Natural Convection Heat Transfer Enhancement in a Closed Cavity with Partition Utilizing Nano Fluids

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Abstract

The principal objective of the present work is to conduct investigations leading to a more complete explanation of natural convective heat transfer in a partitioned cavity utilizing nano fluids. The nano fluid used, which is composed of Aluminum oxide nano particles in suspension of Ethylene glycol, has been provided at various particle concentrations ranging from 0 to 30% in volume. The study is carried out numerically for a range of Rayleigh numbers, partition heights and aspect ratio. The flow and temperature distributions are taken to be two-dimensional. Regions with the same velocity and temperature distributions can be identified as symmetry of sections. One half of such a rectangular region is chosen as the computational domain taking into account the symmetry about the partition. Transport equations are modeled by a stream function-vorticity formulation and are solved numerically by finite-difference schemes. Results are presented in the form of streamline and isotherm plots as well as the variation of local Nusselt number at the partition under different conditions.

Key words: **Nano fluid, natural convection, partition height, Rayleigh number**

Nomenclature

A_r	aspect ratio of the cavity
c	partition position
d	diameter
g	acceleration due to gravity
Gr	Grashoff number
h	partition height
H	height of the cavity
k	thermal conductivity
Nu	Nusselt number
P	dimensionless pressure
Pr	Prandtl number
Ra	Rayleigh number
t	time
T	temperature
u, v	velocity component in x-and y-directions
u_c	characteristic velocity
U, V	dimensionless velocity component in X- and Y- directions
W	width of the cavity
x, y	dimensional Cartesian coordinates
X, Y	dimensionless Cartesian Coordinates

Greek letters

α	thermal diffusivity
β	coefficient of thermal expansion
ϕ	solid volume fraction
ν	kinematic viscosity
ρ	density
θ	dimensionless temperature
ψ	stream function
Ω	vorticity
τ	dimensionless time
μ	dynamic viscosity

Subscripts

avg	average
c	cold
eff	effective
f	fluid
h	hot
nf	nano fluid
o	reference value
s	solid

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I. INTRODUCTION

The augmentation of heat transfer in the field of Nanotechnology is considered to be one of the most important inventions in this century. Convective heat transfer in a partitioned cavity with adiabatic horizontal walls and isothermal vertical walls are a prototype of many industrial applications, such as electronic cooling, transportation, the environment and national security. Nano fluids exhibit superior heat transfer properties in comparison with conventional heat transfer fluids. It refers to a two phase mixture that is composed of saturated liquid and extremely fine metallic particles called nano particles. The suspended ultra fine particles change transport properties and heat transfer performance. The thermal conductivity is strongly dependent on the solid volume fraction and properties of nano fluids.

In the literature, various studies have been published on the mechanism of natural convection in differentially heated cavities with different geometrical parameters and boundary conditions. Nansteel and Grief [1] conducted an experimental study at higher Rayleigh numbers (10^9- 10^{11}) and an aspect ratio of ½. Water was the working fluid and the horizontal end walls were made of Plexiglass. Lin and Bejan [2] carried out a similar high Rayleigh number experimental study with water as the working fluid and for an aspect ratio of ½. Flow patterns similar to those observed by Nansteel and Grief were noted, but the Nusselt number results obtained were considerably lower than Nansteel and Grief data. Zimmerman and Acharya [3] have studied numerically the natural convection heat transfer in a cavity with perfectly conducting horizontal end walls and finitely conducting baffles. Results were obtained at lower Rayleigh numbers, and no flow separation in front of partial divider was noted. Acharya and Jetli [4] have numerically investigated the heat transfer and flow patterns in a partially divided differentially heated square box. Rayleigh numbers studied were in the range of 10^5- 10^6. The flow was weak in this stratified region and a tendency for flow separation behind the divider was noted. Nowak and Novak [5] carried out the natural convection heat transfer in slender rectangular cavities equipped with two small vertical partitions, located in the middle of horizontal walls. Xuan and Roetzel [6] proposed two different approaches for deriving heat transfer correlation of the nano fluid. The effects of transport properties of the nano fluid and thermal dispersion are included. Dagtekin and Oztop [7] have reported the natural convection heat transfer and fluid flow of two heated partitions within an enclosure. The effect of locations and sizes of partitions on heat transfer and fluid was studied. Keblinsky et. al [8] demonstrated that the thermal conductivity increases of nano fluids are due to Brownian motion of particles, molecular-level layering of the liquid at the liquid/ particle interface, the nature of heat transport in the nano particles, and the effect of nano particle clustering. Khanafer et. al [9] was the first to investigate the problem of buoyancy-driven heat transfer enhancement of nano fluids in a two-dimensional enclosure. The results illustrated that the nano fluid heat transfer rate increases with an increase in the nano particle volume fraction. Oztop and Bilgen [10] have numerically investigated the natural convection in a differentially heated, partitioned, square cavity containing heat generating fluid.

