriorates the heat transfer process and this is more pronounced with higher values of Re_E. Averaged heat transfer reduces by 21.35%, 32.85% and 34.64% for the cavity with circular, diamond and squared shaped obstacles compared to cavity without obstacles at $Ra_I = 10^6$. The effect of heat transfer reduction with square and diamond shaped obstacles compared to case without obstacle is less effective with increasing values of Hartmann number. Second law analysis was also performed by using different measures for the normalized total entropy generation.

1. Introduction

Natural convection in cavities has many industrial applications including cooling of electronic devices, heat exchangers, chemical reactors, room ventilation, solar collectors and many others due to its simplicity and low cost. A comprehensive review was given by Ostrach [1]. Most of the natural convection studies deal with the cases where a vertical or a horizontal temperature difference is imposed. However, the cooling and heating may be partial and non-uniformities in the heating and cooling may also be of interest [2–7]. Natural convection in cavities with heat generating fluids has been extensively studied [8–10]. Oztop and Bilgen [11] numerically investigated the natural convection of differentially heated, partitioned square cavity containing heat generating fluid. They observed that the heat transfer was generally reduced when the ratio of internal and external Rayleigh numbers was from 10 to 100. In another study by Oztop et al. [12], numerical study of natural convection in a wavy-wall cavity with volumetric heat source was performed. They observed that both the wavy wall and the ratio of internal Rayleigh number to external Rayleigh number affect the heat transfer and fluid flow significantly. Acharya and Goldstein [10] numerically studied the free convection inside an inclined cavity having uniformly distributed internal energy source. They observed distinct flow pattern systems depending on the ratio of the external to internal Rayleigh number.

Heat transfer and fluid flow within an enclosure or channel can be affected by using an obstruction [13–21]. Khanafer and Aithal [18] numerically studied the mixed convection in a lid-driven cavity having a circular object inside by using finite element method. Their results showed that the Richardson number, cylinder diameter and the location of the cylinder have impact on the transport phenomena within the cavity. Islam et al. [19] inserted an isothermally heated square blockage inside a square cavity and the effects of various different blockage sizes, concentric and eccentric placement of the blockage inside the cavity have been numerically investigated using finite volume method. Billah et al. [20] studied the mixed convection in a lid-driven cavity with a heated circular hollow cylinder. Their simulation results showed that the cylinder diameter and the solid– fluid thermal conductivity ratio have impact on flow field and temperature distribution within the cavity. Kumar and Dhiman [16] numerically studied the heat transfer in laminar

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Nomenclature

$\boldsymbol{B}_0$	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^2K)
Ha	Hartmann number, $B_0H\sqrt{\frac{\sigma_{nf}}{\rho_{nf}\nu_f}}$
k	thermal conductivity (W/m K)
H	height of the enclosure (m)
n	unit normal vector
Nu_x	local Nusselt number
Nu_m	averaged Nusselt number
p	pressure (Pa)
Pr	Prandtl number, $\frac{\nu_f}{\alpha_f}$
Re	Reynolds number, $\frac{u_0H}{\nu_f}$
T	temperature (K)
u, v	–y velocity components (m/s)
x, y	Cartesian coordinates (m)
Greek characters	
α	thermal diffusivity (m^2/s)
β	expansion coefficient (1/K)
ϕ	solid volume fraction
ν	kinematic viscosity (m^2/s)
θ	non-dimensional temperature, $\frac{T-T_c}{T_h-T_c}$
ρ	density of the fluid (kg/m^3)
σ	electrical conductivity (S/m)
Ψ	dimensionless stream function
Subscripts	
c	cold
h	hot
m	average
nf	nanofluid
p	solid particle
st	static

forced convection over a backward facing step with the insertion of an adiabatic circular cylinder. They considered different locations of the circular cylinder for the Reynolds numbers between 1 and 200. Heat transfer enhancement up to 155 % compared to no-cylinder case was observed. Selimefendigil and Oztop [22] numerically studied the pulsating flow at a backward facing step in the presence of a stationary circular cylinder located downstream of the step with nanofluids. They observed that heat transfer was enhanced as the frequency of the pulsation, nanoparticle volume fraction and Reynolds number increase.

Magnetic field effect of electrically conducting fluid on the heat transfer and fluid flow (magnetohydrodynamics-MHD) can be encountered in many engineering applications such as purification of molten metals, coolers of nuclear reactors, MEMs, and many other systems [23]. An external magnetic field can be used to control the convection within cavities as studied by many researchers [24–30]. Oztop et al. [31] 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 [32] 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. In heat transfer applications, nano-sized particles are added in the base fluid such as water or ethylene glycol to improve the thermal conductivity of the base fluid [33]. Nanofluids improve the heat transfer characteristics with little pressure drop as compared to base fluids [33]. MHD with nanofluids offers a good possibility to control the convection as it has been studied by many researchers [34–46]. Sheikholeslami et al. [39] 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. Mahmoudi et al. [34] 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. [35] 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. Hatami et al. [40] analytically investigated the MHD Jeffery– Hamel nanofluid flow in non-parallel walls by using different base fluids and nanoparticles. They found 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 [47–50]. The available energy destruction can be quantified by the measurement of irreversibility during a process which is called entropy generation rate. The performance of the system can be increased by using the entropy generation minimization concept. The fundamentals of entropy generation was presented by Bejan [51]. A review of entropy generation in natural and mixed convection for energy systems may be found in [52]. Second law analysis of natural convection with nanofluids and MHD flow can be found in refs. [53–56]. Cho [57] numerically studied the heat transfer characteristics and entropy generation for free convection of nanofluids filled square cavity with a partial heater and wavy wall. They showed that as the volume fraction of the nanoparticles increases and the amplitude and wavelength decreases the total entropy generation decreases. Esmaeilpour and Abdollahzadeh [58] investigated the effects of Grashof number and nanoparticle volume fraction inside a wavy enclosure by using finite volume method. They observed that with the addition of nanoparticles and with decreasing surface waviness, the entropy generation decreases. Ramakrishna et al. [59] numerically studied the thermal management of natural convection within trapezoidal cavities with distributions of heatlines and entropy generation using the Galerkin finite element method. They identified different optimal design points for thermal processing. Singh et al. [60] studied the entropy generation inside a tilted porous cavity with natural convection effect with various inclination angles. Optimal tilt angles of the square cavity were identified based on minimum entropy generation and reasonable heat transfer rate. Hajialigol et al. [61] studied the mixed convection and entropy generation in a nanofluid filled three dimensional micro-channels with magnetic field effect. They showed that as the magnetic field strength and solid particle volume fraction increases or as the aspect ratio decreases, the total entropy generation decreases. Other relevant studies can be found in refs. [62–65].

Based on the above literature survey and to the best of authors' knowledge, natural convection in nanofluid filled cavity having different shaped obstacles installed under the influence of a magnetic field has never been studied; even its importance in many engineering applications is apparent as outlined above. This study aims at investigating the effects of Rayleigh number, Hartmann number, nanoparticle volume fraction and obstacle shapes on the fluid flow and heat transfer characteristics in a square cavity. Second law analysis of the system for various parameters and for different obstacles shapes is also performed.

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