Thermal performance of nanofluids in rectangular microchannel with vortex generators: Application of electronic components cooling

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Abstract. In this study, the contributions of Au, Cu and Ag nanoparticles for enhancing the heat transfer in the rectangular microchannel heat sink with vortex generators are compared in this work. A two dimensional numerical method is used to simulate the forced convection of water-based suspensions of different nanoparticles in the microchannel heat sink submitted to a constant and uniform temperature (T= 303K) at the wall . The governing equations are solved numerically using code FLUENT based on CFD method. Comparisons with previously published work on the basis of special cases are performed and found to be in excellent agreement. The effect of volume fraction, Reynolds number and type of nanoparticles on the fluid flow and heat transfer processes within the microchannel is analyzed. In addition, an analysis of isothermals and streamlines based on the different nanofluid are developed and presented. It is shown that the different nanoparticles within different thermal conductivity values have substantial effects on the results. Finally, the local and average Nusselt number for various Reynolds numbers and volume fractions are presented**.**

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1 Introduction

Nanofluids are defined as a dispersion of particles with nanometric size (diameter is typically less than 100 nm) [1], named nanoparticles, in a base fluid to improve some thermophysical properties. In the case of heat transfer fluids, one of the first parameters to take into account in order to evaluate the potential heat exchange is the thermal conductivity [2]. However, the most used fluids such as water, oil or ethylene glycol only have a low thermal conductivity compared to that of crystalline solids. With nanofluids, the idea is then to insert, within the base fluid, nanoparticles in order to increase the effective thermal conductivity of the mixture [3-4].

In the recent decenny, cooling high-power and large-scale systems (microprocessors, laser diodes, etc.) require higher heat dissipation [5]. The second heat removal strategy consists of utilizing both the flow properties of liquids and the high thermal connectivity of solid metals [6]. The use of nanofluids based on metal particles or carbon nanotubes has better thermal conductivity and convective heat transfer coefficient compared to the base fluids [7]. This method is certainly the most promising solution in the field of improving heat transfer. In this context, and in the complementary frame work that we will conduct our study. The work that we are going to develop concerns a numerical study of a laminar flow of three nanofluids flow a horizontal two-dimensional channel containing five vortex generators.

2 Computational domain and numerical method

2.1 Computational domain

In this work, we are interested to conduct a numerical investigation of laminar forced convection in two-dimensional horizontal microchannel using different nanofluids with five fins mounted in the lower wall of the channel (figure 1). In our study, we will consider 3 types of nanoparticles: Ag, Cu and Au dispersed in water as the base fluid; emphasizing the influence of certain parameters such as the Reynolds number, the solid volume fraction and the type of nanoparticles suspended in water.

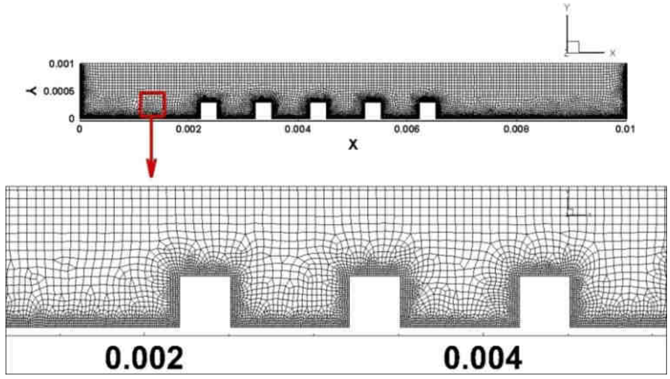


Fig.1. Computational domain

2.1 Governing equations

Assuming that the flow conditions are stable, two-dimensional, homogeneous and laminar, the governing equations continuity, momentum and energy for the fluid and solid domains can be written as following:

$$\nabla.(\rho V) = 0 \quad (1)$$

$$\nabla.(\rho V V) = -\nabla P + \nabla.(\tau_{ij}) \quad (2)$$

$$\nabla.(\rho V C_p T) = \nabla.(K \nabla T) \quad (3)$$

Where$\tau_{ij}$is the stress tensor and can be expressed in terms of fluid viscosity and velocity gradient as follows:

$$\tau_{ij} = \mu.\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}. - \frac{2}{3}\mu\delta_{ij}.\left(\frac{\partial v_i}{\partial x_j}\right) \quad (4)$$

