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Heat Transfer in a Square Inclined Cavity Filled with Nanofluids for Various Thermal Conditions

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Abstract— **The aim of the present investigation is to study the influence of uniform and nonuniform heating on the left wall, the type of nanofluid on convective flow and heat transfer in an inclined square cavity filled with nanofluid. We used the finite volume element method to solve the Navier–Stokes and temperature equations. In this work, we tested the effect of different parameters (nanoparticles volume fraction 0%≤φ≤10%, inclination angle 0%≤ω≤180% and Rayleigh number $10^3 \leq Ra \leq 10^5$) on the flow, temperature profiles and Nusselt number. The results revealed that the way of heating and the type of nanofluid have a significant effect on the flow and the heat transfer. Particle concentration, inclination angle, and Rayleigh number are parameters that affect the heat transfer.**

***Keywords*— heat transfer; nanoparticles; nanofluid; inclination angle; Rayleigh number**

I. Introduction

Today, efforts have been focused on the enhancement of natural convection heat transfer while using a minimum energy input. With this aim, an innovative technique to enhance heat transfer rate by using nanoscale particles (smaller than100 nm) suspended in the base fluid, knownas nanofluids, has been used extensively in recent years. The resulting mixture possesses a substantially larger thermal conductivity compared to that of base fluids. Still, a good deal of research is performed to work toward a better understanding of the effects of nanoparticles [1–3].

In this context, we will study by numerical approach the natural convection in a cavity filled with nanofluid with the heated vertical left wall at uniform and nonuniform heat flux.

Natural convection of heat transfer with uniform and nonuniform temperature is a very important phenomenon in many energy systems due to its wide range of applications in various technologies, including furnaces, heat exchanges, cooling of electronic equipment, solar collectors, energy systems for buildings and safety of nuclear reactors etc.

The nonuniform heating draws attention of several researchers. This is due to a large number of technical applications such as the melting of materials for example the glass. For example, Alsaberyet al. [4] studied the influence of heating with a sinusoidal temperature of a square cavity filled with nanofluid on the streamlines and the temperature field. The numerical findings show that phase deviation increment affects significantly flow behavior and temperature distribution within the cavity. Also, they found that an increase in the concentration of nanoparticles causes an increase in the heat transfer. Hakanet al. [5] studied the effects of the non-isothermal boundary condition on natural convection for an inclined square cavity filled with nanofluid. They observed that the temperature profile is parabolic. The Nusselt number increases due to the increase in the Rayleigh number and the concentration of nanoparticles. The Al2O3+water nanofluid gives a better heat transfer improvement than the TiO_2+water nanofluid. Dalal and Das [6,7] studied the influence of nonuniform temperature profiles on the heat transfer. The results show that the variation of the boundary conditions has a very important effect on the heat transfer and the structure of the flow. Sarris et al. [8] tested the effect of Rayleigh number on the streamlines and Nusselt number for a sinusoidally heated cavity. The results show the intensity of streamlines increase with the Rayleigh number. The increase in the Rayleigh number induces an increase in the local Nusselt number. The numerical work carried out by Sivasankaran et al. [9] of a sinusoidally heated cavity shows that the local Nusselt number changes with the variation of temperature on the heated wall. Nawafet al. [10] tested the effect of variation in temperature on the Nusselt number. They found that the Nusselt number depends of the hot wall temperature.

Therefore, these types of problems attract the attention of several researchers due to their practical importance, especially in the application of solar systems (Goldstein and Sparrow [11]; Sunden and Trollheden [12]; V. Mani Rathnametal. [13]).

The main objective of this work is to make a comparison between uniform and nonuniform boundary conditions, measure its importance, to make another comparison between the different types of nanofluid (metallic-based nanofluid, metallic oxide and carbonic),as well as to study the influence of nanoparticle concentration, Rayleigh number and cavity orientation on the heat transfer and flow.

