Çukurova Üniversitesi Mühendislik Mimarlık Fakültesi Dergisi, 31(ÖS 2), ss. ÖS 143-ÖS 151, Ekim 2016
Çukurova University Journal of the Faculty of Engineering and Architecture, 31(SI 2), pp. SI 143-SI 151, October 2016

Nanoparticle Shape Effect on Natural Convection in a Corner Partitioned Square Cavity

Fatih SELİMEFENDİGİL[*1], Aslı AKYOL İNADA[1]

[1]*Department of Mechanical Engineering, Faculty of Engineering, Celal Bayar University, Manisa*

Geliş tarihi: 20.07.2016 *Kabul tarihi: 15.10.2016*

Abstract

In this study, numerical investigation of natural convection in a corner partitioned square cavity filled with nanoparticles of different shapes was performed by using finite element method. The left and right vertical walls of the cavity are kept at constant temperatures while the horizontal walls are adiabatic and the corner partition is conductive. The numerical study was performed for various values of Rayleigh numbers, solid nanoparticle volume fractions, radii of the corner partition and different nanoparticle shapes. It was observed that average heat transfer enhances as the value of the Rayleigh number, nanoparticle volume fraction and size of the conductive partition increases. Cylindrical shape nanoparticles show the best performance and spherical ones show the worst performance in terms of heat transfer enhancement.

Keywords: Conjugate natural convection, Nanofluids, Corner partition, Finite element method

Köşe Bölmeli Kare Muhafazada Nanopartikül Şekil Etkisinin Doğal Konveksiyon Üzerine Etkileri

Öz

Bu çalışmada, farklı şekillerde nanopartiküller ile doldurulmuş köşe bölmeli kare boşlukta doğal konveksiyonun sayısal incelenmesi sonlu elemanlar yöntemi kullanılarak gerçekleştirilmiştir. Boşluğun sol ve sağ dikey duvarları sabit sıcaklıkta tutulurken, yatay duvarlar adyabatik ve köşe bölmesi iletkentir. Sayısal çalışma farklı nanopartikül şekilleri ve köşe bölmesinin yarıçapı, katı nanopartikül hacim kesirleri, Rayleigh sayılarının çeşitli değerleri için uygulanmıştır. Rayleigh sayısının, nanopartikül hacim kesrinin ve iletken bölmenin boyutunun artması, ortalama ısı transferini arttırdığı gözlemlenmiştir. Silindir şeklindeki nanopartiküller en iyi performansı gösterirken, küresel olanlar da ısı transferinin iyileştirilmesi açısından en kötü performansı göstermektedir.

Anahtar Kelimeler: Konjuge doğal konveksiyon, Nanoakışkanlar, Köşe bölme, Sonlu elemanlar yöntemi

[*]Sorumlu yazar (Corresponding author): Fatih SELİMEFENDİGİL, *fthsel@yahoo.com*

1. INTRODUCTION

Natural convection in cavities is encountered in many engineering applications ranging from electronic cooling to solar power. This mode of heat transfer is cheap but it should be enhanced to have comparable performance to forced convection.

Active and passive methods cane used to control the convection inside the cavities. In one of these methods, partitions are used within the cavity or on the walls of the cavity to affect the fluid motion and heat transfer characteristics [1-5]. In heat transfer applications, nano-size metallic/non-metallic particles are added to the base fluids such as water or ethylene glycol to enhance the heat transfer. The thermal conductivity of the nanoparticles such as Al_2O_3, CuO, Cu, TiO_2, Ag have higher thermal conductivity compared to the heat transfer fluid and inclusion of these particles enhances the thermal transport for heat transfer applications as it is shown in many numerical and experimental studies [6-9]. The size, type effects on the heat transfer enhancements were used in many studies, but there are a few studies related to the shape effect on the heat transfer performance [10-11].