The thermophysical properties of the nanofluid such as density, specific heat and viscosity are determined based on the nanoparticles and base fluid properties from the following equations [2] :

$$\rho_{nf} = (1-\varphi)\rho_f + \varphi\rho_p \quad (5)$$

$$(\rho C_p)_{nf} = (1-\varphi)(\rho C_p)_f + \varphi(\rho C_p)_p \quad (6)$$

$$\mu_{nf} = \mu_f(1 + 2.5\varphi) \quad (7)$$

2.2 Boundary conditions

At the microchannel inlet, temperature T_0 (=293 K) and profiles of uniform axial velocity V_0, prevail. Constant temperature (T= 303K) was applied to the microchannel surface. Moreover, in the case of thermophysical properties of nanofluids , the overall physical properties are considered as the constant values, which are also determined by the previous models at reference temperature (T_{ref}). At the channel exit section, the fully developed conditions are considered and the all axial derivatives are zero. No-slip conditions and uniform temperature are imposed on the microchannel wall. Both the thermal fields and flow are assumed symmetrical with respect to the vertical plane passing through the channel main axis.

3 Numerical method - CFD Approach

3.1 Numerical method

The code ANSYS Fluent [11] is commonly used software in CFD method, and a detailed analysis of its mathematical model can be found in the Fluent User's Guide. The numerical code uses a method based on control volume approach to convert all the governing equations into algebraic equations so that they can be solved numerically, providing a good research solution [12]. The control volume method works by integrating the governing equations for each control volume, and then by discretizing the governing equations that conserve each quantity based on the control volume unit.

The conservation equations found a solution in the control volume technique, since governing equations could be given numerical solutions after being converted into a set of algebric equations. This conducted some of the entailments of governing equations, including diffusion terms, convection terms, and other quantities, which were not properly addressed in a second order upwind scheme. This study uses the Semi-Implicit Method for Pressure Linked Equations (SIMPLE) to pair pressure and velocity in the Fluent CFD program [11] to solve the linear systems resulting from discretization scheme.

3.2 Code validation

In order to obtain the accuracy of the obtained results, the prior validation of our calculation code is necessary, car it gives more credibility. The numerical code was validated with the numerical results of Khanafer et al [10]. The authors reported a numerical investigation of heat transfer enhancement of nanofluids in two-dimensional enclosure of height H = 1cm. The active walls are subjected to thermal conditions of the Dirichlet type (isothermal walls) while the two other walls are adiabatic. Throughout this study, the temperature difference between the active walls is considered constant (ΔT=10 K).

