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NATURAL CONVECTION OF NANOFLUIDS IN AN INCLINED SQUARE CAVITY WITH SIDE WAVY WALLS

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Abstract: In this study, a numerical simulation is performed to study natural convection of water based nanofluid in an inclined square side wavy walls cavity. The the top and bottom walls of the cavity are assumed to be adiabatic and the side walls are at different constant temperatures. Three different nanoparticles, Cu, CuO and Al_2O_3 are used in the study. The computations are conducted for solid volume fractions of 0%, 5% and 10% and for Rayleigh number of 10^4, 10^5 and 10^6**.** The analyses were conducted for 0°, 45^0 and 90° inclination angle for enclosed cavity, 0.05, 0.075, and 0.1 amplitude and 1 and 3 undulation numbers. The results show that heat transfer rate increases with the increase in nanoparticle volume fraction and Rayleigh number. Additionally, it is observed that increasing undulation number increases heat transfer rate significantly.
Keywords: Natural convection, nanofluid, inclination cavity, wavy wall.

YAN DUVARLARI DALGALI EĞİK BİR KARE KAVİTE İÇİNDEKİ NANOAKIŞKANLARIN DOĞAL KONVEKSİYONU

Özet: Bu çalışmada yan duvarları dalgalı, eğik kare bir kavite içindeki, su bazlı nanoakışkanın doğal konveksiyonu nümerik olarak incelenmiştir. Kapalı bölgenin üst ve alt duvarları adyabatik, yan duvarları ise farklı sabit sıcaklıkta tutulmuştur. Bu çalışmada Cu, CuO ve Al_2O_3 olarak üç farklı nanaopartikül kullanılmıştır.Kapalı bölgenin eğim açısı saat ibresi yönünde 0°, 45^0 and 90° olarak seçilmiş olup, genlik değerleri 0.05,0.075, and 0.1 için tek ve üç dalgalı duvarlara sahip kavite için analizler yapılmıştır. Sonuçlara göre, nanopartikül hacimsel konsantrasyonu ve Rayleigh sayısının artmasıyla ısı transfer oranı artmaktadır. Ayrıca, dalga sayısındaki artışla beraber ısı transfer miktarı önemli ölçüde artmaktadır.
Anahtar Kelimeler: Doğal konveksiyon, nanoakışkan, eğik kavite, dalgalı duvar

NOMENCLATURE

c_p	specific heat at constant pressure
g	acceleration due to gravity
k	thermal conductivity
L	length of the cavity
n	undulation number
Nu	Nusselt number
p	pressure
Pr	Prandtl number
Ra	Rayleigh number
T	temperature
u	velocity component in the x direction
v	velocity component in the y direction
x	cartesian coordinates
y	cartesian coordinates
Greek symbols	
α	thermal diffusity
β	thermal expansion coefficient
λ	amplitude
ϕ	solid volume fraction
μ	viscosity
ρ	density
Φ	inclination angle
Superscripts	
*	dimensional variable
Subscripts	
c	cold
f	fluid
h	hot
nf	nanofluid
s	solid

INTRODUCTION

Natural convection heat transfer in enclosed cavities has many important applications in engineering systems, including electronic cooling devices, heat exchangers, MEMS devices, electric machinery and solar energy collectors (Ostrach, 1988). However, the traditional working fluids used in such systems (e.g., water, oil or ethylene glycol) have a low thermal conductivity, thus their heat transfer performance is inevitably limited. Therefore, a requirement appeared for new working fluids with a higher thermal conductivity.

Nanofluids, consisting of nanoparticles with high thermal conductivity (e.g., Cu, Ag, CuO, Al_2O_3, or TiO_2) suspended in a base fluid with low thermal conductivity (e.g., water, oil or ethylene glycol) provide an effective means of improving the heat transfer performance in many engineering systems. The heat transfer enhancement achieved by such fluids was first investigated by Choi (1995). Since then, the thermophysical properties of many different nanofluids have been examined and various models have been proposed for estimating their heat transfer performance (Das *et al*., 2006; Wang and Mujumdar, 2007). It has been shown that nanofluids yield an effective improvement in the heat transfer performance compared to traditional working fluids. However, the extent of the heat transfer enhancement depends on the size, shape, concentration and thermal properties of the nanoparticles used. More specifically, the heat transfer performance improves with an increasing nanoparticle volume fraction, a reducing nanoparticle size, and an increasing thermal conductivity.

In recent years, the problem of natural convection heat transfer in square or rectangular cavities filled with nanofluid has attracted significant attention. Khanafer *et al*. (2003) investigated the problem of buoyancy-driven heat transfer enhancement in a two dimensional square enclosure filled with Cu-water nanofluid. Hwang *et al.* (2007) studied the problem of buoyancy-driven heat transfer within a rectangular cavity filled with water-based Al_2O_3 nanofluid. Oztop and Abu-Nada (2008) investigated heat transfer and fluid flow due to buoyancy forces in a partially heated enclosure using nanofluids using various types of nanoparticles. It was found that the heat transfer enhancement due to using a nanofluid is more pronounced at a low aspect ratio than at a high aspect ratio. Ghasemi and Aminossadati (2009) investigated the natural convection heat transfer performance of water-CuO nanofluid in an inclined enclosure, while Kahveci (2010) examined the heat transfer performance of various buoyancy driven nanofluids in a differentially-heated tilted enclosure. Ogut (2009) numerically investigated the heat transfer enhancement of water-based nanofluids in a two-dimensional inclined enclosure with a constant flux heater for a range of inclination angles, nanoparticles, solid volume fractions, heat source lengths and Rayleigh numbers. The results show that the presence of nanoparticles causes a substantial increase in the heat transfer rate. The length of the heater also affects heat transfer, the latter decreasing with an increase in the length of the heater. While the heater length is increased, the average heat transfer rate actually starts to decrease for smaller inclination angles.