The present paper examines the effect of partitions at different solid volume fractions on the cavity heat transfer and flow patterns. From the literature review it is clear that the case of partition with nano fluids has not been

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addressed. The second objective of the paper is to provide a more unifying picture of the various pertinent parameters on heat transfer characteristics of nano fluids within the cavity.

II. MATHEMATICAL FORMULATION

Consider a two-dimensional cavity of length W and height H filled with a nano fluid as shown in Fig. 1. In the present analysis, Cartesian coordinate system will be applied to the cavity. The nano fluid in the cavity is Newtonian, incompressible, and laminar and is assumed to have uniform shape and size. The nano fluid used, which is composed of Aluminum oxide nano particles in suspension of Ethylene glycol, has been provided at various particle concentrations ranging from 0 to 30% in volume. Moreover, it is assumed that both fluid phase and nano particles are in thermal equilibrium state. The compressibility effects and viscous dissipation in the energy equation are neglected. The Boussinesq approximation is assumed to be valid.

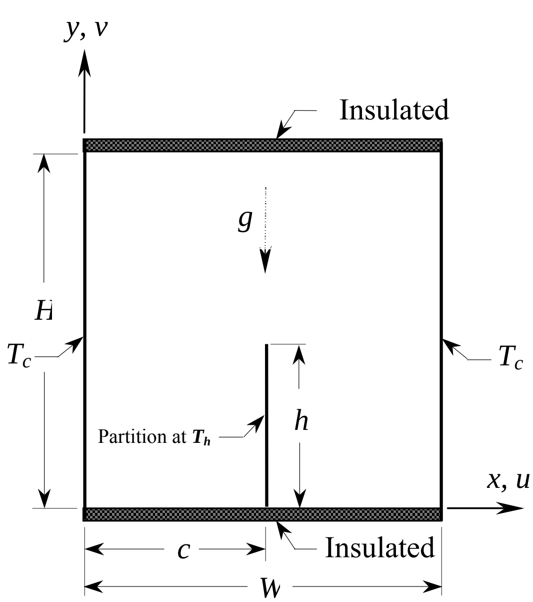

Fig.1 Schematic for the physical model

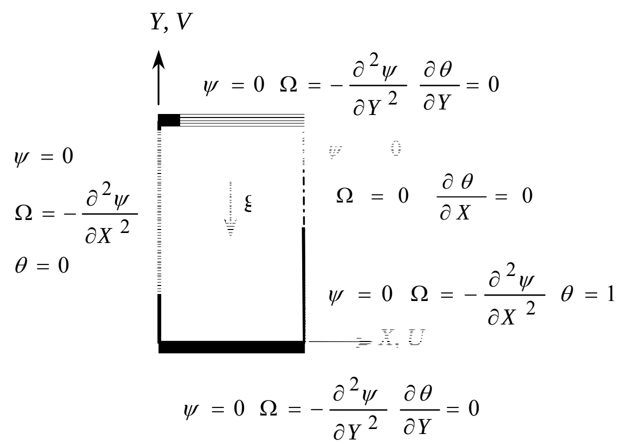

Fig. 2 Computational domain

Fig. 2 depicts the computational domain indicating thereon the most appropriate boundary conditions relevant to the present study. Based upon the previous assumptions and introducing the following dimensionless variables,