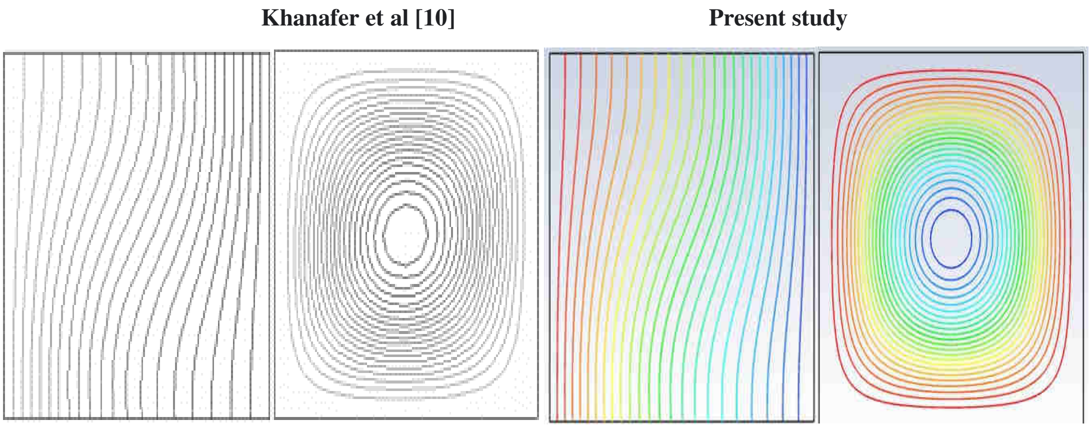


Fig.2. Comparison of the streamlines and the isotherms between the present work and that of Khanafer et al [10] (Pr=0.7, Ra=10^3)

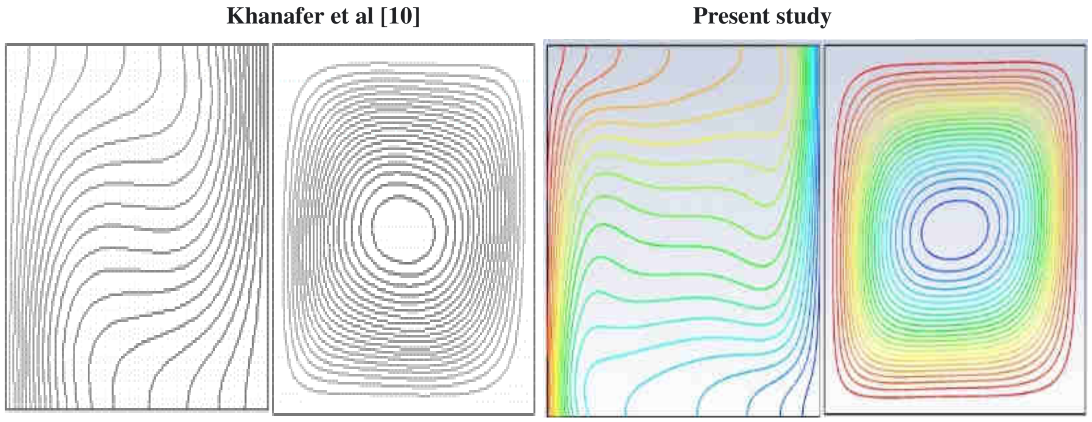


Fig.3. Comparison of the streamlines and the isotherms between the present work and that of Khanafer et al [10] (Pr=0.7, Ra=10^4)

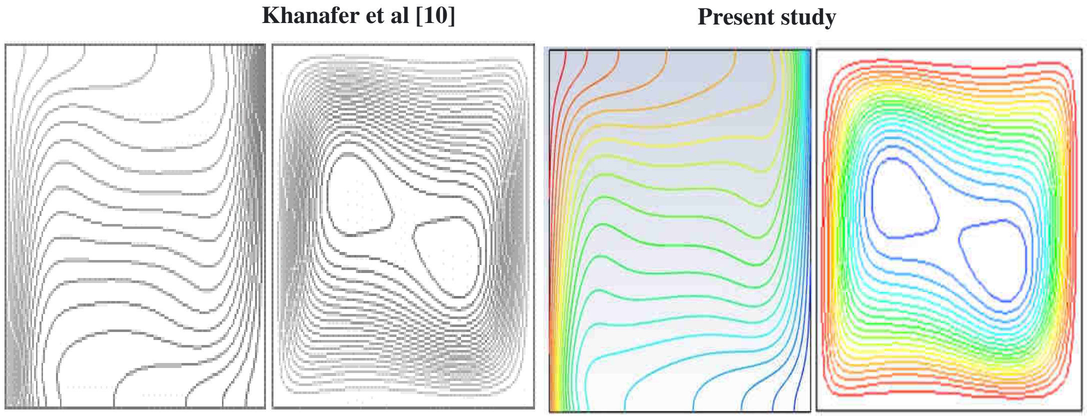


Fig.4 Comparison of the streamlines and the isotherms between the present work and that of Khanafer et al [10] (Pr=0.7, Ra=10^5)

The validation of our numerical code was performed against the results performed by Khanafer et al [10] for pure fluid as shown in Figs. 2–4. It can be seen from these figures that the solution of the present numerical model is in excellent agreement with the numerical results from Khanafer et al [10].