The studies that investigate enclosed cavity with wavy wall filled with nanofluid are not so common, but recently researchers have started to focus on it. Abu Nada and Oztop (2011) investigated heat transfer enhancement of Al_2O_3-water nanofluids in differentially heated wavy cavities numerically. They concluded that heat transfer increases with increasing of geometry parameter for the same Rayleigh number and nanoparticle fraction. Nikfar and Mahmoodi (2012) investigated natural convection heat transfer in complex cavity having wavy side walls with MLPG (Meshless Local Petrov) method. The results show that significant differences exist between the rates of heat transfer in the cavity for the two viscosity models employed. At Ra=10^3 the average Nusselt number of the hot wall increases with increase in the volume fraction of the nanoparticles for both considered viscosity models. At other Rayleigh numbers the average Nusselt number estimated for Brinkman formula increases with increase in volume fraction of the nanoparticles while it decreases for Maiga's correlation. Nasrin *et al.* (2013) studied the numerical modeling of steady laminar combined convection flow in a vertical triangular wavy enclosure filled with water–CuO nanofluid. The left and right vertical walls of the cavity take the form of a triangular wavy pattern. Mansour and Bakier (2013) studied heat transfer by natural convection in a differentially and wavy walled enclosure with uniform internal heat generation numerically. Both the flow field and heat transfer characteristics were affected due to changes in the values of Rayleigh number and the amplitude of the wavy-wall. Cho *et al.* (2013) numerically investigated natural convection heat transfer characteristics and entropy generation of water-based nanofluids in an enclosure bounded by wavy vertical walls and flat upper and lower surfaces. Cho *et al.* (2012) studied natural convection heat transfer performance of Al_2O_3-water nanofluid in an enclosed cavity bounded by vertical isothermal walls with a complex-wavy-surface and straight upper and lower walls with adiabatic conditions. Esmaeilpour and Abdollahzadeh (2012) numerically investigated the effect of adding ultra fine metallic nanoparticles to pure fluid on heat transfer rate and the entropy generation distribution within an enclosure with vertical wavy wall. It was found that the entropy generation increases with increasing Grashof number and also decreases with increasing surface waviness. Ogut (2010) numerically investigated laminar natural convection flow of water based nanofluids in an inclined square enclosure, where adjacent walls heated in a different way and other walls were insulated, using polynom based differential quadrature (PDQ) method. Ogut *et al.* (2014) numerically investigated heat transfer enhancement by natural convection in a two dimensional enclosed cavity that has hot left wall and cold and wavy right wall filled with water based nanofluid. According to the obtained results, the Rayleigh number and the solid volume fraction have considerable effect on flow and heat transfer. When comparing the nanofluid and the water, heat transfer rate is higher in nanofluid due to adding the solid particles that have high thermal conductivity in water. The heat transfer rate increases by intensifying circulation due to increasing Rayleigh number.

In the literature, cases where single wall is wavy, just one amplitude value is used, single nanofluid is considered and inclination angle has no affect as cavity, have been studied in literature. This study differs than others in such a manner that, how flow and heat transfer characteristics affected by factors of number of waves, amplitude value, nano particle usage, inclination angle of cavity and Rayleigh number all together. The present study therefore aims to investigate natural convection in an inclined square cavity with side wavy walls and find the effects of varying the solid volume fraction (Φ), nanoparticle type, Rayleigh number (Ra), inclination angle, undulation number and amplitude on flow and heat transfer.

MATHEMATICAL FORMULATIONS

The cavity with side wavy walls is depicted in Fig. 1. The height of cavity is L. The enclosed cavity rotated clockwise and inclination angle represented with φ. The problem is considered to be two dimensional. The top and bottom walls of the cavity are assumed to be adiabatic and the vertical walls are at different constant temperatures.

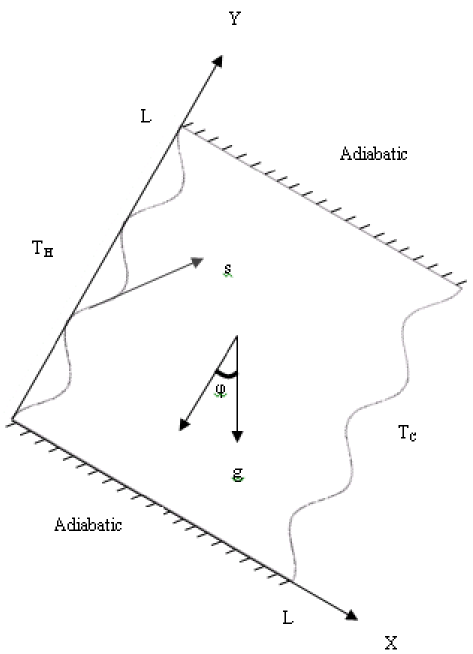


Figure 1. Physical geometry and boundary conditions

The undulation equation is expressed as follows:

$$x_{left}=f(y)=\lambda(1-\cos(2\pi ny)),$$
$$x_{right}=f(y)=[1-\lambda+\lambda(\cos(2\pi ny)] \tag{1}$$

where n and λ are the number of undulations and the amplitude, respectively.

The top and the bottom walls are insulated and the fluid is isothermally heated and cooled by the left and the right side walls at uniform temperatures of T_H and T_C, respectively. Cavity is considered to be filled with Cu, CuO and Al_2O_3 mixture of water. The nanofluid is assumed to be incompressible. It is also assumed that the base fluid and the nanoparticles are in thermodynamic equilibrium and that they flow at the same velocity. The thermophysical properties of the base fluid and the nanoparticles are given in Table 1. The thermophysical properties of the nanofluid are assumed to be constant except for the density variation in the buoyancy force, for which the Boussinesq approximation was used. The viscous dissipation terms and the thermal radiation are also assumed to be negligible.

Table 1. Thermophysical properties of water and nanoparticles

Property	Water	Cu	CuO	Al_2O_3
$\rho(kg/m^3)$	997.1	8933	6500	3970
c_p (j/kg K)	4179	385	535.6	765
k (W/m K)	0.613	400	20	40
$\alpha x10^7$ (m^2/s)	1.47	1163.1	57.45	131.7
$\beta(K^{-1})$	0.00021	0.000051	0.000051	0.000024

The governing equations for laminar, steady-state, natural convection in an enclosure filled with a nanofluid in terms of the Navier–Stokes formulation are given as,

The continuity equation;

$$\frac{\partial u^*}{\partial x^*}+\frac{\partial v^*}{\partial y^*}=0 \tag{2}$$

x-momentum equation;

$$\left(u^*\frac{\partial u^*}{\partial x^*}+v^*\frac{\partial u^*}{\partial y^*}\right)=-\frac{1}{\rho_{nf}}\frac{\partial p^*}{\partial x^*}+\frac{\mu_{nf}}{\rho_{nf}}\left(\frac{\partial^2 u^*}{\partial x^{*2}}+\frac{\partial^2 u^*}{\partial y^{*2}}\right)+ \frac{1}{\rho_{nf}}(\rho\beta)_{nf}\, g\ (T-T_C)\sin\varphi \tag{3}$$

y-momentum equation;

$$\left(u^*\frac{\partial v^*}{\partial x^*}+v^*\frac{\partial v^*}{\partial y^*}\right)=-\frac{1}{\rho_{nf}}\frac{\partial p^*}{\partial y^*}+\frac{\mu_{nf}}{\rho_{nf}}\left(\frac{\partial^2 v^*}{\partial x^{*2}}+\frac{\partial^2 v^*}{\partial y^{*2}}\right)+ \frac{1}{\rho_{nf}}(\rho\beta)_{nf}\, g(T-T_C)\cos\varphi \tag{4}$$

