Heated Obstacle Effect on Natural Convection in Nanofluid full Porous Cavity using Buongiorno's model

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Abstract: Buongiorno's two-phase model was used to study the laminar flow, heat transfer and mass 100transfer of a nanofluid in a porous medium with an irregular, non-uniform octagonal shape. A finite element method was used to study the improvement of the heat transfer rate inside the porous cavity, by equipping the cavity with a heated diamond. at different horizontal positions, as well as different sizes. The left wall of this cavity is maintained at a high temperature, the right wall is subjected to a low temperature, while the other walls are considered to be adiabatic. The aim of this paper is to demonstrate the effect of a heated square inclined at 45° and at different horizontal positions on the evolution of hydrodynamic, thermal and mass profiles. This study takes into account the influence of certain parameters, such as porosity, by assigning the following values to the Darcy number: 10^{-2}, 10^{-4}, and 10^{-6}. In addition, the size of the side of the square is varied between 0.75L, L and 1.25L, where L represents the length of the side of the diamond. The Rayleigh, Lewis and Prandtl numbers are set at 10^4, 1 and 6.2 respectively, while the thermophoresis, buoyancy and Brownian motion ratios are set at 0.5, 1, 0.5 respectively.

Keywords: Natural convection, Porous medium, Buongiorno's Model, Nanofluids, finite element.

1. INTRODUCTION

Engineering systems have made significant developments, and industries are constantly looking for new approaches and innovations to optimize performance. Due to the importance of thermal fluids for heat transfer, researchers have been particularly interested in nanofluids because of their high thermal conductivity. Because of their unique structure, porous media have also been widely studied. Heat transfer is of relevant in many fields, and natural convection in a saturated porous medium has attracted increasing interest over the last decade due to its varied applications, such as solar energy storage, electronic cooling devices, and buildings. Researchers are therefore focusing more on nanofluids because of their high heat conductivity. In their study, A. Aldabesh. et.al. (2021) used the Buongiorno model to examine the Brownian effect and the diffusion parameters associated with thermophoresis. They found that increasing the Reynolds and Prandtl numbers leads to a decrease in the temperature profile. The studies of Izadi M. et al. (2018), Alsabery A.I et al. (2018) and Motlagh S. and Motlagh M. (2017) explored natural convection in nanofluids using Buongiorno's two-phase model, but M.A. Sheremet. et.al. (2015) investigated free convection in corrugated porous cavities using Buongiorno's nanofluid model. The studies of Shafqat H and Sameh Ahmed. (2019), Gholamreza H. et al. (2018), Sheremet M. et al. (2015 a), Sheremet M.A. et al. (2015 b) and Leory T. et al. (2014) examined the natural convection of nanofluids in porous materials using Buongiorno's mathematical model. Saber Y. et.al. (2016) inspected natural convection in an inclined porous nanofluid cavity using Buongiorno's mathematical model. Sara L. et.al (2020) by studying the flow of viscoplastic fluids filled with hybrid nanoparticles, she found that the distribution of particles is the same for both constituents. B. Mahanthesha. et.al. (2021) results show that two heat source mechanisms conduct to improve the temperature profile and the Brownian parameter is sensitive to the heat transfer. A. Sheikhzadeh and S. Nazari (2013) Found that heat transfer increases with the increase of both Rayleigh number and Darcy number. It is further observed that the heat transfer in the cavity is improved by increasing of solid volume fraction parameter of nanofluids.

This paper discusses natural convection in open cavities filled with a porous medium, containing an inclined heated square. The analysis is carried out using Buongiorno's nanofluid model and is structured in five sections. This paper begins with an introduction that reviews previous research in this field. Section 2 presents the fundamental equations governing the problem and the boundary conditions. Section 3 describes the proposed physical geometry, validation results and results found in the literature, and includes a mesh study. Section 4 discusses the results of the computer simulations, highlighting the influence of the position, the size and porosity on the flow of the nanofluid. Finally, section 5 offers a general conclusion summarising the main results obtained in the study.

2. FUNDAMENTAL RELATIONS

2.*1 Governing equations*

The dimensional equations governing laminar flow in a porous medium include conservation of momentum (Navier-Stokes equations), conservation of energy (heat equation) and conservation of dispersion (concentration, according to the Buongiorno model).

