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Mixed convection in alumina-water nanofluid filled lid-driven square cavity with an isothermally heated square blockage inside with magnetic field effect: Introduction

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ABSTRACT

In this work, mixed convection in alumina-water nanofluid filled lid-driven square cavity with an isothermally heated square blockage inside with magnetic field effect has been examined. All the walls of the cavity are at rest except top wall. A square blockage with isothermal heating is maintained at the centre of the cavity. Vertical side walls are adiabatic and bottom wall is kept at some hot temperature. Flow is generated due to motion of top wall and buoyancy forces that are produced in cavity due to temperature gradient. Governing equations are discretized in space using Galerkin finite element method and time discretization is performed using Crank-Nicolson scheme. Newton method is used to cope with discretized nonlinear systems of equations and Gaussian elimination method has been applied to solve the associated linear subproblems in each nonlinear iteration at each time level. Analysis has been performed on numerical results in the form of streamlines, isotherms, tables and some useful plots. Influence of emerging parameters on the flow, in specific ranges such as Reynolds number ($1 \leqslant Re \leqslant 200$), Richardson number ($0.01 \leqslant Ri \leqslant 10$), Hartmann number ($0 \leqslant Ha \leqslant 100$), Eckert number ($0 \leqslant Ec \leqslant 0.01$) as well as nanoparticles volume fraction ($0 \leqslant \phi \leqslant 0.2$) are investigated and findings are very closely comparable to the previous analysis for the special cases in the literature. Calculations of average Nusselt number, entropy generation as well as average temperature in the cavity will be our focus of interest in this study.

1. Introduction

Flow and heat transfer analysis in lid driven cavity is one of the most studied problem in thermo-fluid areas. When buoyancy forces are comparable to the shear forces in the cavity, this flow is characterized by mixed convection flow. Richardson number is equal to unity in such flows. Mixed convection in a cavity has many applications in engineering and industry including cooling of electronic devices, heat exchangers, chemical reactors, solar collectors, heating and cooling of buildings. Some literature on mixed convection in a cavity can be found in [1–18].

Nanofluid is a combination of nanoparticles and base fluid. Nanoparticles include aluminum, copper, silver, titinium, etc., whereas water, ethylene glycol, oils, etc., are examples of base fluid. First time, the term nanofluid was used by Choi [19]. Among other mechanisms to augment heat transfer, nanofluid is one of them. Some of the mixed convective nanofluid case can be consulted from [20–34].

Heat transfer in a cavity with one or more obstacles inside has drawn the attention of many researchers in the last decade. Esfe et al. [35] have discussed mixed convection in a cavity saturated with alumina-water nanofluid with a hot obstacle inside. Their conclusion showed that nanofluid descends downward along the right wall, moves horizontally above the obstacle to the left corner of the cavity along the bottom wall and then moves upward and forms an eddy inside the cavity. Increasing the Richardson number, clockwise rotating vortex becomes larger due to effect of the obstacle. Islam et al. [36] have examined mixed convection in a lid driven cavity with an isothermal block inside and found that for any size of blockage kept at random place in a cavity, the average Nusselt number changed only when Richardson number exceeds order of 1. For Richardson number more than 1, average Nusselt number increased speedily. Moreover, optimal situation for heat transfer was acquired to maintain the block at the top left and bottom right corner of the cavity.

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Nomenclature

Be	Bejan number
C_p	specific heat (J kg^{-1} K^{-1})
Ec	Eckert number, $\frac{U_0^2}{(C_p)_f(T_h-T_c)}$
g	gravitational acceleration (m s^{-2})
Gr	Grashof number, $\beta g \Delta T L^3/\nu_f^2$
Ha	Hartmann number, $B_0 L\sqrt{\frac{\sigma_f}{\mu_f}}$
k	heat conductivity (W m^{-1} K^{-1})
L	cavity length (m)
Nu_{avg}	average Nusselt number
Nu	local Nusselt number
p	pressure (N m^{-2})
P	dimensionless pressure
Pr	Prandtl number, ν_f/α_f
Re	Reynolds number, U_0L/ν_f
Ri	Richardson number, Gr/Re^2
t	time (s)
$T_h - T_c$	temperature gradient
T	temperature (K)
u, v	dimensional velocity components (m s^{-1})
U, V	dimensionless velocity components
U_0	lid velocity
x, y	dimensional space coordinates (m)
X, Y	dimensionless space coordinates

