NATURAL CONVECTION WITHIN Water-ZnO NANOFLUID-FILLED HEMISPHERICAL ENCLOSURE WITH A CUBIC ELECTRONIC DEVICE

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ABSTRACT

This work qualifies and quantifies the nanofluidic natural convective phenomena occurring in a hemispherical enclosure used for electronics applications. This cavity consists of a disk thermally insulated on its rear face, an active cube centered on the disk which generates a constant heat flux and an isothermal dome. The disc of the cavity remains horizontal while its dome is oriented either upwards or downwards. The considered nanofluid is a mixture of water with metallic ZnO nanoparticles. In order to examine the influence of these nanoparticles on the natural convective heat transfer, three values of the volume fraction considered: 0% (pure water), 1% and 5%. The dimensionless governing system of the problem under consideration is solved by means of the control volume method in combination with the SIMPLE algorithm. The structured mesh is composed of triangular surfacic elements and tetrahedral in the volumic domain. Temperature and velocity distributions are presented for some configurations and convective heat transfer is examined for all processed ones. The natural convective heat transfer is quantified by means of Nusselt-Rayleigh-Prandtl correlations.

NOMENCLATURE

a	[m^{2}s^{-1}]	thermal diffusivity
b	[-]	exponent defined in Eq. (6)
C	[J.kg^{-1}K^{-1}]	specific heat at constant pressure
g	[m.s^{-2}]	gravity acceleration
k	*[-]*	coefficient defined in Eq. (6)
L	[m]	side of the active cube
m	[-]	coefficient defined in Eq. (6)
n	[m]	outgoing normal
n^*	[-]	dimensionless outgoing normal $n^* = n / R$
$\overline{Nu}$	[-]	average Nusselt Number
P	[W]	generated power
Pr	[-]	Prandtl Number (-)
q	[Wm^{-2}]	generated heat flux, $q = P / S_h$
R	[m]	radius of the dome
Ra	[-]	Rayleigh number
S_h	[m^2]	exchange area of the cube
T	[K]	temperature
T_{max}	[K]	maximum temperature
T_c	[K]	temperature of the dome
T^*	[-]	dimensionless temperature
u	[m.s^{-1}]	velocity
u_{max}	[m.s^{-1}]	maximum velocity
u^*	[-]	dimensionless velocity $u^* = u / u_{max}$ (-)

Greek symbols

α	[°]	tilt angle with respect to the horizontal plane
β	[K^{-1}]	volumetric expansion coefficient
φ	[-]	volume fraction
λ	[Wm^{-1}K^{-1}]	thermal conductivity
μ	[Pa.s]	dynamic viscosity
ρ	[kg.m^{-3}]	density

Subscripts

f	base fluid (pure water)
nf	nanofluid
s	solid nanoparticles

INTRODUCTION

In cases where high heat flux is generated in engineering assemblies, nanofluids can constitute an effective heat exchange means to enhance the natural convective heat transfer. The review [1] deals with applied hybrid nanofluids. Among the most commonly high thermal conductivity nanoparticles used for their preparation are the Al_2O_3, ZnO, CuO, TiO_2, nanotube particles and the Fe_3O_4. Pure water is the most commonly base fluid used given its low cost. Other fluids are also used such as the ethylene glycol and various oils. Many methods are used to produce the nanofluids. Those concerning the TiO_2 based nanofluid are presented in [2]. The Al_2O_3-based nanofluid implemented for machines lubrication is presented in the review [3]. Knowledge of the thermophysical characteristics of these nanofluids is crucial for applications purposes. Main characteristics (density, thermal conductivity, viscosity, specific heat) of single wall carbon nanofluids are presented in [4] for a volume fraction (proportion of nanoparticles in the base fluid) varying between 0.1 and 0.5%. The study [5] shows that the viscosity of nanofluids consisting of CuO nanoparticles dispersed in a mixture of water and ethylene glycol is highly dependent on the volume fraction. The experimental survey [6] shows that the viscosity of a nanofluid constituted with carbon nanotube particles diluted in pure water and antifreeze decreases with the nanofluid temperature and increases when the volume fraction increases between 0 and 2%. A critical review is presented in [7] concerning the overall heat transfer by using some nanofluids. The use of nanofluids does not always enhance convective heat transfer. It depends on the boundary conditions corresponding to the treated problem as specified in [8]. Rayleigh-Bénard convection with CuO-water nanofluids is enhanced for low Rayleigh number (10^3) but the average Nusselt number is reduced for largest values as shown in [9].