Energy equation;

$$\left(u^*\frac{\partial T}{\partial x^*}+v^*\frac{\partial T}{\partial y^*}\right)=\alpha_{nf}\left(\frac{\partial^2 T}{\partial x^{*2}}+\frac{\partial^2 T}{\partial y^{*2}}\right) \tag{5}$$

The α_{nf} is the thermal diffusion coefficient of the nanofluid and described as follow;

$$\alpha_{nf}=\frac{k_{nf}}{(\rho c_p)_{nf}} \tag{6}$$

To convert governing equation into dimensionless form, the following parameters are used;

$$x=\frac{x^*}{L}\ ,y=\frac{y^*}{L}\ ,\ u=\frac{u^*}{\alpha_f/L}\ ,\ v=\frac{v^*}{\alpha_f/L}\ ,\ p=\frac{L^2}{\rho_f\alpha_f^2}p^*\ ,$$

$$\theta=\frac{T^*-T_C}{T_H-T_C} \tag{7}$$

In this equations u^* and v^* are dimensional form of the velocity component, p^* is dimensional pressure component, T^* is dimensional temperature, ρ_f is fluid density at T_C, α_f is the thermal diffusivity of fluid.

$$Pr=\frac{\gamma_f}{\alpha_f}\ ,\ Ra=\frac{g\beta_f L^3\Delta T}{\gamma_f\alpha_f} \tag{8}$$

In these equations g is the acceleration of gravity, β is the thermal expansion coefficient, γ is kinematic viscosity, ΔT is the temperature difference between side walls.

The effective dynamic viscosity of the nanofluid can be presented by models for two phases mixture. In this study the Brinkman (1952) model for nanofluid with spherical particle is used.

$$\mu_{nf}=\frac{\mu_f}{(1-\phi)^{2.5}} \tag{9}$$

The density, heat capacity and thermal expansion coefficient of the nanofluid are as follows, respectively:

$$\rho_{nf}=(1-\phi)\rho_f+\phi\rho_s \tag{10}$$

$$(\rho c_p)_{nf}=(1-\phi)\rho_f\,c_{pf}+\phi\rho_s\,c_{ps} \tag{11}$$

$$(\rho\beta)_{nf}=(1-\phi)\rho_f\,\beta_f+\phi\rho_s\beta_s \tag{12}$$

In this equation Φ is the volume fraction and “nf”, “f”, and “s” subscripts are presents nanofluid, fluid and solid particles, respectively.

For effective thermal conductivity Yu and Choi (2003) model is used;

$$\frac{k_{nf}}{k_f}=\frac{k_s+2k_f+2(k_s-k_f)(1+\eta)^3\phi}{k_s+2k_f-(k_s-k_f)(1+\eta)^3\phi} \tag{13}$$

In this model, η, which is the ratio of fluid layer thickness to the original particle radius, is fixed to 0.1.

The Nusselt number is evaluated from the following relation:

$$Nu=\frac{h_{nf}L}{k_f} \tag{14}$$

The heat transfer coefficient, h_{nf}, is obtained from

$$h_{nf}=\frac{q}{(T_H-T_C)} \tag{15}$$

The wall heat flux per unit area, q, can be written as

$$q=-k_{nf}\frac{(T_H-T_C)}{L}\frac{\partial\theta}{\partial\zeta} \tag{16}$$

where k_{nf} is thermal conductivity of nanofluid and ζ is normal direction to the wall. Substituting Eqs. (16) and (15) into Eq.(14) yields the following relation for the local Nusselt number:

$$Nu=-\frac{k_{nf}}{k_f}\left.\frac{\partial\theta}{\partial\zeta}\right|_{wall} \tag{17}$$

The average Nusselt number (Nu_a) is obtained by integrating the local Nusselt number along the left wavy surface and is defined by

$$Nu_a=\frac{1}{S}\int_0^S Nu\,ds \tag{18}$$

where S is the total chord length of the wavy surface and s is the coordinate along the wavy surface.

NUMERICAL SOLUTION

In the study ANSYS Fluent 14.0 is used to solve the governing equations. Momentum and energy equations are discretized by second order upwind scheme, the pressure-velocity equation is coupled by SIMPLE algorithm.

To investigate mesh independency, the analysis conducted for 0.1 amplitude and 3 undulation cavity with Cu-water nanofluid for $Ra=10^6$, 0.05 volume fraction. Average Nusselt numbers compared for 41x41, 61x61 81x81 101x101 mesh sized cavity. The results show that from 81x81 mesh size the mean Nusselt number doesn’t distribute to any remarkable change. Therefore analyses were conducted with 81x81 mesh points.

The numerical code is validated with the study of Khanafer *et al.* (2003) where heat transfer enhancement in a two-dimensional enclosed cavity filled with nanofluid by different Grashof numbers and volume fractions is investigated. The results are compared in Table 2. According to the Table 2, there is a very good agreement between results of present study and that of Khanafer.

Table 2. Comparison of average Nusselt numbers

	Gr/ Φ	0	0.04	0.08	0.12	0.16	0.20
Present Study	10^3	1.9	2.1	2.2	2.3	2.4	2.6
Khanaferet al.	10^3	1.9	2.1	2.3	2.4	2.5	2.7
Present Study	10^4	4.1	4.4	4.7	5	5.2	5.5
Khanafer et al.	10^4	4.1	4.4	4.7	5	5.3	5.7
Present Study	10^5	8.1	8.7	9.3	10	10.1	11.2
Khanafer et al.	10^5	8.4	8.9	9.6	10.2	10.9	11.6

RESULTS AND DISCUSSION

Streamlines and isotherms for wavy walls that has one and three undulations are presented for various values of the Rayleigh number ($Ra=10^4$, 10^5 and 10^6) and the solid volume fraction (Φ=0%, 5%, 10%) with fixed Prandtl number (Pr=6.2). In addition, the values of the average Nusselt number are presented for different Rayleigh numbers and amplitudes (0.05, 0.75, 0.1), inclination angles (0°, 45°, 90°) for both Cu-water , CuO-water and Al_2O_3-water nanofluids.

