PRANDTL NUMBER EFFECT ON NANOFLUID FLOW INSIDE A POROUS CAVITY

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Abstract- The problem of lid-driven flows in cavities has been major topic for research studies due to its fundamental nature and owing to the wide spectrum of engineering applications such as electronic device cooling, crystal growth, high-performance building insulations, multi shield structures used for nuclear reactors, food processing, float glass production, solar power collectors, furnace, drying technologies, etc. In this article Numerical study of the effect of Prandtl number on nanofluid flow inside a porous cavity in a two-sided lid driven square closure is studied. The working fluid is Cu/water nanofluid. By Finite Element Method the governing partial differential equations are solved. The highest Pr causes the greatest heat and mass transfer. The enhancing performance of heat and mass transfer rate is more effective for the water-Cu nanofluid than the base fluid. It is assumed that the temperature difference driving the mixed convection comes from the side moving walls, when both horizontal walls are kept insulated. In this research, the effect of Prandtl number from 0.71 to 10 on nanofluid flow is investigated. The values of Richardson number, solid volume fraction of water/Cu nanofluid, Darcy number are kept fixed as 10, 2% and 0.01 respectively. The phenomenon is analysed through streamlines, isothermal lines, iso-concentration lines plots, with special attention to the Nusselt number and Sherwood number. It is found that heat- mass transfer becomes higher by using water/Cu nanofluid than clear water.

Keywords- Mixed convection; porous cavity; nanofluid; finite element method; Prandtl number.

Nomenclature

Symbol	Meaning	Unit
c	Concentration	$[Kgm^{-3}]$
C	Concentration	Dimensionless
Cp	Specific Heat	$[JKg^{-1}K^{-1}]$
Cs	Concentration susceptibility	[m3Kg^{-1}]
D	Solutal diffusivity	$[m^2s^{-1}]$
Da	Darcy number	$[Wm^{-1}K^{-1}L^{-1}]$
D_f	Dufour Parameter	Dimensionless
G	Gravitational acceleration	$[ms^{-2}]$
K	Thermal conductivity	$[Wm^{-1}K^{-1}]$
L	Length of side	[m]
Nr	Buoyancy Ratio number	Dimensionless
Nu	Nusselt Number	Dimensionless
P	Pressure	Dimensionless
Pr	Prandtl Number	Dimensionless
Ra	Rayleigh Number	Dimensionless
Ra_C	Solutal Rayleigh number	Dimensionless
Ra_T	Thermal Rayleigh number	Dimensionless
Re	Reynolds Number	Dimensionless
Ri	Richardson Number	Dimensionless
Sc	Schmidt Number	Dimensionless
T	Temperature	[K]
u,v	Velocity component	[m/s]
U,V	Velocity component	Dimensionless
x,y	Cartesian coordinates	[m]
X,Y	Cartesian coordinate	Dimensionless

Greek Letters

Symbol	Meaning	Unit
α	Thermal diffusivity	$[m^2s^{-1}]$
β	Thermal Expansion Coefficient	$[K^{-1}]$
θ	Temperature	Dimensionless
μ	Dynamic viscosity	$[Nsm^{-2}]$
ν	Kinematic Viscosity	$[m^2s^{-1}]$
ρ	Density	$[kgm^{-3}]$
φ	Nanoparticles Volume fraction	Dimensionless