$$X = \frac{x}{H} \quad Y = \frac{y}{H} \quad U = \frac{u}{u_c} \quad V = \frac{v}{u_c}$$

$$\theta = \frac{T - T_c}{T_h - T_c} \quad \tau = \frac{t\,u_c}{H} \quad A_r = \frac{H}{W}$$

$$Gr = \frac{\beta g (T_h - T_c) H^3}{\nu^2} \quad \Pr = \frac{\mu Cp}{k_f}$$

$$\alpha_{nf} = \frac{(k_{eff})_{stagnant}}{(\rho Cp)_{nf}}$$

$$k_d = C (\rho Cp)_{nf} \left|\overline{V}\right| \phi\, d_p$$

$$\chi = \frac{\left[\dfrac{(k_{eff})_{stagnant}}{k_f}\right]}{(1-\phi) + \phi\dfrac{(\rho Cp)_s}{(\rho Cp)_f}} + C\phi\frac{d_p}{H}\Pr\sqrt{Gr}\sqrt{U^2 + V^2}$$

Where $u_c = \sqrt{g\beta H (T_h - T_c)}$

The governing equations for the problem in dimensionless form are as follows:

Continuity:

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0 \tag{1}$$

X – Momentum:

$$U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}=\frac{\partial P}{\partial X}+\frac{\mu_{eff}}{\rho_{nf,o}}\left(\frac{\partial^2 U}{\partial X^2}+\frac{\partial^2 U}{\partial Y^2}\right) \quad (2)$$

Y – Momentum:

$$U\frac{\partial V}{\partial X}+V\frac{\partial V}{\partial Y}=\frac{\partial P}{\partial Y}+\frac{\mu_{eff}}{\rho_{nf,o}}\left(\frac{\partial^2 V}{\partial X^2}+\frac{\partial^2 V}{\partial Y^2}\right)+\frac{1}{\rho_{nf,o}}\left[\phi\rho_{s,o}\beta_s+(1-\phi)\rho_{f,o}\beta_f\right]g\theta \quad (3)$$

Energy:

$$U\frac{\partial \theta}{\partial X}+V\frac{\partial \theta}{\partial Y}=\frac{1}{\Pr\sqrt{Gr}}\left[\frac{\partial}{\partial X}\left(\chi\frac{\partial \theta}{\partial X}\right)+\frac{\partial}{\partial Y}\left(\chi\frac{\partial \theta}{\partial Y}\right)\right] \quad (4)$$

Stream function equation:

$$\frac{\partial^2 \psi}{\partial X^2}+\frac{\partial^2 \psi}{\partial Y^2}+\Omega=0 \quad (5)$$

Vorticity Transport equation:

$$\frac{\partial \Omega}{\partial \tau}+U\frac{\partial \Omega}{\partial X}+V\frac{\partial \Omega}{\partial Y}=\frac{a1}{\sqrt{Gr}}\left(\frac{\partial^2 \Omega}{\partial X^2}+\frac{\partial^2 \Omega}{\partial Y^2}\right)+\lambda\frac{\partial \theta}{\partial X} \quad (6)$$

Where $a1=\dfrac{1}{(1-\phi)^{2.5}\left[\phi\dfrac{\rho_{s,o}}{\rho_{f,o}}+(1-\phi)\right]}$

$$\lambda=\frac{1}{1+\dfrac{1-\phi}{\phi}\dfrac{\rho_{f,o}}{\rho_{s,o}}}\frac{\beta_s}{\beta_f}+\frac{1}{1+\dfrac{\phi}{1-\phi}\dfrac{\rho_{s,o}}{\rho_{f,o}}}$$