In this numerical stud, natural convection in a square cavity having a conductive partition an filled with nanoparticle of different shapes (spherical, blade and cylindrical) were investigated. The aim was to identify the effects of parameters on the local and average heat transfer characteristics. The results of this study can be used by researchers in different fields that have to develop a thermal design with natural convection for specific applications such as electronic cooling, thermal storage and many others.

2. PHYSCIAL MODEL AND MATHEMATICAL FORMULATION

A schematic description of the problem is shown in Figure 1. The square cavity is filled SiO_2-water nanofluid of different particle shapes (spherical, blade and cylindrical). A quarter circular conductive partition was added in the left upper corner of the cavity with radius r and thermal conductivity of ks. The left and right vertical cavity walls are maintained at constant temperatures of T_h and T_c while the top and bottom horizontal walls are assumed to be adiabatic. The flow is assumed to be 2D, laminar and the density in the buoyancy force was modelled according to Boussinesq approximation.

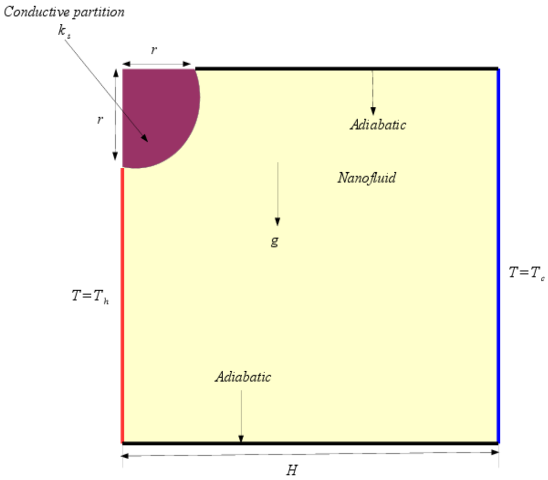


Figure 1. Schematic description of the physical model

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho_{nf}}\frac{\partial p}{\partial x}+\nu_{nf}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \tag{2}$$

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho_{nf}}\frac{\partial p}{\partial y}+\nu_{nf}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+\beta_{nf}g(T-T_c) \tag{3}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha_{nf}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \tag{4}$$

For the conductive solid medium:

$$\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}=0 \tag{5}$$

2.1. Thermo-physical Properties of Nanofluids

The effective thermo-physical properties of nanofluids are defined by using the following formulas:

$$\rho_{nf} = (1-\phi)\rho_{bf} + \phi\rho_p \tag{6}$$

$$\left(\rho c_p\right)_{nf} = (1-\phi)\left(\rho c_p\right)_{bf} + \phi\left(\rho c_p\right)_p \tag{7}$$

$$\left(\rho\beta\right)_{nf} = (1-\phi)\left(\rho\beta\right)_{bf} + \phi\left(\rho\beta\right)_p \tag{8}$$

where the subscripts bf, nf and p denote the base fluid, nanofluid and solid particle, respectively. The effective thermal conductivity of the nanofluid is given as:

$$k_{nf} = k_f\left[\frac{(k_p+2k_f)-2\phi(k_f-k_p)}{(k_p+2k_f)+\phi(k_f-k_p)}\right] \tag{9}$$

Viscosity of the nanofluid given according to Brinkman model as:

$$\mu_{nf} = \frac{\mu_f}{(1-\phi)^{0.25}} \tag{10}$$

2.2. Different Nanoparticle Shapes

For nanoparticle shapes other than spherical, thermal conductivity and viscosity are given by using the following formulas [11]:

$$k_{nf} = k_f\left(1+C_k\phi\right) \tag{11}$$

$$\mu_{nf} = \mu_f\left(1+A_1\phi+A_2\phi^2\right) \tag{12}$$

Constants in the above formulations are given in Table 1 and Table 2.