4 Results and discussions

4.1 Effect of Reynolds number

In order to study the effect of Reynolds number (Re = 5, 10, 100) and the type of nanoparticles on flow structure and heat transfer, isotherms and streamlines for pure water and for the three nanofluids (Water-Cu, Water-Au, Water-Ag)with 1.8 vol%, are illustrated in figure 5.

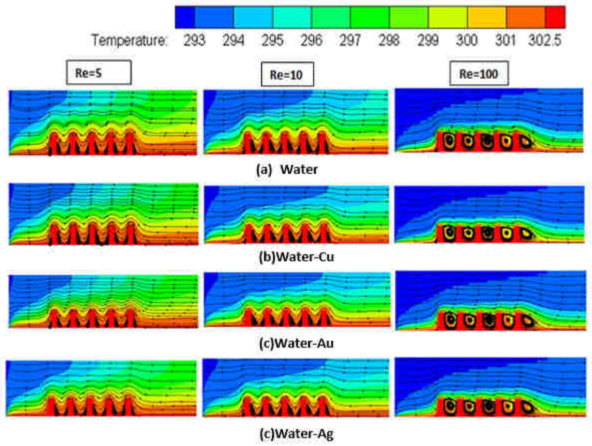


Fig.5. Isothermal and streamlines for a) water, b) Water-Cu, c) Water-Au and Water-Ag for different Reynolds numbers

These lines draw our attention that the presence of the obstacles (fins) cause a congestion of the power lines in the upstream corner, and it can be observed recirculation zones downstream of the fins, for pure water and nanofluid, at different Reynolds numbers. The streamlines show that increasing Reynolds number makes a remarkable evolution on the flow structure, and the vortices that form behind the fins become larger and stronger. The higher Reynolds number improves heat transfer. At Re = 5, there is no significant difference between the lines of stream of nanofluid and pure water. We can see the impact of the presence of nanoparticles on streamlines whenever the Reynolds number increase ; in this case, the pure water is associated with a larger vortex behind the fins only for the nanofluid; The reason for this behavior can be explained by greater density and dynamic viscosity of the nanofluid, i.e., the existence of the nanoparticles motivates the effective dynamic viscosity of the nanofluid. We also note that the presence of nanoparticles in water promotes and reduces the flow field intensity compared to the case of pure water.