Streamlines for φ=0° inclination angle, 1 undulation and 0.05 amplitude cavity are given in Fig. 2. The cavity is filled with Cu-water nanofluid. As seen in the figure, an eddy was formed at the center of flow region which rotates in clockwise direction . It has been observed that, an elliptical flow cell occurs at the center of cavity in the cases for low values Rayleigh number. With the increasing of Rayleigh number circular/elliptic flow cell transforms into the rectangular form. Increasing the nanoparticle volume fraction does not affect flow curves significantly. The high values of stream functions show that the circulation and vortex are getting stronger with increasing Rayleigh numbers.

Isotherms for $\varphi=0^0$ inclination angle, 1 undulation and 0.05 amplitude cavity with Cu-water nanofluid are given in Fig. 3. For low values of Rayleigh number, convection is so weak that isotherms are similar with those of pure conduction situation. With increasing Rayleigh numbers, convection becomes dominant and circulation gets stronger. Fluid particles heated near hot wall, moves upward through left side wall and cold fluid particles move down through right side wall. With the increase in flow rate due to increase in Rayleigh number, isotherms moves to center of cavity and reach to a parallel view. Additionally, thermal boundary layers appear at side walls with increasing Rayleigh number. Heat transfer increases and thermal boundary layers get thinner, with increasing flow rate due to increasing Rayleigh number.
Streamlines for $\varphi=0^0$ inclination angle, 3 undulations and 0.05 amplitude cavity with Cu-water nanofluid are given in Fig. 4. In the graphs for different Rayleigh numbers, an elliptic fluid cell forms in the middle of the cavity. Due to increasing Rayleigh number, fluid circulation scales up and elliptic fluid cell transforms into rectangular form and quadratic form eventually. Increase in the volume fraction does not have a significant effect on the circulation region in the cavity.

Isotherm contours for $\varphi=0^0$ inclination angle, 3 undulations and 0.05 amplitude cavity with Cu-water nanofluid are given in Fig. 5. When isotherms were analyzed, fluid expands upward along the hot wall (left wall) and falls down along the cold wall. With increasing fluid circulation due to increasing Rayleigh number, the isotherm contours come into parallel with each other in the middle of the cavity. With increasing Rayleigh number, the convection becomes stronger and boundary layer grows along the wavy walls. Increasing volume fraction doesn't effect isotherms contours considerably. The heat transfer rate increases, due to surface area increasing with augmenting number of undulation number.

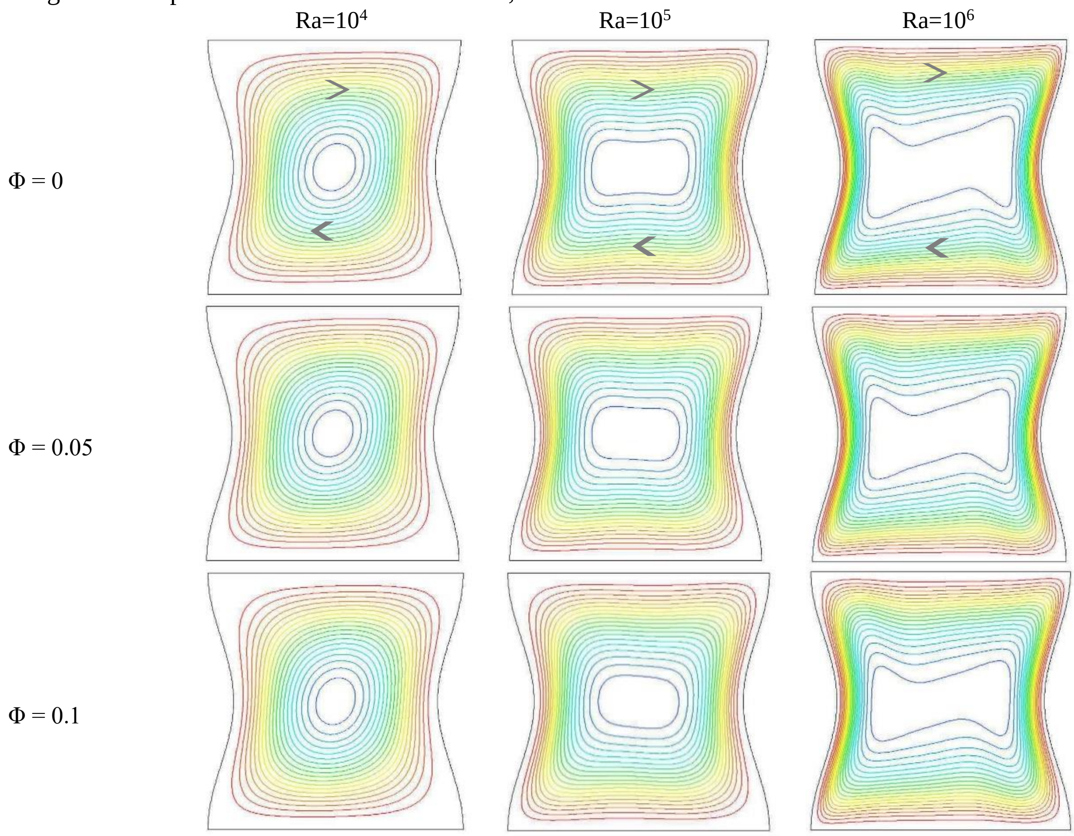


Figure 2. Streamlines for Cu-water nanofluid in cavity with one undulation for λ=0.05 and φ=0° .