Table 1. Constants for thermal conductivity of nanofluids for different nanoparticle shapes

Nanoparticle type	C_k
Cylindrical	3.95
Bricks	3.37
Blades	2.74

Table 2. Constants for viscosity of nanofluids for different nanoparticle shapes

Nanoparticle type	A_1	A_2
Cylindrical	13.5	904.4
Bricks	1.9	471.4
Blades	14.6	123.3

2.3. Boundary Conditions

The relevant dimensionless physical and geometrical parameters are:

$$\mathrm{Gr} = \frac{g\beta_f(T_h-T_c)H^3}{\nu_f^{\,2}},$$

$$\mathrm{Pr} = \frac{\nu_f}{\alpha_f}, \quad \mathrm{Ra=GrPr}, \tag{13}$$

$$Kr = \frac{k_s}{k_f}, \quad R = \frac{r}{H}$$

The appropriate forms of the dimensional boundary conditions are:

For the hot vertical wall: $u = v = 0,\ T = T_h$

For the cold wall: $u = v = 0,\ T = T_c$

Along the interface of fluid domain with the solid domains:

$$k_f\left(\frac{\partial\theta}{\partial n}\right)_f = k_s\left(\frac{\partial\theta}{\partial n}\right)_s$$

For the adiabatic walls:

$$u = v = 0, \quad \left(\frac{\partial\theta}{\partial n}\right)_w = 0$$

Local Nusselt number along the hot wall of the enclosure is calculated as:

$$Nu_y = -\frac{k_{nf}}{k_f}\left(\frac{\partial\theta}{\partial n}\right)_{n=0} \tag{14}$$

where θ represents the non-dimensional temperature and S denotes the non-dimensional coordinate along the wall. Averaged Nusselt number is obtained after integrating the local Nusselt number along the hot wall as:

$$Nu_m = \frac{1}{H-r}\int_0^{H-r} Nu_y dy \tag{15}$$

2.4. Solution Methodology

In order to solve the resulting governing equations as described above, Galerkin weighted residual finite element method was used. Weak form the governing equations with Galerkin procedure is established. Each of the flow variables within the discretized finite elements are approximated by using interpolation functions and then the approximations are substituted into the governing equations. Residuals for each of the conservation equation are then obtained. The convergence of the solution is assumed and the solution is terminated when the relative error for each of the variables denoted by Φ satisfy the following convergence criteria:

$$\left|\frac{\Phi^{n+1}-\Phi^{n}}{\Phi^{n+1}}\right| \le 10^{-5} \tag{16}$$

3. RESULTS AND DISCUSSIONS

Figure 2 and Figure 3 demonstrate the effects of varying Rayleigh number and corner partition on the flow and thermal fields within the cavity (ϕ=0.02, spherical nanoparticles). For low Rayleigh number and in the absence of the partition, a singular recirculating vortex is formed. As the value of the Rayleigh number increases, the shape of the vortex is distorted and multi-cellular flow structure is seen within the cavity due to the increased fluid kinetic energy.

The presence conductive partition on the corner affects the flow field and isotherm distribution with the cavity. At R=0.1, the discrepancy between the isotherms is higher at the highest value of Rayleigh number and the diagonal oriented streamline in the absence of partition at R=0, becomes flattened. Further increment of the size of the partition to R=0.4, multi-cellular structure in the flow field disappears at the highest value of the Rayleigh number. Isotherms are more clustered in the lower part of the hot wall and temperature gradients become steeper as the value of Rayleigh number increases. Isotherms within the cavity become parallel to the horizontal walls which indicate the increased effect of convection. The presence of the partition affects the isotherms within the cavity especially at higher values of Rayleigh numbers.

Local Nusselt number distributions along the hot wall in the absence of corner partition and for spherical nanoparticle at ϕ=0.02 are shown in Figure 4 for different values of Rayleigh numbers. Local heat transfer enhancement is seen with increasing R values and this is more effective in the lower part of the hot wall. The average Nusselt number enhances with Rayleigh number and nanoparticle volume fraction as it is seen in Table 3.