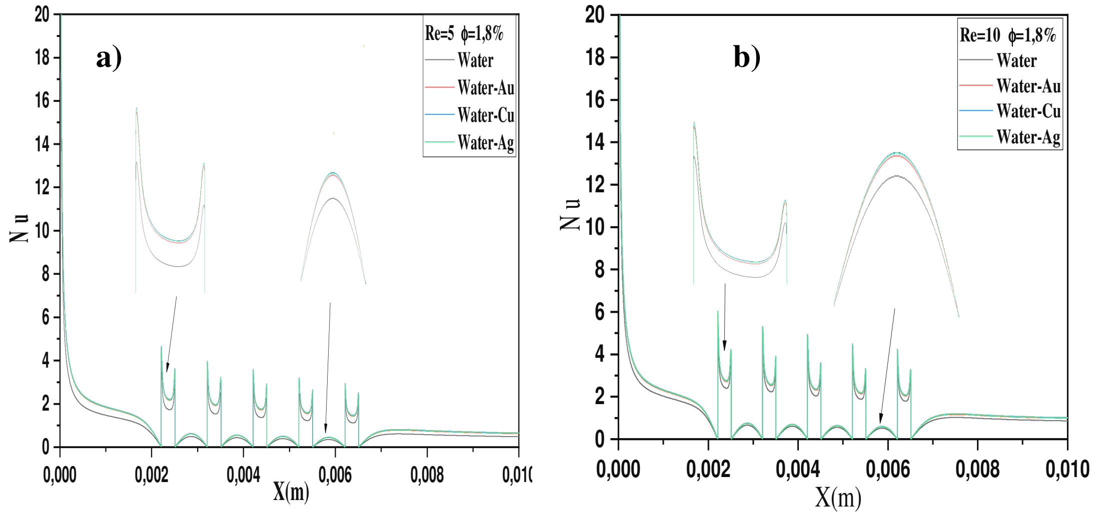
4.2. Effect of nanoparticle type

In this section, the obstacles are cooled with different types of nanofluids in a horizontal channel, with the aim of improving the heat transfer rate, at different values of volume fraction (ϕ=0.05, 1.2 and 1.8) and Reynolds numbesr Re= 5, 10 and 100, respectively.

Figure 6 illustrates the evolution of the local Nusselt number along the microchannel for different types of nanofluids 1.8 vo%l. Fluid dynamics is not influenced by the type of nanoparticles, because the viscosity of the nanofluid is only sensitive to the volume fraction of solid particles, according to the

It is noticed that at low Reynolds numbers, conduction is the dominant mechanism of heat transfer. Therefore, the isotherms stretched above the vortex generators and extending to occupy a considerable part of the channel. We can also observe a stratification of the temperature on each side of the fins. For Re=10 this extension of the isotherms is reduced a little. As Re is increased, convection becomes the dominant mechanism, and the isotherms propagate and press against the flow near the lower corner downstream of the fins due to the influences of clockwise rotating recirculation, and the strong inflow cold pushes the isotherms which tend to become horizontal and provides good evacuation of hot fluid outside the channel. The comparison between the isotherms of the nanofluid and pure water shows that at each channel point, the temperature of the nanofluid is higher than the pure water. It is due to the higher thermal conductivity of the nanofluid.

Brinkman equation, and is not sensitive by the type of nanoparticles. On the other hand, according to Maxwell's equation, the type of nanofluid motivated thermal conductivity, thus providing a significant improvement of the heat transfer rate .Au nanoparticles have the lowest thermal conductivity value compared to Cu and Ag nanoparticles, as a result, water-Ag nanofluid has the lowest values of Nusselt number than water-CU and water-Ag nanofluids



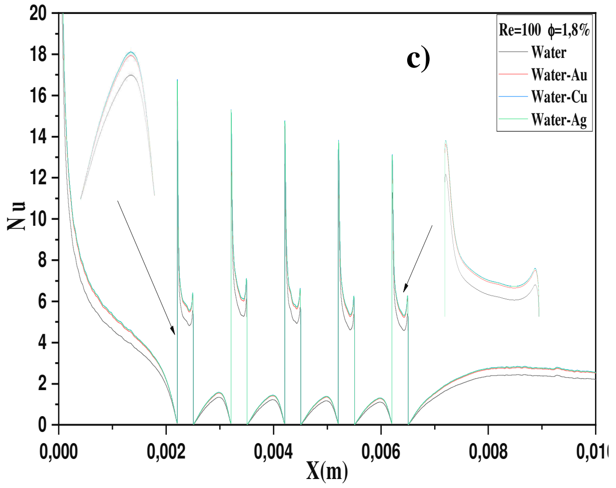
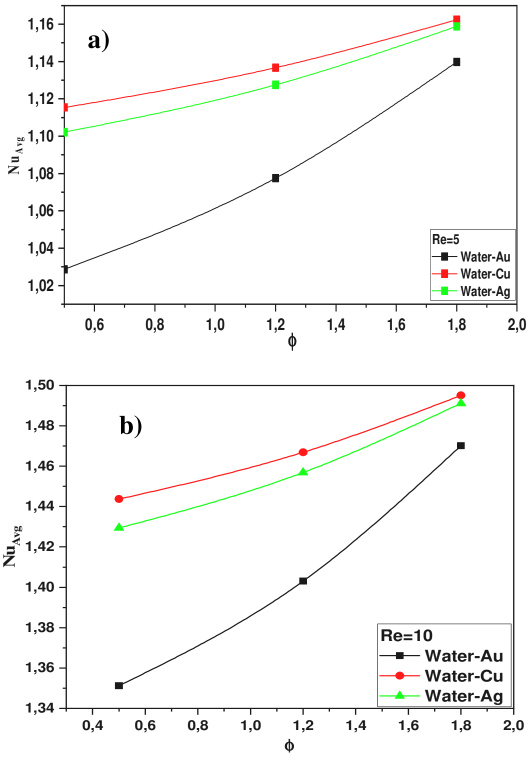