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \quad (1)$$

$$\rho\left(u\frac{\partial u}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)-\frac{\mu}{K}u \quad (2)$$

$$\rho\left(u\frac{\partial u}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{\partial p}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)-\frac{\mu}{K}v+\left[(1-C_c)\rho_f(T-T_c)\beta_f-(C-C_c)(\rho_s-\rho_f)\right]g \quad (3)$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)+\delta\left\{D_B\left(\frac{\partial T}{\partial x}\frac{\partial C}{\partial x}+\frac{\partial T}{\partial y}\frac{\partial C}{\partial y}\right)+\frac{D_T}{D_C}\left[\left(\frac{\partial T}{\partial x}\right)^2+\left(\frac{\partial T}{\partial y}\right)^2\right]\right\} \quad (4)$$

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D_B\left[\left(\frac{\partial^2 C}{\partial x^2}+\frac{\partial^2 C}{\partial y^2}\right)+\frac{D_T}{D_C}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)\right] \quad (5)$$

$D_B = K_b T_0 / 3\pi\, d_p \mu$ the Brownian motion coefficient,
$D_T = \beta\mu C_0 / \rho_f$, is the thermophoresis coefficient,
α is the effective thermal conductivity and the parameter is defined by $\delta = (\rho C_P)_s / (\rho C_P)_f$.

In order to generalise the phenomenon studied, a set of adimensional variables has been introduced. These variables, appropriately defined, reveal adimensional groups characteristic of the problem. This approach makes it easier to analyse the results and compare them with other studies. It is defined as follows:

$$X=\frac{x}{H};\ Y=\frac{y}{H};\ U=\frac{uH}{\alpha_f};\ V=\frac{vH}{\alpha_f};\ \theta=\frac{(T-T_c)}{(T_h-T_c)};$$

$$\emptyset=\frac{(C-C_c)}{(C_h-C_c)};\ Ra=\frac{(1-C_c)g\beta_f(T_h-T_c)H^3}{v_f\alpha_f}$$

$$Pr=\frac{v_f}{\alpha_f};L=\frac{\alpha_f}{D_B};P=p\frac{H^2}{\rho_f\alpha_f^2};$$

$$Nr=\frac{(C_h-C_c)(\rho_s-\rho_f)}{(1-C_c)\beta_f\rho_f(T_h-T_c)};Da=\frac{K}{H^2};$$

$$Nb=\frac{(C_h-C_c)D_B(\rho Cp)_s}{\alpha_f(\rho Cp)_f}=\frac{D_B\delta(T_h-T_c)}{\alpha_f};$$

$$Nt=\frac{D_T(\rho Cp)_s(T_h-T_c)}{T_c(\rho Cp)_f\alpha_f}=\frac{D_T\delta(T_h-T_c)}{T_c\alpha_f}$$

$$\frac{\partial U}{\partial Y}+\frac{\partial V}{\partial Y}=0 \quad (6)$$

$$U\frac{\partial U}{\partial X}+V\frac{\partial V}{\partial Y}=-\frac{\partial P}{\partial X}+Pr\left(\frac{\partial^2 U}{\partial X^2}+\frac{\partial^2 U}{\partial Y^2}\right)-\frac{Pr}{Da}U \quad (7)$$

$$U\frac{\partial U}{\partial X}+V\frac{\partial V}{\partial Y}=-\frac{\partial P}{\partial Y}+Pr\left(\frac{\partial^2 V}{\partial X^2}+\frac{\partial^2 V}{\partial Y^2}\right)-\frac{Pr}{Da}V+Ra\,\mathrm{Pr}\,(\theta-Nr\emptyset) \quad (8)$$

$$U\frac{\partial \theta}{\partial X}+V\frac{\partial \theta}{\partial Y}=\left(\frac{\partial^2 \theta}{\partial X^2}+\frac{\partial^2 \theta}{\partial Y^2}\right)+Nt\left[\left(\frac{\partial \theta}{\partial X}\right)^2+\left(\frac{\partial \theta}{\partial Y}\right)^2\right] \quad (9)$$

$$X\frac{\partial \emptyset}{\partial X}+V\frac{\partial \emptyset}{\partial Y}=\frac{1}{L}\left(\frac{\partial^2 \emptyset}{\partial X^2}+\frac{\partial^2 \emptyset}{\partial Y^2}\right)+\frac{Nt}{Nb}\left[\left(\frac{\partial^2 \theta}{\partial X^2}+\frac{\partial^2 \theta}{\partial Y^2}\right)\right] \quad (10)$$

2.2 *Boundary conditions*

The envisaged problem is subject to the following boundary conditions in the dimensionless form of the cavity walls:

- On the left wall of the cavity: *U=0; V=0; ϕ=1; Θ=0.*
- On the right wall of the cavity: *∂U/∂X=0; ∂V/∂X=0; Θ= 1; ϕ=1.*
- On the top wall of the cavity: *∂U/∂Y=0; ∂V/∂Y=0; ∂Θ /∂Y=0,∂ ϕ /∂Y=0.*
- On the bottom wall of the cavity: *∂U/∂Y=0; V=0; ∂Θ /∂Y=0; ∂ϕ/∂Y=0.*

2.3 *quantification number*

The Nusselt number is an essential dimensionless variable for heat transfer analysis. It quantifies the relationship between heat transfer by convection and heat transfer by conduction. his dimensionless variable is defined by this simple mathematical formula:

$$Nu=\frac{hW}{k} \quad (11)$$

the coefficient of heat transfer *h* is given by:

$$h=\frac{q}{T_h-T_c} \quad (12)$$

The heat flux q at the wall is:

$$q=-k\frac{(T_h-T_c)}{W}\frac{\partial \theta}{\partial X}\bigg|_{X=0} \quad (13)$$

$$Nu=\frac{\partial \theta}{\partial X}\bigg|_{X=0} \quad (14)$$

$$Nu_{avg} = \frac{1}{L_S}\int_0^{L_S} Nu\, ds \qquad (15)$$

2.4 Nomenclature

k	Thermal conduction ($Wm^{-1}K^{-1}$)
g	Gravitational acceleration ($m\ s^{-1}$)
C_p	Specific heat ($J\ kg^{-1}K^{-1}$)
Pr	Prandtl number
Nu	Nusselt number (local)
Ra	Rayleigh number
Da	Darcy number
Nr	Buoyancy ratio number
Nb	Brownian motion parameter
L	Lewis number
Nt	thermophoresis parameter
Nu_{avg}	Average Nusselt
x, y	Space coordinates in dimensional form (m)
X, Y	Dimensionless space coordinate
u, v	Velocity components in dimensional form (m^{-1})
p	Pressure (Nm^{-2})
T	Temperature in dimensional form (K)
U, V	Dimensionless velocity components
P	Dimensionless pressure
ν	Kinetic viscosity (m^2s^{-1})
μ	dynamic viscosity ($kg\ m^{-1}s^{-1}$)
β	Thermal expansion coefficient (K^{-1})
ρ	density ($kg\ m^{-3}$)
α	thermal diffusivity ($m^2\ s^{-1}$)
θ	dimensionless temperature
ϕ	dimensionless concentration
c	cold
h	hot
f	fluid

3. FUNDAMENTAL RELATIONS

3.1 Validation

The present study was validated by comparing its results with the work of Hussain Shafqat and Ahmed Sameh E. (2019) for the following parameters: $Ra=10^5$, $Da=10^{-5}$, $Nr=Le=1$, $Nt=Nb=0.5$ and $Pr=6.2$. Validation was carried out on an open rectangular porous cavity filled with nanofluid, for a Darcy number value of 10^{-6}. A comparison of the isotherms and streamlines, shown in Figure 1, reveals that the results display identical variations.

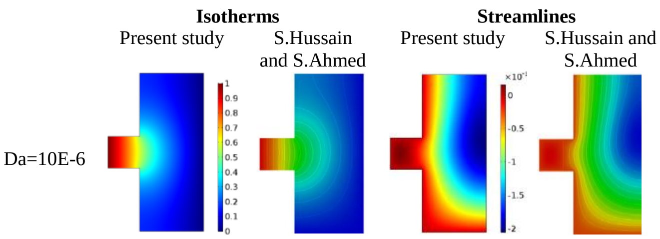

Figure 1. Isotherms and streamlines between the comparison of reference study and the present study.

In addition, a comparison of the average Nusselt number was carried out under the same conditions. An overall difference of 2.56% was observed, as shown in Figure 2, confirming the consistency of the results obtained with those of the reference study.

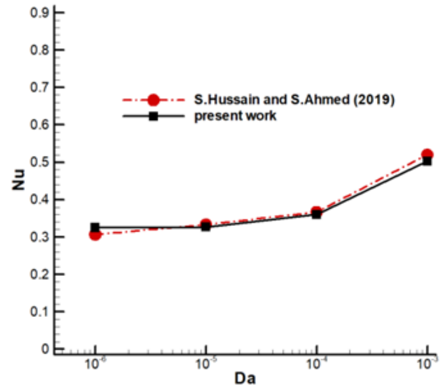

Figure 2. Comparison of the average Nusselt number between the Hussain S. and Ahmed S. study and the present study.