Natural convection in horizontal hemispherical enclosures has been examined in [10,11] based on fluids whose Prandtl numbers vary between 6 and 13000. Both studies show that the Prandtl number has a low influence on the natural convective heat transfer which is quantified by means of Nusselt-Rayleigh type correlations. Air-filled and tilted hemispherical enclosures have been examined with various thermal boundary conditions leading to specific correlations of the Nusselt-Rayleigh type synthesized in [12]. However, to the knowledge of the authors, no work has treated the natural convective phenomena concerning the inclined hemispheric enclosure filled with nanofluids.

The objective of this work is thus to examine the case of a hemispherical enclosure whose dome is maintained isothermal and oriented either upwards or downwards. A cube centered on the disk generates a constant heat flux leading to high Rayleigh numbers reaching $4.2\text{x}10^{10}$. Some volume fraction of the monophasic Water base ZnO nanofluid are considered. This 3D numerical survey done by means of the volume control method based on the SIMPLE algorithm qualifies the natural convective phenomena occurring in this assembly. The natural convective heat transfer is quantified by means of Nusselt-Rayleigh-Prandtl type correlations which optimize the thermal design of these enclosures used in electronics.

EXAMINED CONFIGURATION

The considered assembly is presented in Fig. 1(a). An active cube of side *L* is centered on the disc of the hemispherical cavity of radius *R* thermally insulated on its rear face. This cube generates a power *P* ranging from 5 to 400W, while the dome is maintained isothermal at temperature T_c=300K. The disc remains horizontal while its dome is oriented either upwards or downwards as presented in Fig. 1(b) and Fig 1(c) respectively. These positions correspond to the intended application in electronics. The considered nanofluid is a water base-ZnO nanoparticles. In order to examine the influence of the ZnO metallic nanoparticles on the natural convective heat transfer, three values of the volume fraction are considered: 0% (pure water), 1% and 5%. The surface of the active cube subjected to convective phenomena is denoted as S_h. Moreover, the indices concerning the basic fluid (pure water), the nanofluid and the solid are denoted as f, nf and s respectively. The Prandtl *Pr* and Rayleigh *Ra* numbers are based on the nanofluid and water thermophysical characteristics respectively

$$Pr = \frac{\mu_{\text{nf}} C_{\text{nf}}}{\lambda_{\text{nf}}} = \left(\frac{\mu C}{\lambda}\right)_{\text{nf}} \; ; Ra = \left(\frac{\beta \rho}{\mu \lambda a}\right)_{\text{f}} g R^4 q \qquad (1)$$

where $q = P / S_h$ is the heat flux generated by the cube.