Figure 5 demonstrates the effects of nanoparticle shape on the local Nusselt number distributions along the hot wall for two values of corner partition radius at the highest solid nanoparticle volume fraction (Ra=10^5). For both R values, the cylindrical nanoparticle shapes gives the best performance and spherical ones give the worst performance in terms of local heat transfer enhancement. The local enhancement is higher in the location where heat transfer is higher which is the lower part of the hot vertical wall. Table 4-6 show the influence of varying solid nanoparticle volume fraction and shape on the average Nusselt number for different radii of the corner partition at Ra=10^5. Average heat transfer enhances as the solid volume fraction of the nanoparticle increases which is due to the increasing conductivity and better thermal transport with the inclusion of nanoparticles.

Average heat transfer is highest for the cylindrical and lowest for the spherical nanoparticle shapes

($Nu_{cylindrical}$ > Nu_{brick} > Nu_{blade} > $Nu_{spherical}$) for the same volume fraction. Average heat transfer enhances by about 11.22% for the spherical nanoparticle shapes and 19.85% for the cylinder nanoparticle shapes at the highest volume fraction (ϕ =0.04) compared to base fluid (ϕ =0) in the absence of the corner partition. As the size of the partition is increased to R= 0.4, 12.78% and 16.41% average heat transfer enhancements are obtained for the highest nanoparticle volume fractions.

Increasing the size of the conductive partition increases the average Nusselt number. Average heat transfer enhancement is 28.78% and 28.76% when R=0 is increased to R=0.4 for spherical and cylindrical type nanoparticles at the highest volume fraction at ϕ =0.04.