II. Statement of the Problem

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Figure 1 shows the geometrical of the enclosure. It is a two-dimensional inclined square cavity with a water-based nanofluid containing different types of nanoparticles. The left vertical wall is maintained at a uniform and nonuniform temperature, while right one is cooled to constant one. The other walls are assumed adiabatic.

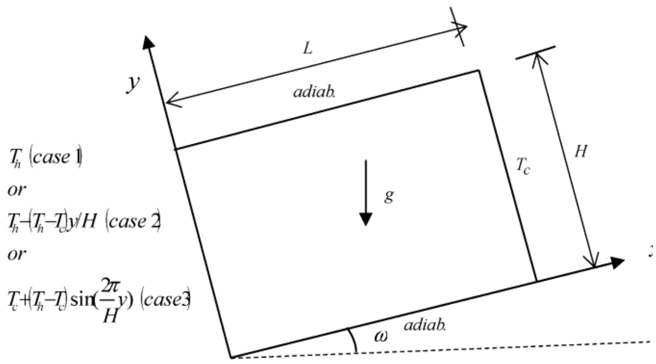

Fig. 1Studied problem with boundary conditions and coordinate system.

Table 1 illustrates the thermophysical parameters of water and nanoparticles which are assumed to be constant.

TABLE 1 PHYSICAL PROPERTIES OF PURE WATER AND DIFFERENT TYPES OF SOLID PARTICLES.

	ρ(kg m^{-3})	C_p(J kg^{-1}K^{-1})	k(Wm^{-1}K^{-1})	β(K^{-1})
Pure water	997.1	4179	0.613	2.1×10^{-4}
CuO	6320	531.8	76.5	1.8×10^{-5}
Al_2O_3	3880	765	40	0.8×10^{-5}
ZnO	5600	519.3	15	0.65×10^{-5}
TiO_2	4250	686.2	8.95	0.9×10^{-5}
Cu	8933	385	400	1.67×10^{-5}
Ag	10,500	235	429	1.89×10^{-5}
Au	19,320	128.8	314.4	1.41×10^{-7}
CNT	1350	650	3500	4.2×10^{-5}

The nanofluid of the work possesses constant thermophysical properties, with the exception the density variation of water which is given as a function of the Boussinesq approximation.

III. TEST VALIDATION

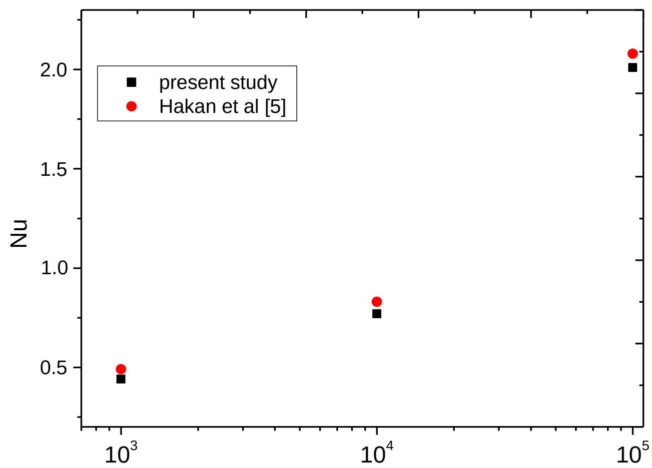

Fig.2 Test validation: Comparison between present study and other work from Hakan et al. [5] with Ra=10^5,φ=0% and Pr=7.06.

The present work was validated, comparing the numerical results with those reported by Hakan et al. [5] for horizontal cavity and φ=0%. The obtained results of the present computations in figure 2 show an excellent agreement with Hakan et al [5]. This gives us confidence for the use of the present code.

IV. RESULTS AND DISCUSSION

In this section, we will test the influence of uniform and nonuniform heating on the heat transfer as well as the flow. In this work, we considered a wide range of governing parameters such as the nanoparticles' volume fraction, inclination angle, Rayleigh number and types of nanoparticles. We study the effects of the nanoparticles' volume fraction varied between $0\%\leq\varphi\leq10\%$, inclination angle varied between $0°\leq\omega\leq180°$, Rayleigh number varied from 10^3 to 10^5, while the Prandtl number is kept constant at a 7.06 value. The nanoparticles used are the following: Cu, Ag, Au, CNT, CuO, Al_2O_3, ZnO and TiO_2.