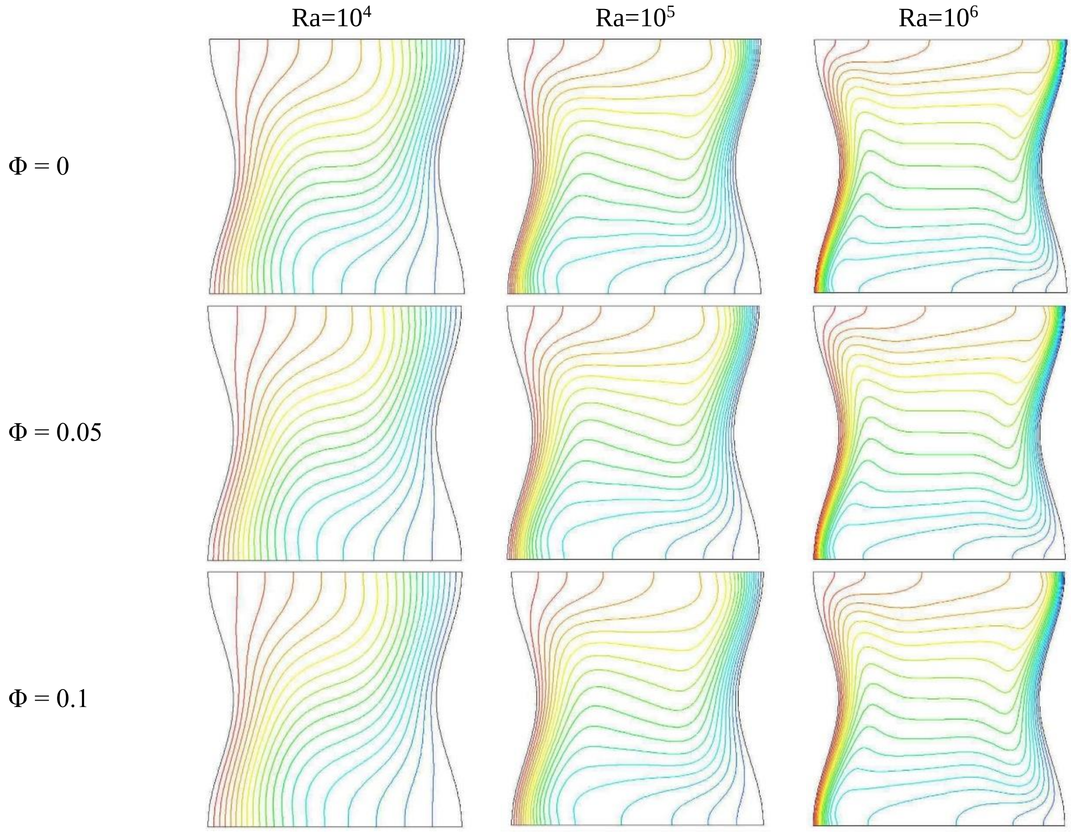


Figure 3. Isotherms for Cu-water nanofluid in cavity with one undulations for λ=0.05 and φ=0°

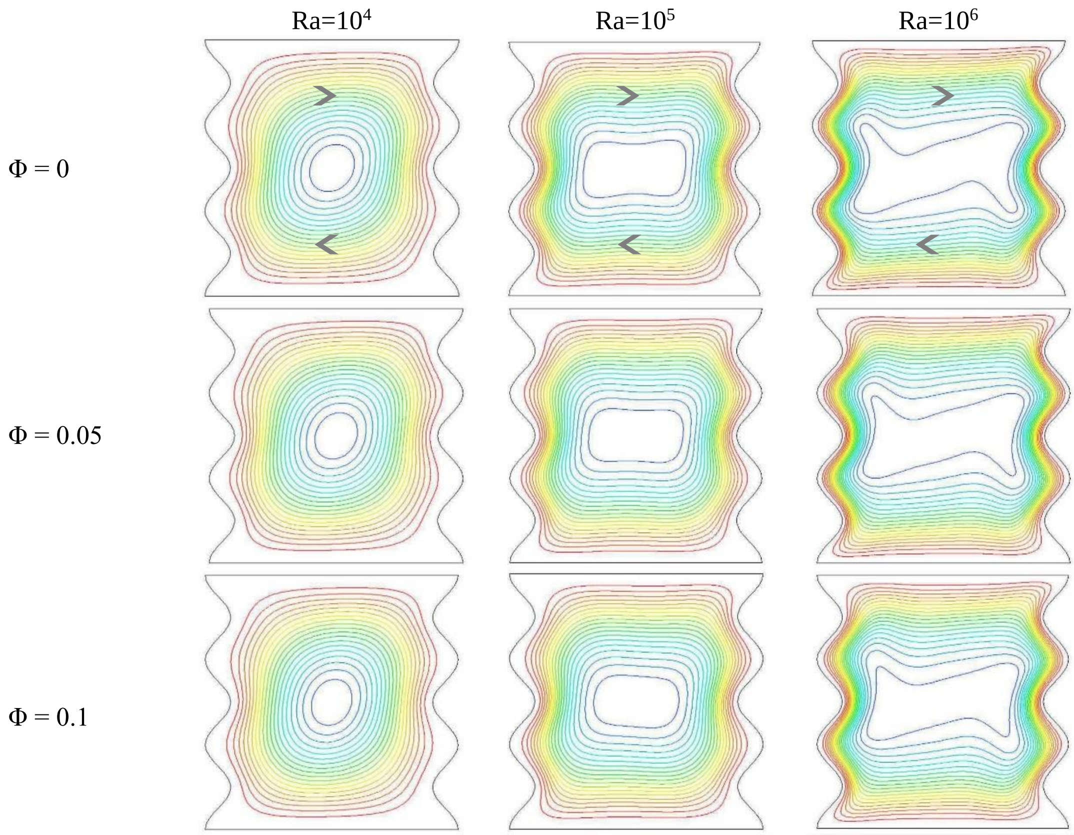


Figure 4. Streamlines for Cu-water nanofluid in cavity with three undulations for λ=0.05 and φ=0° .