Subscripts

c	Cold
h	Hot
nf	Nanofluid
s	Solid particle

I. INTRODUCTION

The Prandtl number is the ratio of viscosity to thermal diffusivity. The Prandtl number will influence the fluid flow as long as the temperature and velocity field are coupled, such as in the context of the Boussinesq approximation. The Boussinesq approximation consists of assuming that density of the fluid varies with temperature linearly, but that the only non vanishing effect of this variation is due to the force of gravity. Thus there is no difference in the inertial mass due to temperature variations. This assumption leads to the Boussinesq equations, which are a set of coupled PDEs, one which is the Navier Stokes equation with a body force term coming from gravity and proportional to temperature, and the other which is the advection diffusion equation for the temperature field. Heat and mass transfer induced by double-diffusive mixed convection in fluid saturated porous media have practical importance in many engineering applications. This aspect of fluid dynamics is gaining attention towards researchers all over the world. Migration of moisture in fibrous insulation, drying processes, chemical reactors, transport of contaminants in saturated soil and electro-chemical processes are some examples of double diffusive natural convection phenomenon [1-3]. Double diffusion occurs in very wide range of fields such as oceanography, astrophysics, geology, biology and chemical processes, as well as in many engineering applications such as solar ponds, natural gas storage tanks, crystal manufacturing and metal solidification process [4-6] Nanofluid is a new kind of heat transfer medium, containing nanoparticles (1–100 nm) which are uniformly and stably distributed in a base fluid. These distributed nanoparticles, generally a metal or metal oxide greatly enhance the thermal conductivity of the nanofluid, increases conduction and convection coefficients, allowing for more heat transfer [7-8]

The Effects of heat and mass transfer are investigated in a cylindrical geometry for a wide range of non-dimensional parameters. They extended their investigation for a mixed convection flow in a square cavity whose top wall is moving from left to right with the combined buoyancy effects of heat and mass diffusion. Nusselt and Sherwood numbers at the bottom wall are studied for the selected non-dimensional parameters. Khanafer and vafai [9] presented an unsteady laminar mixed convection heat transfer in a lid-driven cavity. The forced convective flow inside the cavity was attained by a mechanically induced sliding lid, which was set to oscillate horizontally in a sinusoidal fashion. The natural convection effect was sustained by subjecting the bottom wall to a higher temperature than its top counterpart. The two vertical walls were kept constant. Chen and Cheng [10] numerically investigated the Periodic behaviour of the mixed convective flow in a rectangular cavity with a vibrating lid. Heat transfer performance of nanofluid in a complicated cavity due to Prandtl number variation studied by Parvin, et al. [11].R. Nasrin and Alim [12]numerically investigated effect of Prandtl number on free convection in a solar collector filled with nanofluid. Whereas effect of Prandtl number on forced convection in a two sided open enclosure using nanofluid analysed by Parvin et al. [13]. Therefore in the present study attention will be focused on effect of Prandtl number on nanofluid flow inside two sided lid driven square porous cavity [14-19]. The effect of velocities, stream line contours, temperature and concentration gradients are investigated over the range of different Prandtl number including nanofluid concentration.

II. MATHEMATICAL ANALYSIS

Consider a square cavity filled with a porous medium of length L as shown in Figure 1. Top and bottom wall are insulated, and impermeable to mass transfer and the left and right wall are kept at constant temperature and concentration. The right wall is kept at high temperature (θ_h) and concentration (C_h), whereas, the left wall is at low temperature (θ_c) and concentration (C_c). the forced convection is provided by the movement of the left and right walls with constant velocity V_0 in y+ direction. The cavity is filled with an incompressible Newtonian fluid. Also the properties of the fluid such as thermal conductivity and diffusivity are kept at constant except for density.

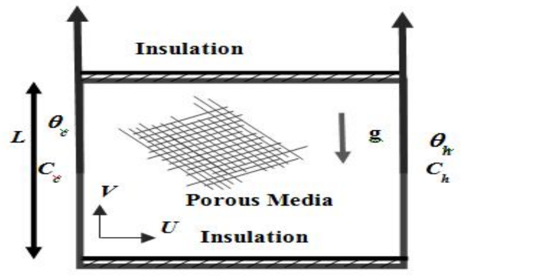

FIGURE 1: Schematic geometry and boundary condition

Under the above considerations, the dimensionless governing equations of mass, momentum and energy of the system are followed by momentum and energy of the system are followed by

Continuity Equation:

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0 \quad (1)$$

X Momentum Equation:

$$U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}=-\frac{\rho_f}{\rho_{nf}}\frac{\partial P}{\partial X}+\frac{\nu_{nf}}{\nu_f}\frac{1}{Pr}(\nabla^2 U)-\frac{\nu_{nf}}{Da}U \quad (2)$$

Y Momentum Equation:

$$U\frac{\partial V}{\partial X}+V\frac{\partial V}{\partial Y}=-\frac{\rho_f}{\rho_{nf}}\frac{\partial P}{\partial Y}+\frac{\nu_{nf}}{\nu_f}\frac{1}{Pr}(\nabla^2 V)-\frac{\nu_{nf}}{Da}V+Ri(\theta+NrC) \quad (3)$$

Energy Conversation Equation

$$U\frac{\partial \theta}{\partial X}+V\frac{\partial \theta}{\partial Y}=\frac{\alpha_{nf}}{\alpha_f}\frac{1}{Pr}\left(\frac{\partial^2\theta}{\partial X^2}+\frac{\partial^2\theta}{\partial Y^2}\right)+Df\left(\frac{\partial^2 C}{\partial X^2}+\frac{\partial^2 C}{\partial Y^2}\right) \quad (4)$$

Concentration Conversation Equation

$$U\frac{\partial C}{\partial X}+V\frac{\partial C}{\partial Y}=\frac{D_{nf}}{D_f}\frac{1}{Sc}\left(\frac{\partial^2 C}{\partial X^2}+\frac{\partial^2 C}{\partial Y^2}\right)+Sr\left(\frac{\partial^2\theta}{\partial X^2}+\frac{\partial^2\theta}{\partial Y^2}\right) \quad (5)$$

Where the non- dimensional Parameters are defined in the following forms,

$$X=\frac{x}{L},\ Y=\frac{y}{L},\ U=\frac{u}{U_0},\ V=\frac{v}{U_0},\ P=\frac{p}{\rho_{nf}U_0^{\ 2}},$$

$$\theta=\frac{T-T_c}{T_h-T_c},\ C=\frac{c-c_c}{c_h-c_c},$$ with $T_h>T_c$ and $C_h>C_c$

Here $Pr=\nu_f/\alpha_f$ be the Prandtl number, $Ri=Ra/\mathrm{Re}^2$ be the Richardson number, $Ra=g\beta_f(T_h-T_c)L^3/\nu_f\alpha_f$ be the Rayleigh number, $Ra_T=g\beta_{Tf}(T_h-T_c)L^3/\nu_f\alpha_f$ be the thermal Rayleigh number, $Ra_c=g\beta_{cf}(T_h-T_c)L^3/\nu_f\alpha_f$ be the solutal Rayleigh number, $Nr=Ra_c/Ra_T$ be the buoyancy ratio number, $Sc=(\nu/D)_f$ be the Schmidt number, $Df=\left(\frac{D}{\nu}\right)_f\frac{\kappa_{Tf}(C_h-C_c)}{C_s\ C_p\ (T_h-T_c)}$ be the Dufour coefficient and $Sr=\left(\frac{D}{\nu}\right)_f\frac{\kappa_{Tf}\ (T_h-T_c)}{T_m\ (C_h-C_c)}$ be the Soret coefficient.

Thermo Physical Properties of Cu-water nanofluids like effective density, thermal diffusivity, heat capacities and thermal expansion co efficient of nanofluids are given by

$$\rho_{nf}=(1-\varphi)\rho_f+\varphi\rho_p,\quad \alpha_{nf}=k_{nf}/(\rho c_p)_{nf}$$

$$(\rho c_p)_{nf}=(1-\varphi)(\rho c_p)_f+\varphi(\rho c_p)_p,$$

$$(\rho\beta)_{nf}=(1-\varphi)(\rho\beta)_f+\varphi(\rho\beta)_p$$

According to the Brinkmannmodel , the effective dynamic viscosity of the nanofluid is agreed by

$$\mu_{nf}=\frac{\mu_f}{(1-\varphi)^{2.5}}$$

The Thermal conductivity of the nanofluid is modelled by Maxwell- Garnett Model as

$$\frac{k_{nf}}{k_f}=\frac{k_p+2k_f-2\varphi(k_f-k_p)}{k_p+2k_f+\varphi(k_f-k_p)}$$