Greek symbols

α	thermal diffusivity (m^2 s^{-1})
ν	kinematic viscosity (m^2 s^{-1})
β	thermal expansion coefficient (K^{-1})
ρ	density (kg m^{-3})
τ	dimensionless time
θ	dimensionless temperature
μ	dynamic viscosity (kg m^{-1} s^{-1})
ϕ	volume fraction of the nanoparticles

Subscripts

nf	nanofluid
c	cold
h	hot
s	nanoparticles
f	fluid

Oztop et al. [37] have considered fluid flow due to combined convection in lid driven enclosure having a circular body. It was indicated that the most effective parameter on flow field and temperature distribution is the orientation of the moving lid. The circular body can be a control parameter for heat and fluid flow. Billah et al. [38] have investigated mixed convection in a lid-driven cavity with a heated circular hollow cylinder and found that heat transfer and fluid flow are strongly dependent on the diameter of the hollow cylinder. Considerable influence of cylinder on the flow for the cases of forced, mixed and natural convection has been observed. For fixed Richardson number, cylinder augmented heat transfer with increasing diameter. Mehrizi et al. [39] have analyzed mixed convection in a ventilated cavity with hot obstacle considering the influence of nanofluid and outlet port location. They have shown that heat transfer enhanced with increasing nanoparticles volume fraction for various Richardson numbers and outlet port positions. Moreover, augmentation in Richardson number caused to change main flow direction from top to bottom of obstacle. Rahman et al. [40] have examined magnetohydrodynamic mixed convection and Joule heating in a lid driven cavity having a square block inside and observed that flow field and temperature profile mainly depend on magnetic parameter, Joule heating parameter and size of the inner block for the mixed convection regime. Khanafer and Aithal [41] have discussed mixed convection flow and heat transfer in a lid driven cavity with a circular cylinder. It was observed that the optimal heat transfer results could be obtained while placing the cylinder near the bottom wall for different Richardson numbers. For natural and mixed convection, the average Nusselt number increased with an increase in the radius of the cylinder for various Richardson numbers. Selimefendigil and Oztop [42] have considered MHD mixed convection in a nanofluid filled lid driven square enclosure with a rotating cylinder inside and their conclusion showed that heat transfer enhancement for $Ri = 10$ was 17% more than calculated for $Ri = 1$. A numerical study on mixed convection in a lid driven cavity with a circular cylinder has been conducted by Zheng et al. They showed that fluid flow and heat transfer characteristics in the cavity strongly depend on the position of the circular cylinder as well as on the relative magnitude of the forced convection and the natural convection caused by the movement in the top wall of the cavity and the heating at the hot bottom wall, respectively.

Entropy generation suppresses the thermodynamic efficiency of a system. It indicates the location of a system in which more energy dissipation occurs. Bejan [43] has investigated the fundamental principles to mitigate the entropy generation. Since entropy is one reason out of many for the wastage of energy in heat transfer process, therefore sometimes it becomes necessary to measure entropy generation in a very accurate way. More study on entropy generation can be consulted from [44–54]. Selimefendigil and Oztop [55] have investigated natural convection and entropy generation of nanofluid filled cavity having different shaped obstacles under the influence of magnetic field and internal heat generation. It was observed that the presence of the obstacles deteriorated the heat transfer process and that was more pronounced with higher values of Re.

In this study, we are going to investigate mixed convection and entropy generation in alumina-water nanofluid filled lid-driven square cavity with an isothermally heated blockage under the influence of magnetic field. This work has been elaborated in detail by the help of isotherms, streamlines and various plots. Mixed convection in nanofluid filled cavity with an isothermally heated blockage under the influence of magnetic field has not been considered and investigated yet.

This study is organized in the following way: Section 2 illustrates problem configuration. Section 3 contains information about space and time discretizations of the governing equations, the numerical method, code validation and grid independence test. Results based on the numerical simulation have been elaborated in Section 4. Finally, conclusion has been drawn in Section 5.

2. Problem formulation

2.1. The problem configuration

The geometry of the present problem is shown in Fig. 1. It displays a lid driven square cavity of width L containing alumina-water nanofluid. An isothermally heated square blockage with an average temperature of both top cold and bottom hot walls and of width equal to $L/4$ is placed in the middle of the cavity [56]. Top wall is moving to the right with constant speed U_0, other walls are at kept at rest. Vertical side walls are adiabatic and bottom wall