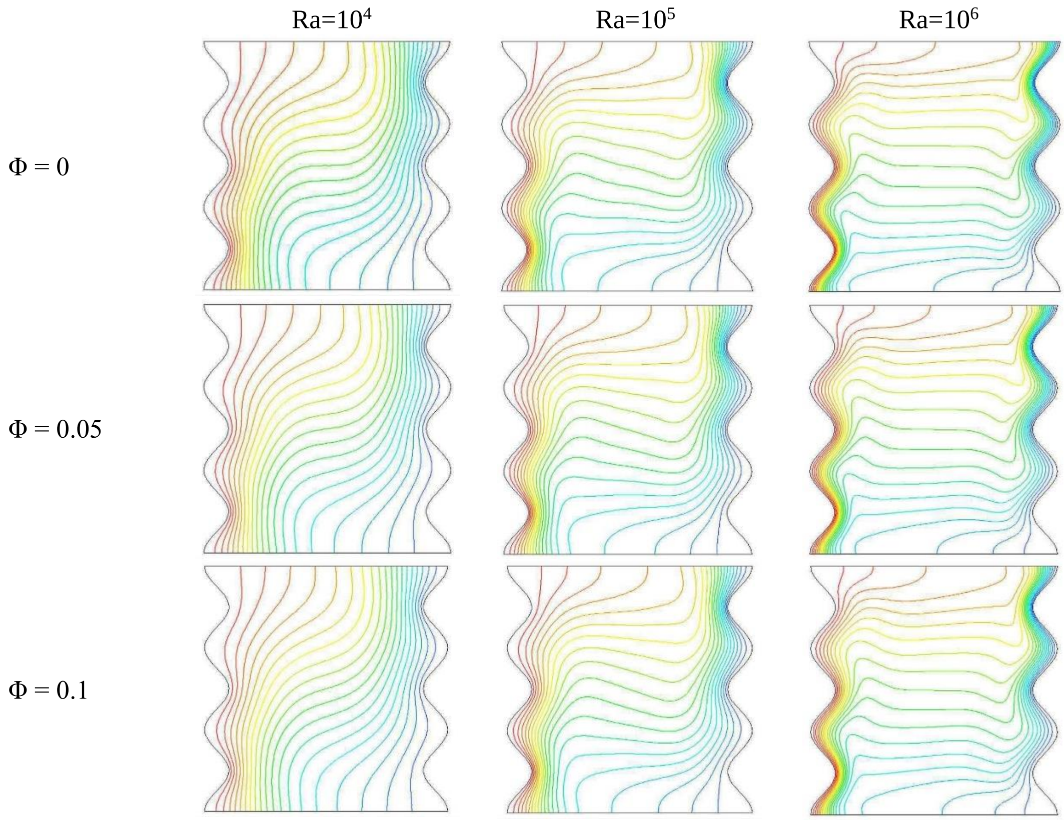


Figure 5. Isotherms for Cu-water nanofluid in cavity with three undulations for λ=0.05 and φ=0° .

Effects of Different Parameters on The Local Nusselt Number

Effect of Rayleigh number

Fig. 6 shows variation of local Nusselt number along hot wall for a) 0°, b) 45° and c) 90° inclination angle, 1 undulation, 0.05 volume fractions, 0.05 amplitude cavity filled Cu-water nanofluid. As shown for 0° inclination angle cavity, isotherms at the bottom of hot wall are more intense, while the temperature gradient is higher, to the upward, distance between curves increase and temperature gradient declines. As a result, the local Nusselt number takes a maximum value at the bottom of hot wall, while it decreases toward upper wall. Local Nusselt value is increasing by increasing of Rayleigh number as a result of increasing convective heat transfer rate. For φ=45° inclination angle cavity local Nusselt value is lower comparing to the 0° inclination angle cavity.

The reason is that, for φ=45° inclination angle, the hot wall affects temperature gradient negatively, with the effect of gravity, and get closer to the up side so the circulation gets weaker in the enclosed cavity. Increase in Rayleigh number causes higher differences in local Nusselt number at the bottom of the hot wall while this difference decreases to the upward. For φ=90° inclination angle, the convective heat transfer rate decreases because of hot wall moving to upside. In this case, heat transfer occurs by conduction. For that reason, local Nusselt value

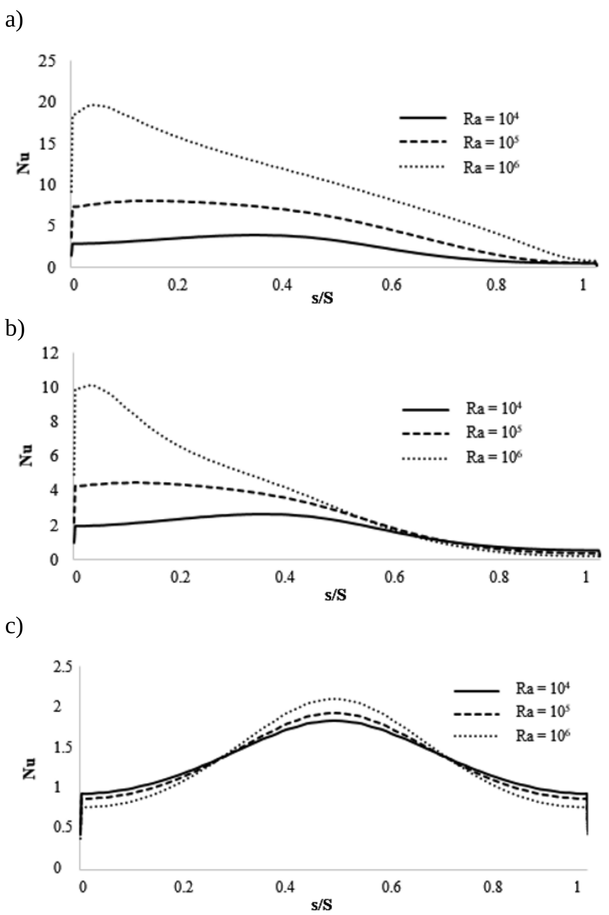


Figure 6. Variations of the local Nusselt number along the hot wavy wall for different Rayleigh numbers for λ=0.05,Φ=0.05, n=1 and a) φ=0° ,b)φ=45° and c) φ =90° (Cu-water nanofluid)

takes minimum value comparing to the other cases. Therefore, increasing Rayleigh number shows its effect in the middle of the wall and causes local Nusselt value to increase.

Effect of the amplitude

Fig. 7 shows variation of local Nusselt number for a) φ=0°, b) φ=45° and c) φ=90° inclination angle, 1 undulation, 0.05 volume fractions, varying amplitude cavity filled Cu-water nanofluid along hot wall. With increasing amplitude value local Nusselt number decreases at the bottom of the hot wall, at the peak of the wave with increasing amplitude local Nusselt number increases. At upside of the hot wall again local Nusselt number values decreases by increasing amplitude. At the closer upside area of the hot wall local Nusselt numbers are under 1, it means heat transfer rate is weaker than heat transfer rate with conduction. While comparing φ=45° with φ=0°, it can be noted that, the difference occurs at the bottom of the hot wall, reoccurs at the top the wave, vanishes to the upward. Local Nusselt number takes minimum value at the top of the hot wall as an indicator of isotherms behaviours. For φ=90°, at the bottom of the hot wall, increasing amplitude causes local Nusselt number to decrease, to the top of the wave increasing of amplitude causes significant increase for local Nusselt number. At the highest level of hot wall, a similar behavior is observed as bottom wall.

a)