3.2 the proposed geometry

A rectangular open cavity filled with a porous medium saturated with nanofluid and a square moving vertically along the height of the rectangle was used to study the natural convection. The cavity has horizontal adiabatic walls, the vertical wall and the square inside are kept to a high constant temperature *Th*, a vertical open face is fixed to a low temperature *Tc* and the vertical walls above and below the aperture are maintained insulated.

To obtain and analyse results, some simplifications are taken into account: the nanofluid is Newtonian and incompressible; the influence of the slipping, the effect of thermal radiation and viscous dissipation are supposed neglected; the porosity and permeability of the porous medium are supposed to be uniform, and the flow is laminar

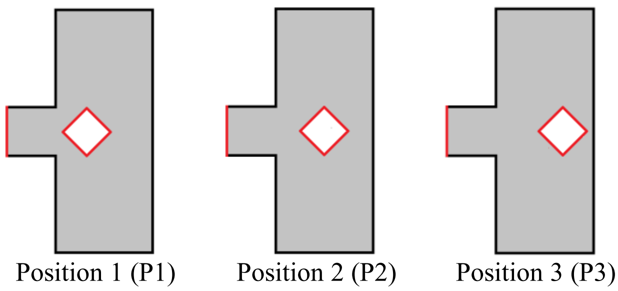

Figure 2. Model varying the horizontal position of the inclined square.

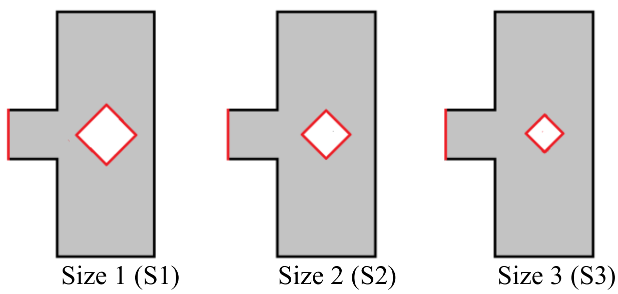

Figure 3. Model varying the size of the inclined square.

In order to investigate the influence of the position and size of the inclined square, two models have been proposed.

The horizontal position of the inclined square: Three positions were considered: a/4, a/2 and 3a/4, where a represents the width of the cavity. As shown in figure 2

The size of the inclined square: As Figure 3 illustrates, three sizes were also studied: 0.75b, b and 1.25b, where b corresponds to the length of the side of the inclined square.

3.3 Mesh test

A mesh test was carried out in order to select the mesh that would give stable results with a minimum number of elements and optimum calculation time. An unstructured mesh composed of triangular and quadrilateral elements was applied to the computational domain. Five meshes were tested to compare the evolution of the mean Nusselt number (Nu) with temperature (T) for the following conditions: $Ra=10^5$, $Da=10^{-3}$, $Nr=Le=1$, $Nt=Nb=0.5$ and $Pr=6.2$, as shown in Table 1. For this study, we chose the fourth mesh.

Table 1. Independence mesh test for present configuration.

Elements	17720	26986	39170	**65936**	104290
Time	42 s	61 s	91 s	**154 s**	251 s
T	0.18409	0.18304	0.18251	**0.18188**	0.18154

4. RESULTS AND DISCUSSION

The impact of the horizontal positions and the size of the heated inclined square (obstacle) on the natural convection was explored. The numerical results are presented by isotherms, streamlines, and the average Nusselt number for different values of the Darcy number and various positions and sizes of the diamond.

Figure 6 and figure 7, respectively show the effect of the positions (P1 to P3) and sizes (S1, S2, S3) of a heated obstacle on isotherms and streamlines assuming the following constants: $Nt = Nb = 0.5$, $Nr = Le=1$, $Da = 10^{-4}$, $Ra = 10^4$ and $Pr=6.2$.

We can see on figure 6 that whatever the size of the obstacle, the isotherms will always be concentrated to the left of it, particularly in the prominent part, in a relatively symmetrical way with a slight diffusion towards the exit due to buoyancy forces. As the size of the obstacle increases and as it moves to the right, the isotherms cover a larger part of the cavity.

The streamlines flow clockwise from the cold wall to the hot wall as shown in figure 7. The position and size of the obstacle have a minimal impact on the distribution of the flow streamlines. However, it can be seen that heat transfer by convection is increased on the left side and decreased on the right. When the tetragonal heat source is moved from position p1 to position p3, the flow becomes more intense on the left side of the obstacle and weaker on the right side. This is because, with the obstacle deflected from the centre of the cavity, resistance to fluid movement is reduced on the left- side due to the larger area available for fluid movement.