A. *Effect of Particle Material on the Heat Transfer*

The influence of nanoparticles types on the Nusselt number for uniform heating (case 1) is presented in Figure 3.We can seethat the addition of nanosolids in the classic fluid (water) leads to an increase in the Nusselt number. Under the conditions of this work, an enhancement of 15% for Cu nanoparticles, 12.5% for Au nanoparticles, 14.5%for Ag nanoparticles, 13% for CNT nanoparticles, 13% for Al_2O_3 nanoparticles, 12% for CuO nanoparticles, 10% for TiO_2 nanoparticles and 11.5% for ZnO nanoparticles is achieved at a particle concentration of 10% relative to the water.We also note that the value of the average Nusselt number decreases according to the following ordering of nanoparticles: Cu, Ag, CNT, Al_2O_3,Au, CuO, ZnO and TiO_2.

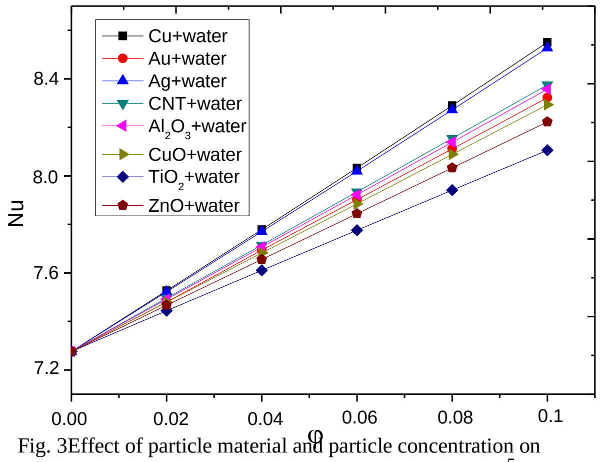

Fig. 3Effect of particle material and particle concentration on the Nusselt number for uniform heating (case 1) at Ra=$10^5$and ω=0°.

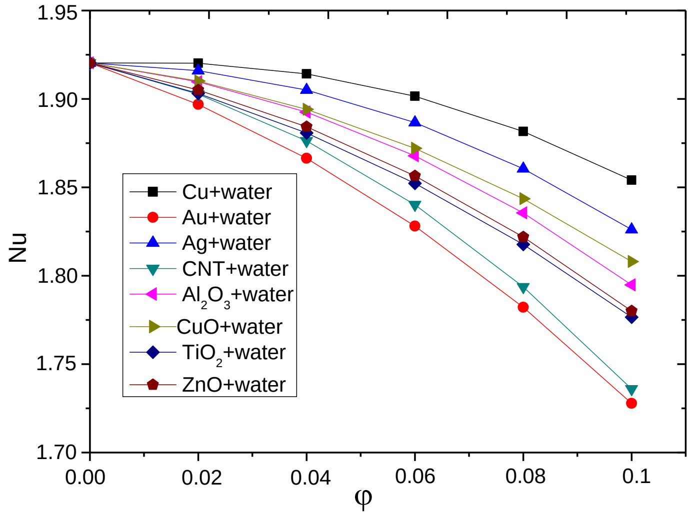

Fig. 4Effect of particle material and particle concentration on the Nusselt number for linearly heated wall (case 2) at Ra=10^5 and ω=0°.

Cu and Au produce a greater enhancement in the rate of heat transfer, since they have high thermal conductivities. Also, these nanoparticles are very stable due to the repulsive forces between the particles which dominate the attractive forces; therefore the agglomeration of these nanoparticles is weak.

The TiO_2 and ZnO nanoparticles produce a slight improvement in the heat transfer compared to the other nanoparticles, since they have a low thermal conductivity (Table 1).

Therefore for this type of configuration (uniform heating: case 1), Cu or Ag should be used as working nanoparticles.