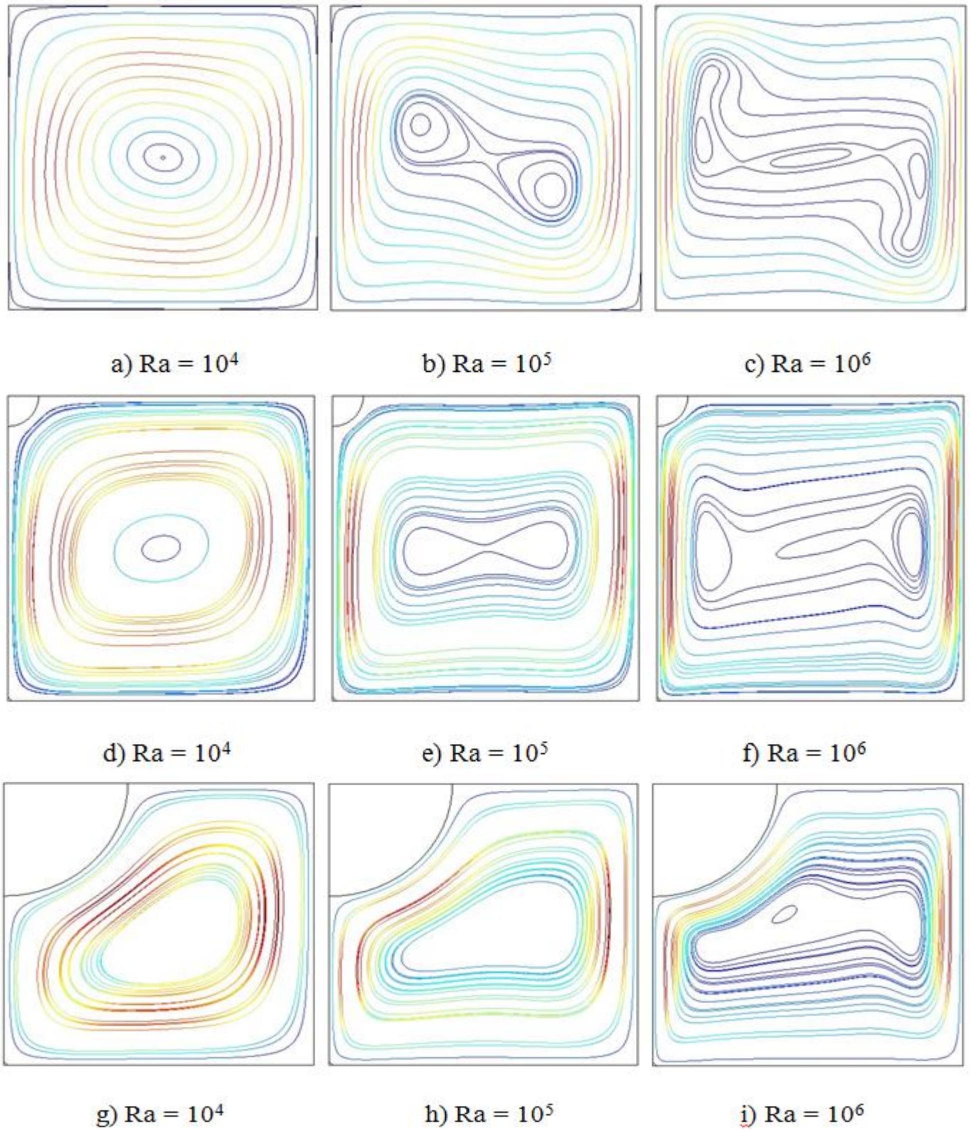


Figure 2. Effects of Rayleigh number on the streamline distributions for various radius of the corner partition (Kr=10, ϕ=0.02, spherical nanoparticles)

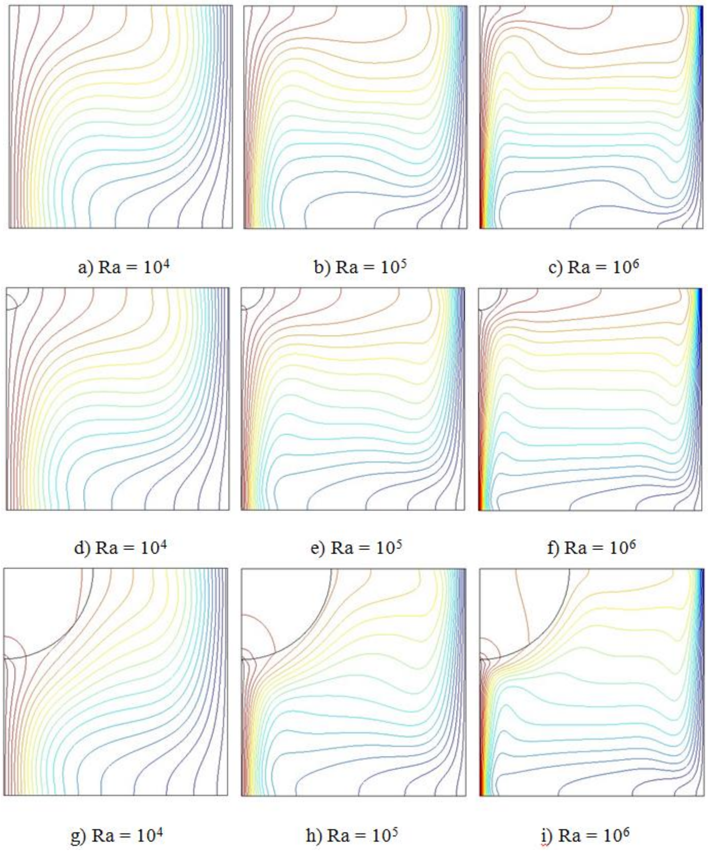


Figure 3. Effects of Rayleigh number on the isotherm distributions for various radius of the corner partition (Kr=10, ϕ=0.02, spherical nanoparticles)