The boundary conditions for the present problem are specified as :

Boundary conditions	T	C	U	V
Left Wall; X=0; 0≤Y≤1.0	θc	Cc	0	1
Right Wall; X=L; 0≤Y≤1.0	θh	Ch	0	1
Top Wall; 0≤X≤1.0; Y=L;	$\frac{\partial\theta}{\partial y}=0$	$\frac{\partial C}{\partial y}=0$	0	0
Bottom Wall; 0≤X≤1.0; Y=0;	$\frac{\partial\theta}{\partial y}=0$	$\frac{\partial C}{\partial y}=0$	0	0

The average Nusselt number at the heated wall is calculated by integrating the local Nusselt number (Nu) is given by $Nu=\frac{1}{L}\int_0^1\overline{Nu}\,dY$

where, $\overline{Nu}=-\frac{k_{nf}}{k_f}\frac{\partial\theta}{\partial X}$

The average Nusselt number is defined as

$$Nu=-\frac{k_{nf}}{k_f}\frac{1}{L}\int_0^1\frac{\partial\theta}{\partial X}\,dY$$

Similarly, the average Sherwood number at the heated wall is calculated by $Sh=-\frac{D_{nf}}{D_f}\frac{1}{L}\int_0^1\frac{\partial C}{\partial X}\,dY$

III. NUMERICAL IMPLEMENTATION

The Galerkin finite element method is used to solve the non-dimensional governing equations along with boundary conditions for the considered problem. The equation of continuity has been used as a constraint due to mass conservation and this restriction may be used to find the pressure distribution. The finite element method is used to solve the Eqn.(2) - (5), where the pressure P is eliminated by a constraint. The continuity equation (1) is automatically fulfilled for large values of this penalty constraint. Then the velocity components (U, V), temperature (θ) and concentration (C) are expanded using a basis set. The Galerkin finite element technique yields the subsequent nonlinear residual equations. Three points Gaussian quadrature is used to evaluate the integrals in these equations. The non-linear residual equations are solved using Newton–Raphson method to determine the coefficients of the expansions. The convergence of solutions is assumed when the relative error for each variable between consecutive iterations is recorded below the convergence criterion ε such that, $\left|\psi^{n+1} - \psi^{n}\right| \leq 10^{-4}$ where n is the number of iteration and Ψ is a function of U, V, θ and C.

3.1 Mesh Generation

The Finite element meshing of the computational Domain is displayed by the figure 2. Extra Fine meshing is chosen for this geometry.

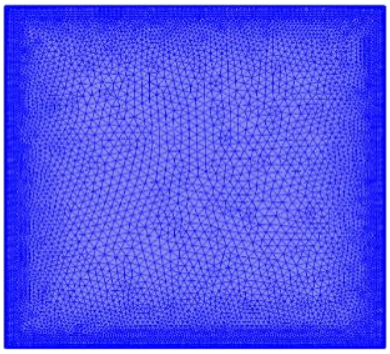

Figure 2 : Mesh generation of the 2D domain

3.2 Grid check

A grid-independent check is performed at Ri = 10; Pr = 5.8; Df = 2, Da = 0.01; Sc = 1; Sr = 1, Nr = 1 and φ = 0.02. Five different non-uniform grid systems are checked with the number of elements: 1504, 2540, 6578, 17038, 26300. Heat and mass transfer rate for different mesh for water-cupper nanofluid (φ=2%) is considered as supervising parameter. It is noticed that the fifth and sixth column of Table 1 that there is no considerable alternation in the value of mean Nusselt and Sherwood number. Thus extra fine Mesh with 17038 elements is considered.