Figure 4 shows clearly the effect of the nanosolids' volume fraction for different types of nanoparticles on the heat transfer through the enclosure heated with linear temperature profile case2.It is noted that, for all the nanoparticles, the Nusselt number decreases linearly with the increase in the concentration of nanoparticles. This behavior is due to the increase of the viscosity and the decrease of the buoyancy force during the addition of nanoparticles in the water. Therefore for this type of configuration (linearly heated wall), water is the best heat transfer fluid compared to the nanofluid.

Figure 5 illustrates the variation of Nusselt number with nanoparticles volume fraction for its different types in a cavity heated with sinusoidally temperature profile (case 3).We note that, for all types of solid particles, the Nusselt number increases during the addition of nanoparticles in the base fluid (water).Except for the Au nanoparticles, *Nu* increases to φ=2% and then decreases. In this case the CNT nanoparticles in water are the best heat transfer fluid compared to other nanoparticles.

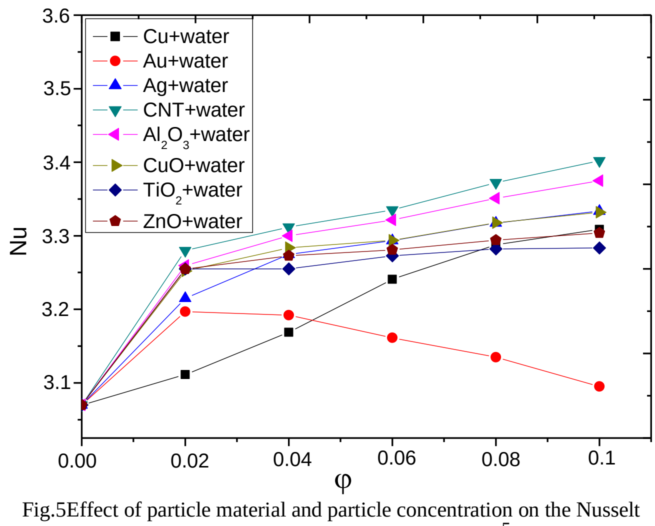

Fig.5Effect of particle material and particle concentration on the Nusselt number for sinusoidal heated wall (case 3) at Ra=10^5 and ω=0°.

B. Effect of the cavity inclination angle on the flow

Figure 6a–c show the streamlines for different inclination angles and for three cases of heating (uniform, linear and sinusoidal) with φ=4% and Ra=10^5.We note that for the uniform heating, case 1 (Figure 6a), and for a horizontal cavity ω=0°, the streamlines are constituted by a single cell occupying the totality of the cavity. At ω=60°, it can be seen from the streamlines that a main cell occupies the upper part of the cavity and other recirculation cell occupies the lower part. This recirculation cell constitutes a braking voltage for the flow, that is to say, a decrease of the flow velocity.

The streamlines for the linearly heating is shown in Figure 6b (case 2). At ω = 0°, the flow is characterized by the appearance of a single clockwise-rotating eddy occupying the whole cavity. The change of the inclination leads to a change in the convection strength.