III. NUMERICAL METHOD

The governing equations (4) to (6) were discretized using second order accurate finite difference schemes resulting in a system of linear algebraic equations. The coefficient matrix associated with these equations possesses pentadiagonal structure. These equations are solved, by using Gauss-Seidel line-by-line method [11] of iterative solution procedure and famous Thomas Algorithm. The numerical results presented and discussed in the succeeding section are obtained using a computer code developed exclusively for the present investigation. Numerical experiments with different grid sizes, which correspond to 11x11, 21x21 and 41x41, are conducted to ascertain an optimum grid size. On the basis of this experiment, the grid size corresponding to 41x41 is found to be an optimum one. To test the computer code developed in this study, the problem of buoyancy-driven flow in a square cavity that has different heated vertical walls and adiabatic upper and bottom walls are studied [12]. A good agreement is obtained between the present solution and the previous works as illustrated in Table I. The Nusselt number are averaged and evaluated along the partition which may be expressed as

Table I: Comparison of values with previous works for different Ra values

	Present study	Barakos et al.[13]	G De Vahl Davis[12]	Fusegi et al.[14]
Ra =	**10^3**			
Nu_{avg}	1.152	1.114	1.118	1.105
U_{max} at Y	0.136 (0.825)	0.153 (0.806)	0.136 (0.813)	0.132 (0.833)
V_{max} at X	0.139 (0.175)	0.155 (0.181)	0.138 (0.178)	0.131 (0.200)
Ra =	**10^5**			
Nu_{avg}	4.636	4.51	4.519	4.646
U_{max} at Y	0.166 (0.887)	0.132 (0.859)	0.153 (0.855)	0.147 (0.855)
V_{max} at X	0.258 (0.062)	0.258 (0.066)	0.261 (0.066)	0.247 (0.065)
Ra =	**10^6**			
Nu_{avg}	9.241	8.806	8.799	9.012
U_{max} at Y	0.153 (0.937)	0.077 (0.859)	0.079 (0.850)	0.084 (0.856)
V_{max} at X	0.261 (0.037)	0.262 (0.039)	0.262 (0.038)	0.259 (0.033)

$$Nu_{avg}=\int_2^{Np}\frac{(k_{eff})_{stagnant}}{k_f}\left.\frac{\partial \theta}{\partial X}\right|_{X=\frac{1}{2A_r}}dY \quad (7)$$

IV. RESULTS AND DISCUSSION

The ranges of Rayleigh number for this investigation are $10^3 \le Ra \le 10^6$. The range of solid volume fraction ϕ used in this study varied between $0 \le \phi \le 30\%$. The thermo physical properties of fluid and solid phase are shown in Table II. Fig. 3 plots the streamlines

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Table II: Thermo physical properties of different phases

Property	Ethylene glycol	Aluminum oxide
C_p (J/kg K)	2382	765
ρ (kg/m^3)	1116	3970
k (W/m K)	0.249	46
β (K^{-1})	0.65 x10^{-3}	7.4 x10^{-6}

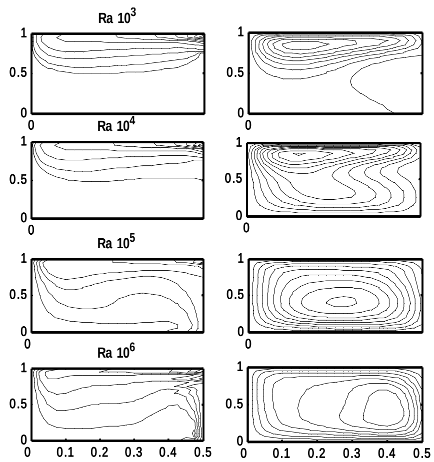

Fig. 3 Isotherms and streamlines of the cavity with h 0.75, ϕ 10%, Pr 204, Ar 1.0 for different Rayleigh numbers.