Table 1: Grid Sensitivity Check at Ri = 10; Pr = 5.8; Df = 2, Da = 0.01; Sc = 1; Sr = 1, Nr = 1 and φ = 0.02

Mesh type	Normal	Fine	Finer	Extra Fine	Extremely fine
Elements	1504	2540	6578	17038	26300
Nu	0.564	0.774	0.985	1.126	1.127
Sh	0.5012	0.712	0.859	1.097	1.098
Time (s)	62	105	184	234	295

3.3 Thermo-physical properties

The thermo-physical properties of the base fluid and the nanoparticles are taken from R.Nasrin and Alim [14]

Table 2.Thermo-physical properties of water-Cu nanofluid

Physical Properties	water	Cu
$C_p[JKg^{-1}K^{-1}]$	4179	385
ρ $[kgm^{-3}]$	997.1	8933
k $[Wm^{-1}K^{-1}]$	0.61	401
$\alpha \times 10^7[m^2s^{-1}]$	1.47	1163.1
$\beta \times 10^5[K^{-1}]$	21	1.67

3.4 Code Validation

The present code results for average Nusselt (Nu) number with Pr = 0.71 and Ra = 10^5 in comparison with Tiwari and Das [20] and Nasrin and Alim [21]. Table 3 shows the comparison between the result obtained with new model and the presented in the literature. The quantitative comparisons for the average Nusselt numbers along the hot wall and the maximum velocity values and their corresponding locations indicate an excellent agreement.

Table 3: Comparison of base fluid solutions with previous works in an enclosure for Pr = 0.71 and Ra = 10^5

	Present	Nasrin and Alim [21]	Tiwari and Das [20]
U_{max}	34.931	35.892	34.30
y	0.859	0.861	0.856
V_{max}	68.8621	68.9321	68.7646
x	0.6023	0.06429	0.05935
Nu	4.439	4.431	4.450

IV. RESULT AND DISCUSSION

Mathematical consequences of velocity, temperature and concentration for various Prandtl number (Pr) with water/ copper nanofluid through a square shaped lid-driven porous cavity are displayed. The considered values of Pr are Pr = (0.71, 5.8, 7 and 10) while Ri = 10, Df = 2, Da = 0.01, Sc = 1, Sr = 1, Nr = 1 and φ = 0.02 are kept fixed. Also, the mean Nusselt and Sherwood numbers are shown graphically for the pertinent parameter.

4.1 Effect of Prandtl number

The effect of Pr on stream function, isotherm and Iso-concentration is shown in Fig 4-6. For different Pr number numerical investigations of velocity, isotherm and concentration with water based nanofluid having copper nanoparticle through a square cavity are displayed. The darcy number Da = 0.01, Richardson Number, Ri = 10,Dufour coefficient Df = 2, Soret coefficient Sr = 1, Rayleigh number Ra = 10^4 and Schmidth number Sc = 1 are kept fixed. The considered values of Pr number are Pr (= 0.71, 5.8, 7 and 10). Also, for the above mentioned parameter, the mean Nusselt number, mean Sherwood number inside the cavity are revealed graphically. Da signifies the degree of porosity in the fluid, the higher the Da, the lower the porosity. For Pr = 0.71, the viscosity is low, hence the heat transfer by convection and fluid flow behaviour increases. However at Pr = 5.8, the concentration and temperature profiles drift towards the left slightly.