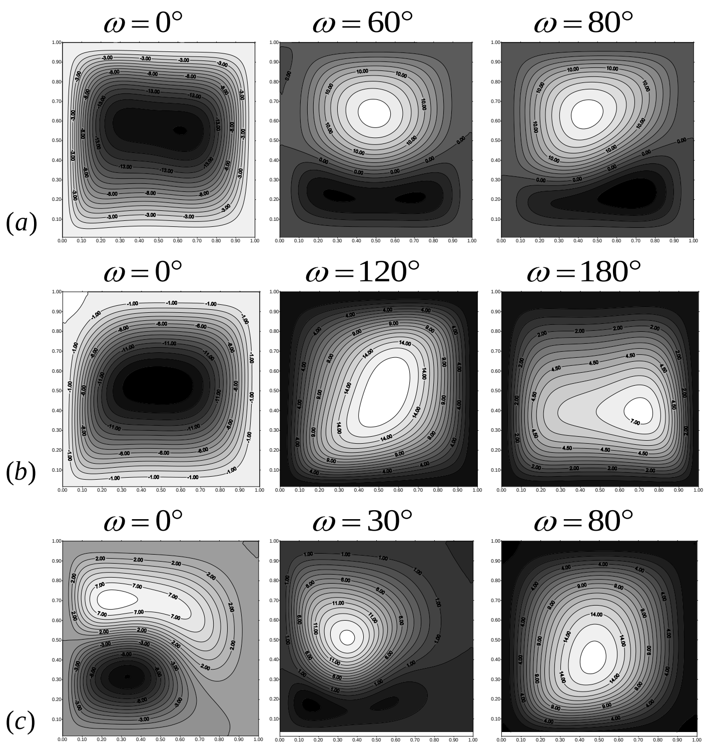

Fig.6 (a–c) Streamlines for different inclination angles and different configurations (a: case 1; b: case 2;c: case 3) for Ra=$10^5$and φ = 4%.

For the case of sinusoidal heating (case 3), at *ω*=0° the flow is characterized by the pairing of a main cell, which rotates in acounterclockwise direction and another recirculation cell, which rotates clockwise. The orientation of the cavity up to *ω*=30° results in a reduction in the size of the recirculation cell, which increases the heat transfer .The recirculation cell disappears at *ω*=80° and the flow becomes unicellular, which leads to an increase in heat transfer.

C. Effect of Inclination Angle on the Heat Transfer for Three Configurations

The influence of the inclination angle on the average Nusselt number for different Rayleigh number with uniform heating (case 1) is presented in Figure 7. It can be noticed that, at *Ra*=10^3, the Nusselt number does not change with an increase in the inclination angle. So, the dominant mode of heat transfer is conduction. In contrast, at high Rayleigh numbers, where the convection is strong, the inclination angle is a very important parameter that acts on the heat transfer. For example, for *Ra*=10^4, when the inclination angle increases, the Nusselt number decreases, reaching a minimum value at *ω*=80°, then increases. The maximum of the Nusselt number occurs at an inclination angle about 120°. When we increase of the Rayleigh number to 10^5, convective heat transfer becomes stronger and the effect of cavity orientation becomes greater. A first increase in the inclination angle to 10° results in an increase of the Nusselt number. A further increase of *ω* leads to a decrease of the Nusselt number up to *ω*=60°. Therefore, we can conclude thatfor*Ra*=10^5, the heat transfer reaches its maximum at *ω*=10° and its minimum at *ω*=60°.

The variation of the Nusselt number against various inclination angles for different Rayleigh numbers in the cavity filled with Cu+waternanofluid and linearly heated (case 2) are depicted in Figure 8. It was found there is no change in the Nusselt number at *Ra*=10^3 on changing the cavity inclination angle.For*Ra*=10^4, we observe an increase in the Nusselt number while increasing the inclination angle at 10°. Increasing again of *ω* to 60° leads to a decrease of Nusselt number. Another increase of *ω* leads to an increase and then decrease of this latter. The maximum of *Nu* is recorded at *ω*= 120°. At high Rayleigh numbers (*Ra*=10^5), with increasing the inclination angle first, *Nu* number increases and reaches to its maximum value and then reduces.

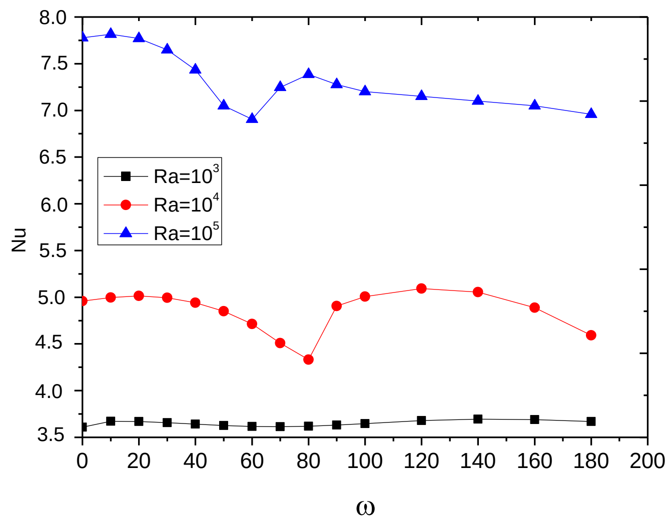

Fig.7Variation of average Nusselt number versus the inclination angle for three values Rayleigh number, 10^3, 10^4 and 10^5 with uniform heating.