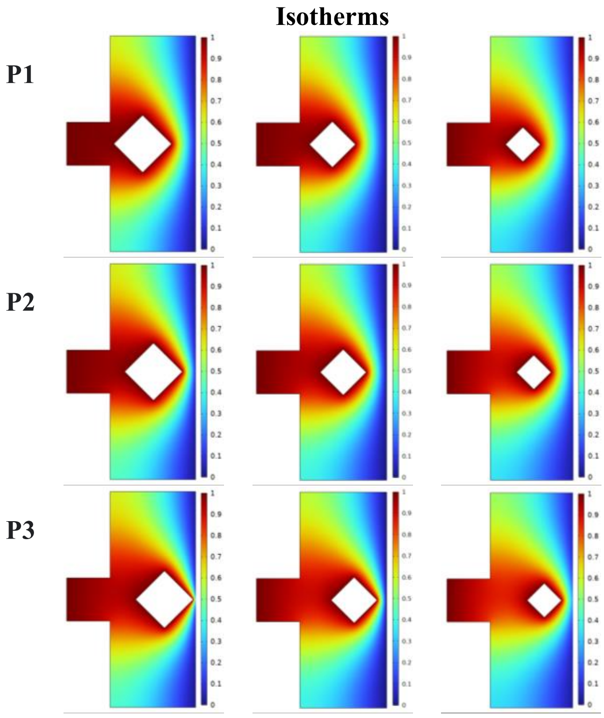

Figure 6. Evolution of isotherms for natural convection in an open cavity varying the position and the size for $Nt = Nb = 0.5$, $Nr = Le=1$, $Da = 10^{-4}$, $Ra = 10^4$ and $Pr=6.2$.

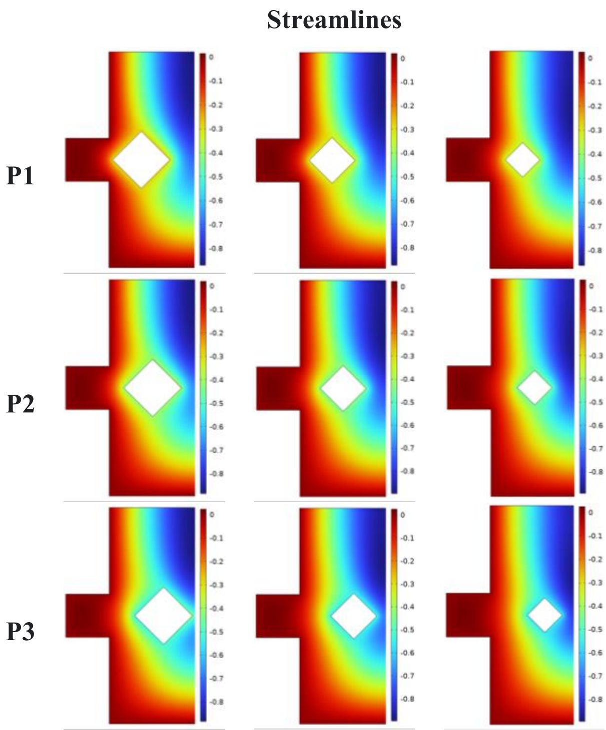

Figure 7. Evolution of streamlines for natural convection in an open cavity varying the position and the size for $Nt = Nb = 0.5$, $Nr = Le=1$, $Da = 10^{-4}$, $Ra = 10^4$ and $Pr=6.2$.

Figure 8, show isotherms and streamlines by varying $10^{-6} \leq Da \leq 10^{-2}$ at position 2 (P2) for the size 2 (S2). It can be noticed that the Darcy number affects the isotherms and streamlines.