Fig.6. Nusselt number variation a long the channel for different nanofluidsat different Reynolds numbers a) Re=5, b) Re=10 and c) Re=100

Figure 7 shows the effect of nanoparticle volume fraction (ϕ) on the average Nusselt number (N_{avg}) and for different Reynolds numbers. It is observed that the average Nusselt number increases by increasing the Reynolds number for all values of ϕ, therefore the heat transfer is improved by increasing the inertial effects. It should also be noted that the average Nusselt number increases linearly with the increase of the volume fraction of the nanoparticles for all values of the Reynolds number. There are two factors influencing the heat transfer when increasing the volume fraction of nanoparticles: The first factor is the increase in the viscosity of the nanofluid which slows down its movement and reduces the heat transfer rate; the second factor is increasing thermal conductivity of the nanofluid which improves the heat exchange. The effect of the viscosity is less than the effect of the conductivity, and the heat transfer rate increases by increasing the volume fraction of the nanoparticle solid. This figure shows the same behavior observed in figure 6, Cu and Ag nanoparticles have the highest mean Nusselt values, compared to Au nanoparticles which have the lowest value of thermal conductivity compared to other nanoparticles.



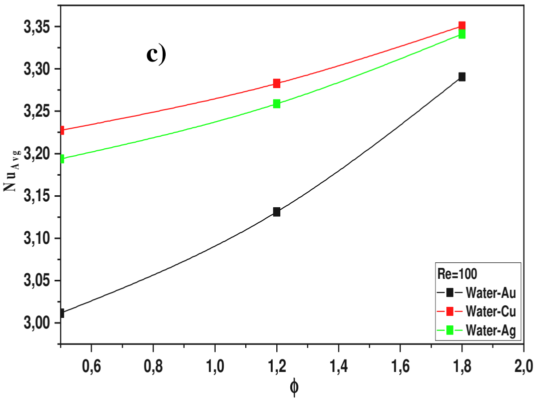


Fig.7. Average Nusselt number as function of volume fraction for different nanofluidsat different Reynolds numbers a) Re=5, b) Re=10 and c) Re=100

5 Conclusion

Heat transfer enhancement in a two-dimensional microchannel with obstacles is studied numerically for a range of volume fractions and Reynolds numbers. The contributions of Au, Cu and Ag nanoparticles for enhancing the thermal performance of working fluid in the microchannel were compared in this study. The present results show that the different suspended nanoparticles substantially increase the heat transfer rate at any given Reynolds number. In addition, the results illustrate that the nanofluid heat transfer rate increases with an increase in the nanoparticles volume fraction. The presence of vortex generators in microchannel is found to alter the structure of the fluid flow which becomes more stable. A comparative study of different parameters based on this study: the effect of volume fraction, type of nanoparticles and Reynolds number, is analyzed. The main findings are listed as follows:

- Increasing Reynolds number produced a larger vortex generators behind the fins. This is also associated with increased heat transfer.
- Nanoparticles dispersed in water increase the thermal conductivity of the fluid which increases the heat transfer
- As the volume fraction of solids increases, the heat transfer is improved for all values of the Reynolds numbers, this improvement is greater when Re is high.
- Nanoparticles with higher thermal conductivity will prove the best cooling performance of the considered system
- The presence of obstacles in microchannel can change the nanofluidflow structure by producing recirculation zones which can destroy the thermal bounder layer, therefore the heat transfer increases

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