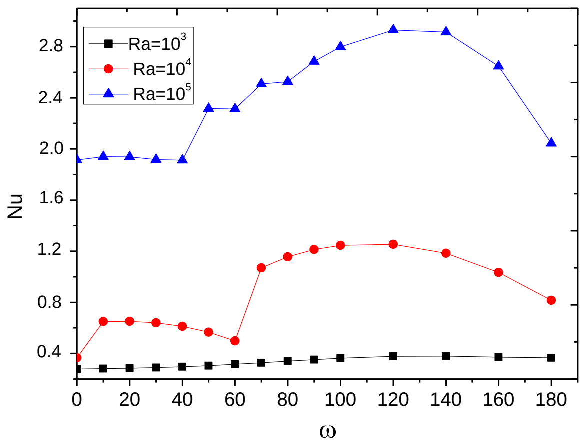

Fig.8Variation of average Nusselt number versus the inclination angle for three values of Rayleigh numbers (10^3, 10^4 and 10^5) with linear heating (case 2).

The effect of the inclination angle on the Nusselt number for a cavity filled with CNT+water nanofluid and heated sinusoidally is represented in Figure 9. For weak Rayleigh numbers (Ra=10^3), the orientation of the cavity does not affect the heat transfer. The mode of heat transfer is conduction. For Ra=10^4, the increase of the inclination angle leads to an increase in the Nusselt number. The maximum is recorded at 70°; this was similar to Ra=10^5 but the maximum is recorded at 80°.

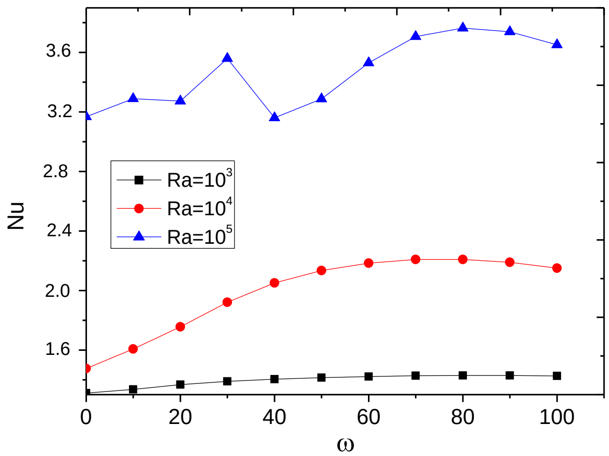

Fig.9Variation of average Nusselt number versus the inclination angle for three values Rayleigh number (10^3, 10^4 and $10^{5)}$ with sinusoidal heating (case 3).

V. Conclusions

The main objective of this study was to study the effect of the types of solid particles, as well as the continuous and discontinuous boundary conditions, on their flow characteristics and heattransfer performance. We have used the finite element method to obtain numerical solutions based on streamlines and isotherms for a wide range of Ra, ω and φ for uniform and nonuniform heating of the left wall.

In view of the results and discussion presented, the following conclusions have been drawn:

1. The flow structure changes with the inclination angle for uniform and nonuniform heating.
2. Cu+water nanofluid provides better heat-transfer performance for case 1.
3. The water provides better heat transfer performance for case 2.
4. CNT+water nanofluid provides better heat transfer-performance for case 3.
5. At Ra=10^5, the Nusselt number reaches its maximum at ω=10° for case 1, ω = 120° for case 2 and ω= 80° for case 3.
6. The heat transfer increases with an increase in the temperature gradient for the three cases of heating.

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