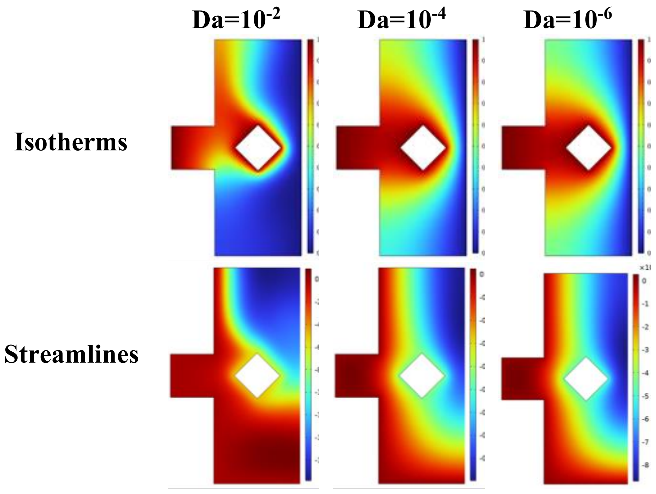

Figure 8. Evolution of isotherms and streamlines for natural convection in an open porous cavity in function *Da* for (S2) at P2 and for $Nt = Nb = 0.5$, $Nr = Le = 1$, $Da = 10^{-4}$, $Ra = 10^4$ and $Pr = 6.2$.

An increase of the darcy number causes an improvement of the temperature difference inside the cavity which leads to an increase of the natural convection by reducing the resistance force to the flow of the nanofluid in the porous medium as showin figure 8. The streamlines are significant to the left of the diamond for different values of Darcy number. By increasing Da, buoyancy increases because the increased permeability allows nanofluids to flow more easily, reducing fluid friction in the porous medium, which leads to better natural convection.

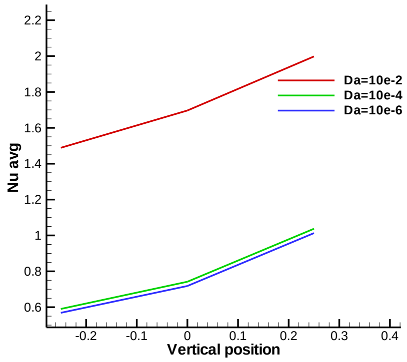

Figure 9. Variation of the average Nusselt number as a function of the position for different Da.

Figure 9 illustrates the variation in the average Nusselt number for different values of Darcy number as a function of the position of the obstacle. It can be seen that increasing the Darcy number leads to an increase in the average Nusselt number. A notable observation is that, for $Da=10^{-2}$, thermal convection is significantly improved compared with the other values.

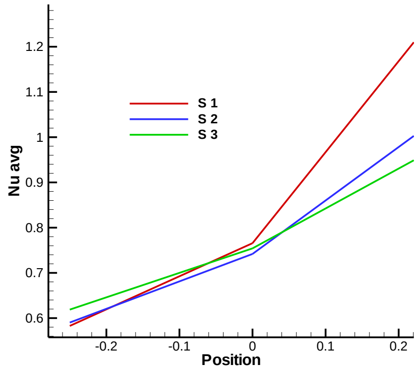

Figure 10. Variation of the average Nusselt number as a function of the position for different sizes of the obstacle.

When the obstacle moves to the left of the centre of the cavity, it can be seen that the greater the size of the obstacle, the greater the convective heat transfer. However, when the obstacle moves to the right, the effect is the opposite: the average Nusselt number is higher for the smallest obstacle size when it is in position P3.

5. CONCLUSIONS

The numerical results obtained to study the impact of the movement of a hot inclined square on the steady natural heat transfer in an open rectangular enclosure saturated with a porous medium filled with nanofluids are presented in this article. The Darcy model and the Buongiorno model were used to simulate the porous medium and the nanofluids, respectively. The transport equations were presented and converted into dimensionless form, then solved numerically using the finite element method. The streamlines, isotherms and mean Nusselt number were defined for the governing parameters: the size and position of the heated obstacle and the Darcy number. The main conclusions are as follows:

- Heat transfer by convection increases on the left and decreases on the right of the obstacle.
- An increase in the Darcy number leads to an increase in the heat transfer by convection.
- By increasing the Darcy number (Da), buoyancy increases allowing nanofluids to flow more easily, by reducing fluid friction in the porous medium and leading to improved natural convection.
- The increase in the Darcy number leads to an increase in the average Nusselt number.
- When the obstacle moves to the left of the center of the cavity, the greater the size of the obstacle, the greater the heat transfer by convection.
- When the obstacle moves to the right, the effect is the opposite: the average Nusselt number is higher for the smaller obstacle when it is in position P3.

This study makes a significant contribution to academic and engineering research, as the geometry considered can be used as a passive technique to control heat transfer. Furthermore, natural convection in porous media has been an attractive research topic for many authors and remains relevant today due to its various practical applications in different fields. These applications include mechanical engineering, solar heating systems, geothermal energy extraction, oil recovery, heat exchangers and agricultural storage.

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