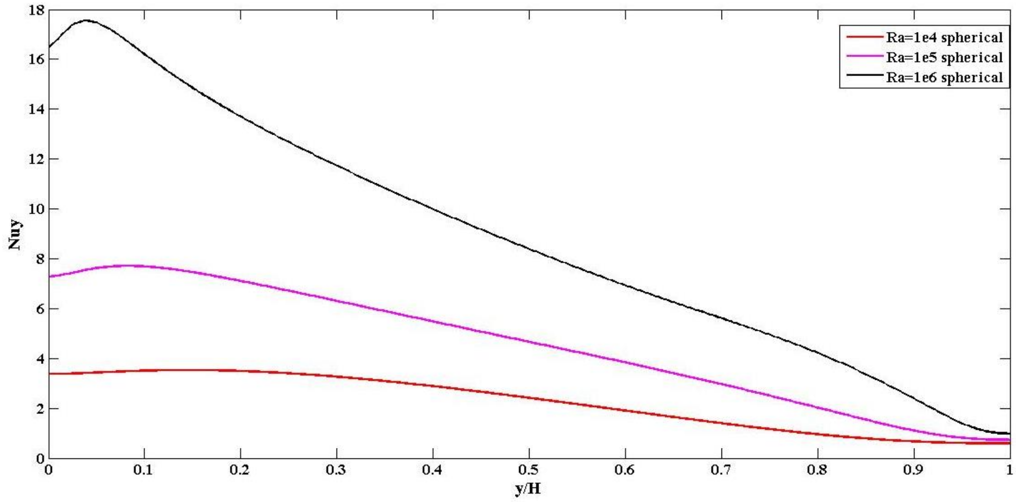
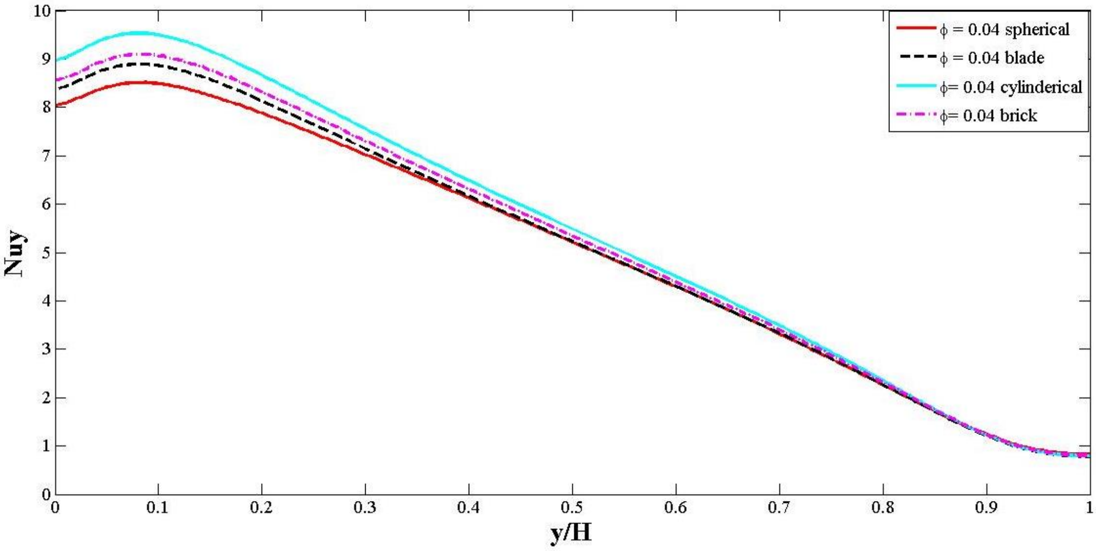
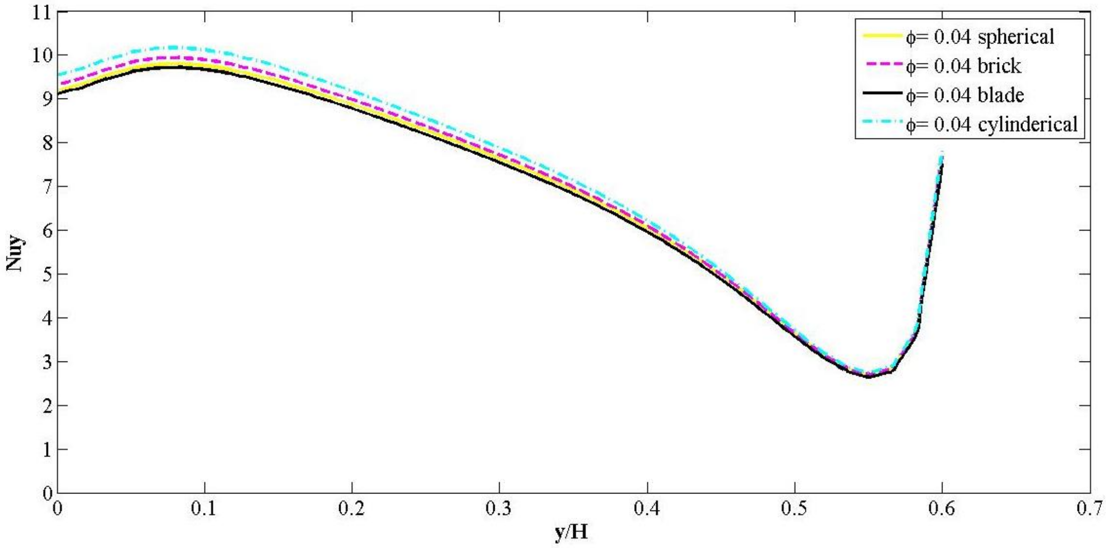