and isotherms for different Rayleigh numbers of aspect ratio 1 to assess further the accuracy of the physical concept of this model. In Fig. 3, the flow rate exists with maximum value in the centre of the circulation. As the parameter Ra increases, the flow rates at the centers of circulation increase. The temperature drops gradually from the value at the partition to the value at the center. This behavior is clearly similar to the related flow pattern in all ranges of buoyancy parameter. The effect of the solid volume fraction on the streamlines and isotherms of nano fluids for various Rayleigh numbers is shown in Fig. 4. For a low Rayleigh number, a central vortex appears as a dominant characteristic of the fluid flow. As the solid volume fraction increases, the velocities at the center of the cavity increase as a result of higher solid-fluid transportation of heat. The effect of partition height on the isotherms and streamlines of the cavity is shown in Fig.5. The isotherms in Figs.4 and 5 showed that the vertical stratification of the isotherms breaks down with an increase in the solid volume fraction for higher Rayleigh numbers. This is due to a number of effects such as gravity, brownian motion, ballistic phonon transport, layering at the solid/liquid interface, clustering of nano particles, and dispersion effect. It is shown that the average Nusselt number at the partition is increased as the aspect ratio decreased.

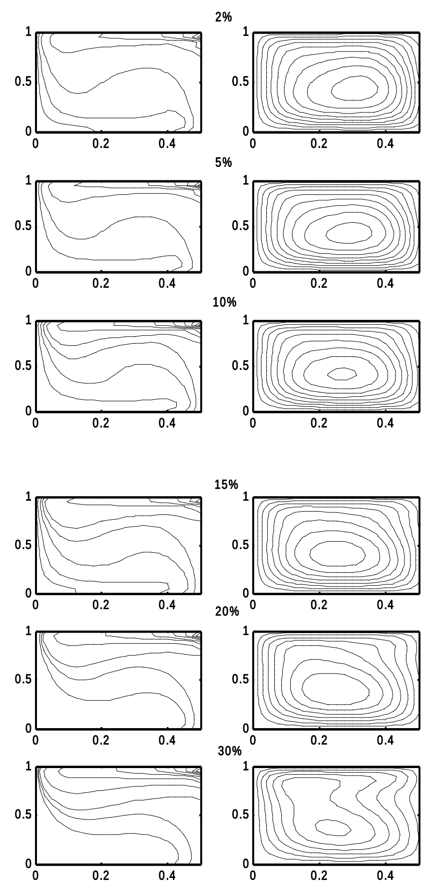

Fig. 4 Isotherms and streamlines of the cavity with h 0.75, Pr 204, Ra 10^5 for different volume fractions.

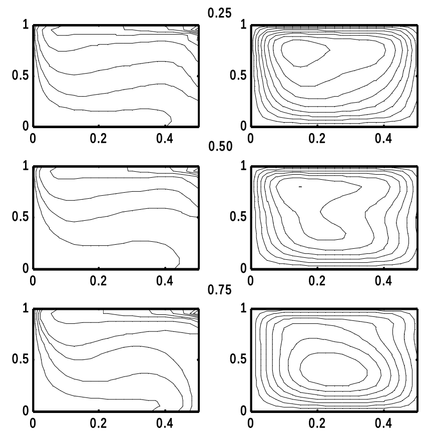

Fig. 5 Isotherms and streamlines of the cavity with ϕ 20% and Ra 10^5 for different partition heights.

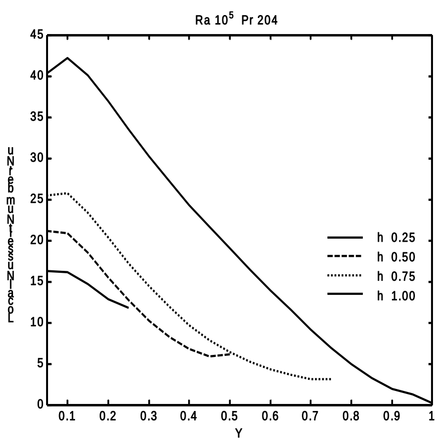

Fig. 6 Variation of local Nu along the partition for different partition heights, for fixed values of Ra $10^5$and ϕ 20%.

In this study we considered only the effect of dispersion that may coexist in the main flow of a nano fluid.

V. CONCLUSIONS

In this study heat transfer enhancement of nano fluid in a partitioned cavity is investigated for various pertinent parameters like solid volume fraction, partition height, Rayleigh numbers and aspect ratio of the cavity. The results illustrate that the nano fluid heat transfer rate increases with an increase in the nano particles solid volume fraction. The presence of nano particles in the fluid is found to alter the structure of the fluid flow.

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