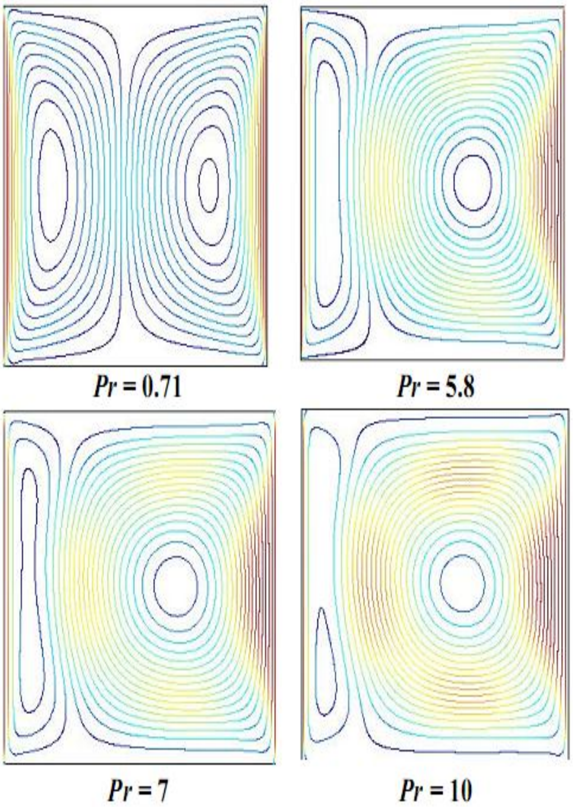

Figure 4: Streamline for Ri = 10, Df = 2, Da = 0.01, Sc = 1, Sr = 1, Nr = 1 and φ = 0.02

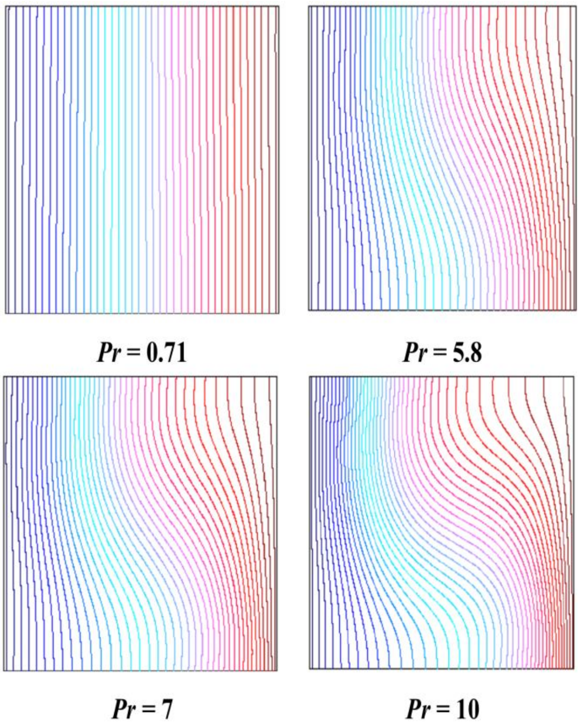

Figure 5: Isothermal contour for Ri = 10, Df = 2, Da = 0.01, Sc = 1, Sr = 1, Nr = 1 and φ = 0.02

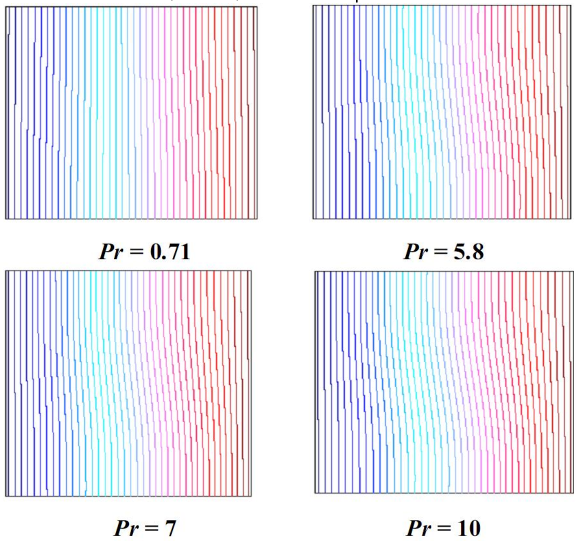

Figure 6: Iso-concentration contour for Ri = 10, Df = 2, Da = 0.01, Sc = 1, Sr = 1, Nr = 1 and φ = 0.02