Figure 4. Local Nusselt number distributions along the hot wall for various values of Rayleigh numbers (R=0, Kr=10, ϕ=0.02, spherical nanoparticles)



a) R=0, ϕ =0.04



b) R=0.4, ϕ =0.04

Figure 5. Local Nusselt number distributions along the hot wall for various nanoparticle shapes and two values of corner partition radius ($Ra=10^5$, Kr=10)

Table 3. Effects of Rayleigh number on the average Nusselt number for corner partition radius of R=0 (spherical, Kr=10)

Ra	ϕ=0	ϕ=0.04
10^4	2.2422	2.5105
10^5	4.5185	5.0255
10^6	8.8294	9.8166

Table 4. Effects of nanoparticle solid volume fraction and nanoparticle shapes on the average Nusselt number for corner partition radius of R=0 (Ra=10^5, Kr=10)

ϕ	Spherical	Blade	Brick	Cylindrical
0	4.5185	4.5185	4.5185	4.5185
0.01	4.6423	4.6715	4.6769	4.7376
0.02	4.7681	4.8236	4.8562	4.9721
0.03	4.8958	4.9737	5.0466	5.2001
0.04	5.0255	5.1215	5.2388	5.4158

Table 5. Effects of nanoparticle solid volume fraction and nanoparticle shapes on the average Nusselt number for corner partition radius of R=0.1 (Ra=10^5, Kr=10)

ϕ	Spherical	Blade	Brick	Cylindrical
0	4.8908	4.8908	4.8908	4.8908
0.01	5.0398	5.0268	5.0574	5.0869
0.02	5.1919	5.1628	5.2246	5.2831
0.03	5.3471	5.2987	5.3919	5.4792
0.04	5.5055	5.4346	5.5592	5.6749

Table 6. Effects of nanoparticle solid volume fraction and nanoparticle shapes on the average Nusselt number for corner partition radius of R=0.4 (Ra=10^5, Kr=10)

ϕ	Spherical	Blade	Brick	Cylindrical
0	6.2841	6.2841	6.2841	6.2841
0.01	6.4778	6.4623	6.5014	6.5409
0.02	6.6755	6.6403	6.7200	6.7980
0.03	6.8772	6.8180	6.9390	7.0540
0.04	7.0830	6.9954	7.1578	7.3088

4. CONCLUSION

Numerical simulation results are presented for the natural convection in a nanofluid filled corner partitioned square cavity. Different nanoparticle shapes and conductive partition was considered. Following conclusions can be drawn as:

* The flow and thermal fields are affected by the presence of the conductive partition and different nanoparticle shapes.