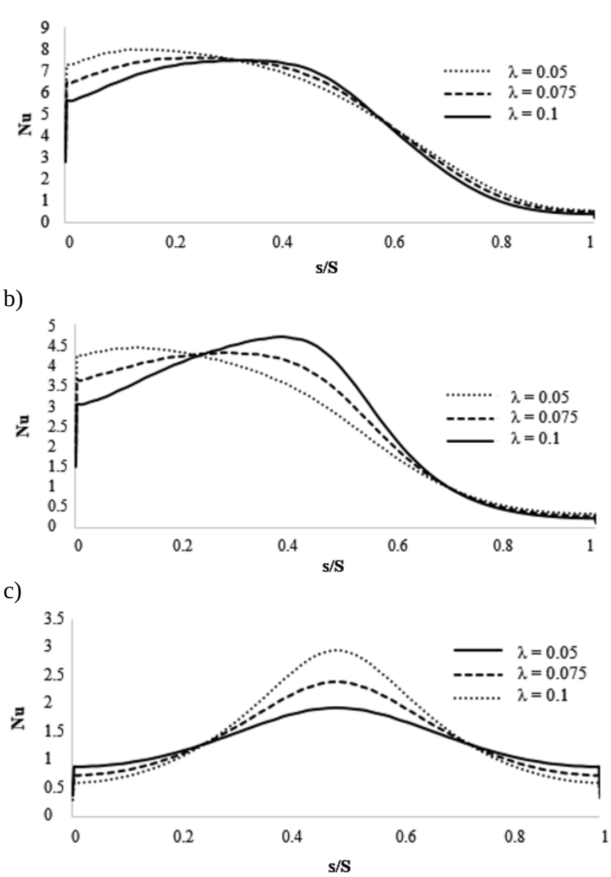


Figure 7. Variations of the local Nusselt number along the hot wavy wall for different amplitude for Ra= 10^5 ,Φ=0.05, n=1 and a) φ=0° , b) φ=45° and c) φ =90° (Cu-water nanofluid)

Effect of the volume fraction

Fig. 8 shows variation of local Nusselt number for 0°, 45° and 90° inclination angle, 1 undulation, 0.05 volume fractions, 0.05 amplitude cavity filled with Cu-water nanofluid along hot wall. Compared to pure fluid, using nanoparticles that have high thermal conductivity, depending to the increasing volume fractions, increases heat transfer rate. Due to increase in heat transfer rate, local Nusselt number increases along the hot wall. With increasing inclination angle, local Nusselt number decreases. For 90° of inclination angle, local Nusselt number takes maximum value in the middle of the hot wall, at the top of the wave.

a)

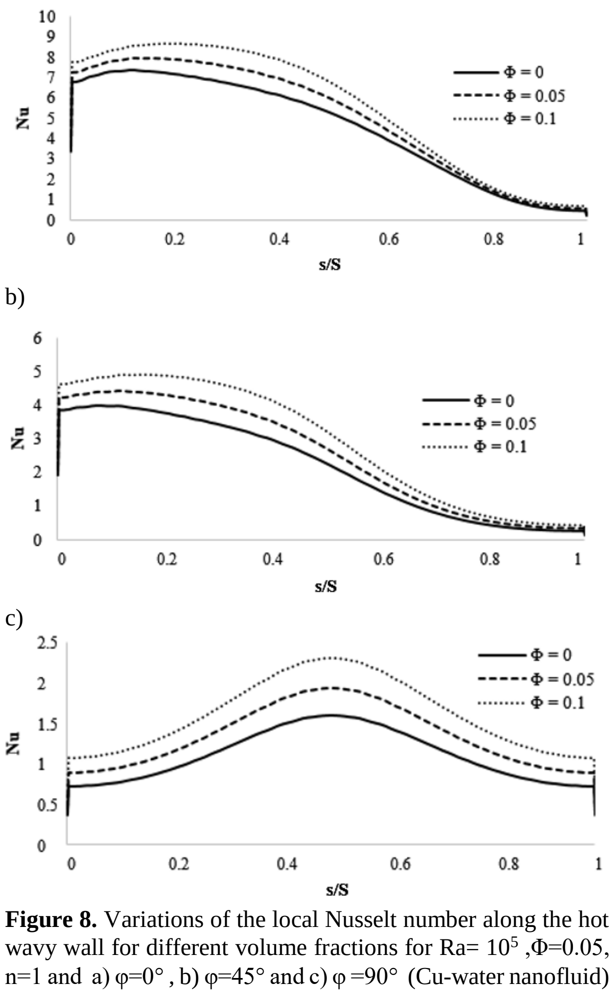
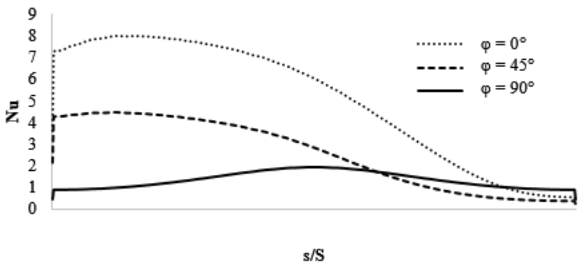


Figure 8. Variations of the local Nusselt number along the hot wavy wall for different volume fractions for Ra= 10^5 ,Φ=0.05, n=1 and a) φ=0° , b) φ=45° and c) φ =90° (Cu-water nanofluid)

Effect of the angle of inclination

Fig. 9 shows variation of local Nusselt number for varying inclination angle, 1 and 3 undulations, 0.05 volume fractions, 0.05 amplitude cavity filled with Cu-water nanofluid along hot wall. With increasing inclination angle, the hot wall gets closer to the upside and the nanofluid became warmer, can't carry out circulation, heat transfer occurs by conduction with stable situation. For that reason, the clockwise inclination angles decreases local Nusselt number. For 3 undulation numbers, with increasing inclination angle local Nusselt number decreases along hot wall similarly with 1 undulation number results. On the other hand, with increasing undulation number heat transfer rate and local Nusselt number values increase.

a)



b)

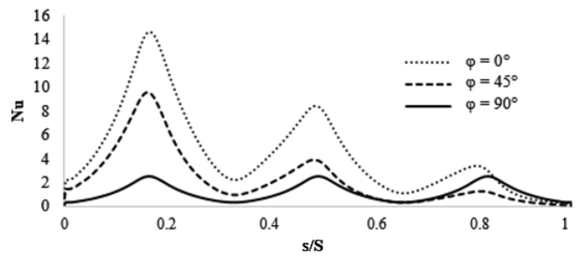


Figure 9. Variations of the local Nusselt number along the hot wavy wall for different inclination angle for Ra= 10^5 , λ=0.05 and a) n=1 and b) n=3 (Cu-water nanofluid)

Fig.10 shows variation of average Nusselt number for varying volume fractions for Ra=10^5, 1 undulation, 0.05 amplitude cavity with different nonaparticles. It is noted that, nanofluid with metal nanoparticles have higher Nusselt value and enhance heat transfer rate compared to the nanofluid include oxide nanoparticles. Adding the nanoparticles that have higher thermal conductivity to the pure fluid increases heat transfer rate. While comparing average local Nusselt number for Cu, CuO and Al_2O_3 water nanofluid, the nanofluid that include Cu nanoparticles have higher heat transfer rate since, thermal conductivity for nanoparticles with Cu, is higher compared to Al_2O_3.