For Pr = 0.7, the temperature and concentration profiles are analogous to each other, because the thermal and mass diffusivity are same and at the same time the flow in dominated by a counter clockwise describing the dominancy of convection, At low Pr, The molecules of substances are loosely packed and heat and mass transfer is taking place in an anticlockwise direction. Therefore, the effect of the lid with the movement of low-density fluid particles near the right wall accelerates the flow in an antilock wise direction. As the Pr increase to 10, the momentum diffusivity dominates the thermal diffusivity and hence the temperature distribution takes places mainly due to convection.

The effects on streamline are observed and it is clearly seen how the flow pattern increase from right heated wall to left cold wall at the change of Pr from 0.71 to 10. Here in two streamline right streamlines flowing in counter clockwise direction with hot fluid whereas the lower streamlines in the clockwise direction with cold fluid is observed.

The effect on isotherm and iso concentration as observed in the given result that the changes in isotherm are remarkable with the change of Pr, but the changes in iso concentration are quite similar. Increase of Pr from 0.71 to 10,figure shows the flow on top right slightly drift to left in isotherm.

4.2 Mean Nusselt and Sherwood number

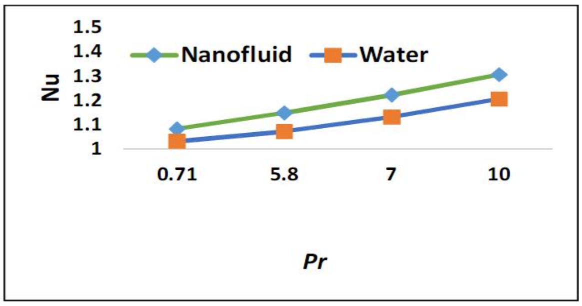

Figure 7: Average Nusselt number against Pr

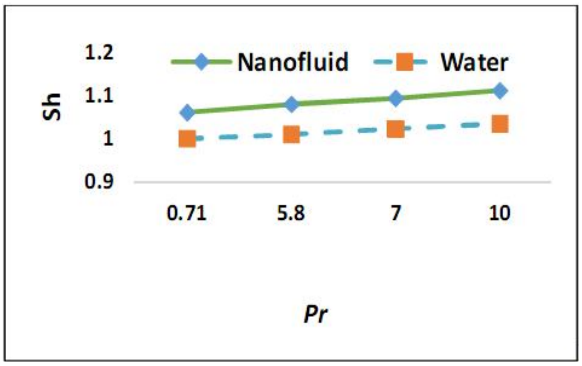

Figure 8: Average Sherwood number against Pr

From the plot of the average Nusselt number (Nu) a measure of heat transfer is optimized at the highest Pr for both types of fluids. Fig 7 shows that heat transfer rate increase by 41% and 36% due to rising Pr from 0.71 to 10 for nanofluid and base fluid respectively. Thus heat transfer rate is more effective for nanofluid than the base fluid.

Again figure 8 shows that mass transfer rate increase by 0.59% and 0.48% due to rising Pr from 0.71 to 10 for nanofluid and base fluid respectively. Thus mass transfer rate is not so changeable for nanofluid than the base fluid. But in comparison of water it is clear that due to use of nano particle the heat and mass transfer rate increases.

CONCLUSION

Prandtl Number Effect on Nanofluid Flow inside a Porous Cavity filled with Cu-water nanofluid has been studied numerically. Various Pr number have been considered for streamline, isotherm and iso concentration to calculate heat and mass transfer rate. The result of the numerical analysis lead to the following conclusion:

⇨ The structure of the fluid flow and temperature field within the closed chamber is found significantly depend upon Pr number.

⇨ The nanoparticle within the highest Pr is established to be most effective in enhancing performance of heat transfer rate.

⇨ Mass transfer rate following Sh values have the same pattern for all the values of Pr because the concentration profiles do not change significantly for values of Pr.

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