* As the value of Rayleigh number and size of the corner partition increase, average heat transfer enhances. Average Nusselt number increases by about 28.78% when R=0 is increased to R=0.4 for spherical type nanoparticles at the highest volume fraction.

* Due to the increased thermal conductivity and better thermal transport properties, local and average heat transfer enhance with the inclusion of nanoparticles and its value gets higher as the solid volume fraction of the nanoparticles increase.

* Cylindrical shape nanoparticles show better heat transfer performance compared to spherical ones.

* Average Nusselt number increases by about 11.22% for the spherical nanoparticle shapes and 19.85% for the cylinder nanoparticle shapes at the highest volume fraction compared to base fluid when there is no partition.

5. REFERENCES

1. Selimefendigil, F., Oztop, H.F., 2016. Conjugate Natural Convection in a Cavity with a Conductive Partition and Filled with Different Nanofluids on Different Sides of the Partition, Journal of Molecular Liquids, vol. 216, pp. 67-77.

2. Oztop, H.F., Varol, Y., Koca A., 2009. Natural Convection in a Vertically Divided Square Enclosure by a Solid Partition into air and Water Regions, International Journal of Heat and Mass Transfer, vol. 52, pp. 5909-5921.

3. Varol, Y., Oztop, H.F., Pop, I., 2008. Natural Convection Flow in Porous Enclosures with Heating and Cooling on Adjacent Walls and Divided by a Triangular Massive Partition, International Communications in Heat and Mass Transfer, vol. 35, pp. 476-491.

4. Ahmed, E.S., Oztop, H.F., Al-Salem, K., 2014. Natural Convection Coupled with Radiation Heat Transfer in an Inclined Porous Cavity with Corner Heater, Computers & Fluids, vol. 102, pp. 74-84.

5. Selimefendigil, F., Oztop, H.F., 2015. Natural Convection and Entropy Generation of Nanofluid Filled Cavity Having Different Shaped Obstacles under the Influence of Magnetic Field and Internal Heat Generation, Journal of the Taiwan Institute of Chemical Engineers, vol. 56, pp. 42-56.

6. Selimefendigil, F., Oztop, H.F., 2014. Pulsating Nanofluids Jet Impingement Cooling of a Heated Horizontal Surface, International Journal of Heat and Mass Transfer, vol. 69, pp. 54-65.

7. Bouhalleb, F., Abbasi, H., 2015. Natural Convection in an Inclined Rectangular Enclosure Filled by $CuO–H_2O$ Nanofluid, with Sinusoidal Temperature Distribution, International Journal of Hydrogen Energy, vol. 40, pp. 13676-13684.

8. Zakaria, I., Azmi, W.H., Mamat, A.M.I., Mamat Rizalman Saidur, R., Abu Talib, S.F., 2016. Thermal Analysis of Al_2O_3–Water Ethylene Glycol Mixture Nanofluid for Single PEM Fuel Cell Cooling Plate: An Experimental Study, International Journal of Hydrogen Energy, vol. 41, pp. 5096-5112.

9. Shahnazar, S., Bagheri, S., Abd Hamid, S.B., 2016. Enhancing Lubricant Properties by Nanoparticle Additives, International Journal of Hydrogen Energy, vol. 41, pp. 3153-3170.

10. Selimefendigil, F., Oztop, H.F., Abu-Hamdeh, N., 2015. Mixed Convection Due to Rotating Cylinder in an İnternally Heated and Flexible Walled Cavity Filled with SiO_2–Water Nanofluids: Effect of Nanoparticle Shape, International Communications in Heat and Mass Transfer, vol. 71, pp. 9-19.

11. Selimefendigil, F., Oztop, H.F., 2015. Mixed Convection in a Two-sided Elastic Walled and SiO_2 Nanofluid Filled Cavity with İnternal Heat Generation: Effects of Inner Rotating Cylinder and Nanoparticle's Shape, Journal of Molecular Liquids, vol. 212, pp. 509-516.