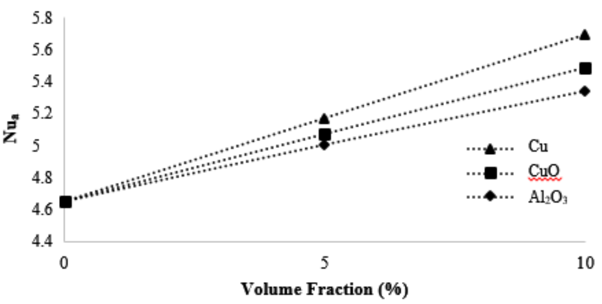


Figure 10. Variation of average Nusselt number with volume fraction for different nanoparticles, and Ra= 10^5, λ=0.05 and n=1

Table 3 shows variation of average Nusselt number for varying volume fractions and Rayleigh numbers for 1 and 3 undulations, 0.05 amplitude cavity filled with Cu-water nanofluid. With increasing Rayleigh number fluid circulation intensifies and average Nusselt number increases. For 3 undulation number average Nusselt numbers are higher compared to the 1 undulation condition as shown in Table–3. With increasing inclination angle average Nusselt number decreases, since the hot wall gets closer to the upside and the circulation is being suppressed. Also with increasing undulation number average Nusselt number increases too.

Table 3. Average Nusselt numbers for λ=0.05 (Cu-water nanofluid)

		n=1		
	Φ/Ra	10^4	10^5	10^6
φ=0°	0%	2.2386	4.6491	9.2631
	5%	2.4826	5.1673	10.3716
	10%	2.7259	5.6862	11.4913
φ = 45°	0%	1.5204	2.2382	3.1941
	5%	1.7606	2.5960	3.7163
	10%	2.0238	2.9833	4.2841
φ =90°	0%	1.1307	1.1335	1.1389
	5%	1.3713	1.3742	1.3804
	10%	1.6487	1.6516	1.6585
		n=3		
	Φ/Ra	10^4	10^5	10^6
φ=0°	0%	2.3175	4.6755	9.3501
	5%	2.5747	5.2133	10.4180
	10%	2.8305	5.7582	11.4951
φ = 45°	0%	1.5834	2.3742	3.4804
	5%	1.8305	2.7468	4.0336
	10%	2.1008	3.1488	4.6320
φ =90°	0%	1.1622	1.1623	1.1639
	5%	1.4096	1.4098	1.4112
	10%	1.6948	1.6949	1.6963

Variation of average Nusselt number for different amplitude and Rayleigh number values, at 0.05 volume fraction, for 0° inclination angle and 1 and 3 wave cavities has been shown in Table 4. For low values of Rayleigh numbers, increasing amplitude doesn't effect average Nusselt number and circulation structure significantly. For higher Rayleigh numbers, at Ra=10^6, with increasing amplitude average Nusselt number increases significantly.

Table 4. Average Nusselt numbers for Φ=0.05 and φ=0° (Cu-water nanofluid)

	n=1			n=3		
λ/Ra	10^4	10^5	10^6	10^4	10^5	10^6
0.05	2.4826	5.1673	10.3716	2.5747	5.2133	10.4180
0.075	2.4668	5.1429	10.4459	2.6029	5.2107	10.5981
0.1	2.4461	5.1467	10.5576	2.6281	5.2480	10.8119

Average Nusselt numbers between Cu-water based nanofluid in square cavity by Kahveci (2010) and wavy cavities has been compared in Table 5. Heat transfer rate increases up to 6 % with the increase in number of waves. Nusselt value increases by usage of nanoparticles and considering above mentioned affect there is an increase in heat transfer rate up to 28 %.

Table 5. Comparison of average Nusselt numbers for square cavity and wavy wall cavity for λ =0.1

	Ra	Square cavity (Kahveci, 2010)	n=1	n=3
$\Phi = 0$	10^4	2.27	2.31	2.36
	10^5	4.72	4.73	4.74
	10^6	9.23	9.32	9.68
$\Phi = 0.05$	10^4	2.48	2.55	2.63
	10^5	5.20	5.22	5.25
	10^6	10.24	10.41	10.71
$\Phi = 0.1$	10^4	2.68	2.79	2.90
	10^5	5.66	5.72	5.81
	10^6	11.23	11.49	11.84

CONCLUSIONS

In this study, a numerical simulation is performed to study natural convection of water based nanofluid in an inclined square side wavy walls cavity. The top and bottom walls of the cavity were assumed to be adiabatic. The left wall of the cavity is hot where right wall of the cavity is cold. According to the results, Rayleigh number, volume fraction, nanoparticle type, amplitude, undulation number and inclination angle have significant effect on the circulation structure and heat transfer rate.
Heat transfer rate increases, with increasing fluid circulation due to Rayleigh number. Heat transfer is arised by conduction for for low values of Rayleigh numbers, while it is arised by convection for high values of Rayleigh numbers.

It can be seen from the study that, nanofluids with nanoparticles having high heat conductivity, increases heat transfer rate compared to pure fluids. Average Nusselt number is higher for nanofluids with Copper nanoparticles. Heat transfer rate increases, while increasing volume fraction of nanofluids.

Although there is no significant effect on average Nusselt number by changing amplitude it is noted that, for Ra= 10^6 , heat transfer rate increases by increasing amplitude. While examining effect of the inclination angle of the enclosed cavity, it can be seen that heat transfer rate significantly decreases, while heated wall approaches to upside, due to inclinations applied in clockwise direction.

Considering the undulation number effect, while comparing square, 1 undulation and 3 undulation cavities, it is noted that, with increasing undulation numbers heat transfer rate increases significantly. Wavy form of the cavity increases average Nusselt values up to 6%, and with consideration of the nanofluid usage, this value rises up to 28%.

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