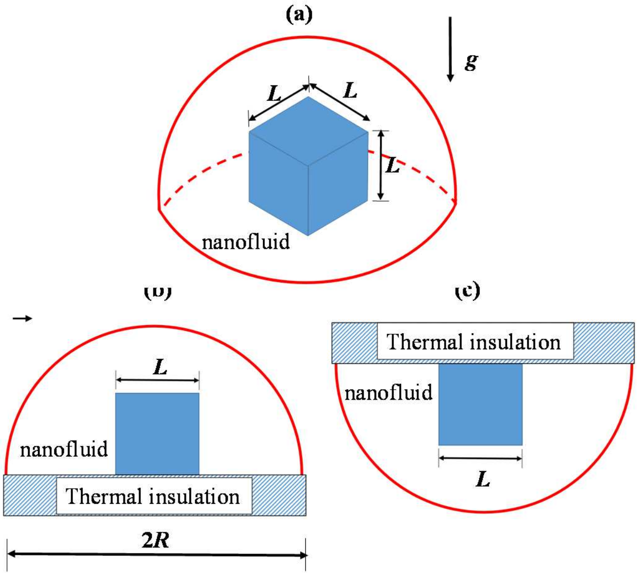

Figure 1. The treated configurations

The Rayleigh values corresponding to the generated power considered in this work (5-400W) vary between $5.2\text{x}10^8$ and $4.2\text{x}10^{10}$. The dimensionless temperature T^* is defined as

$$T^* = \left[\frac{T - T_c}{\frac{qR}{\lambda_{\text{nf}}}} \right] \qquad (2)$$

In the numerical procedure, the whole assembly is initially at T_c =300K. The dome constituting the cold wall of the assembly is kept isothermal at T_c and the external face of the disc is assumed as adiabatic. The no-slip condition is imposed on the inner face of the dome, the external faces of the cube and the inner face of the disc in contact with the nanofluid. The Boussinesq approximation is applied. Since only natural convective phenomena are examined in this numerical work, radiation is not considered. This condition is realized by imposing a global IR emissivity equal to zero to all the internal surfaces of the cavity. The solution of the governing system detailed in [13] is obtained by means of a home-made software and some configurations are calculated with the commercial software Ansys [14] based on the control volume method in combination with the SIMPLE algorithm. The computational domain is constituted with the not structured mesh presented in Fig. 2.

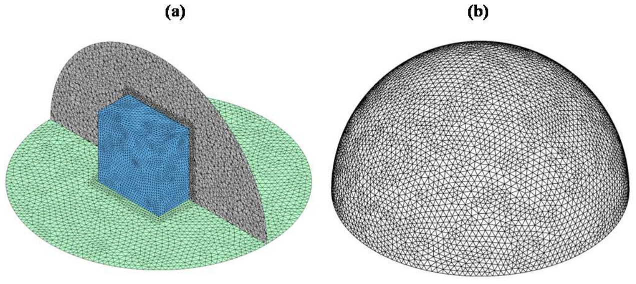

Figure 2. The adopted mesh

As shown in Fig. 2(a), a refinement of the disc all around the cube is done to better take the conductive effects into consideration. The fluid mesh is also refined around the hot active surface (cube) to determine with precision the distribution of the parietal thermal gradients and the corresponding wall temperature. The local Nusselt number *Nu* is calculated by means of a heat balance at the surface of the cube with

$$Nu = \frac{\lambda_{\mathrm{nf}}}{\lambda_{\mathrm{f}}}\left(\frac{\partial T^*}{\partial n^*}\right) \tag{3}$$

where $n^* = n/R$ is the dimensionless outgoing normal. The average Nusselt number $\overline{Nu}$ is obtained by integration of the local values through the corresponding surfaces as

$$\overline{Nu} = \left(\frac{1}{S_h}\iint T^* dS\right)^{-1} \tag{4}$$

The numerical solution is considered to be mesh independent when successive 2% increases of the mesh do not lead to a $\overline{Nu}$ variation more than 3%. The iterative process is stopped when the relative difference between results of two successive iterations are lower than 10^{-5} for the velocity components and 10^{-6} for the energy. The optimized final mesh associated to these conditions is finally constituted with 452,741 elements. The thermophysical characteristics of the ZnO nanoparticles is presented in Table 1.

Table 1. Thermophysical characteristics of the ZnO nanoparticles [15]

λ ($\mathrm{Wm^{-1}K^{-1}}$)	ρ ($\mathrm{kg.m^{-3}}$)	C ($\mathrm{J.kg^{-1}K^{-1}}$)	β ($\mathrm{K^{-1}}$)
80	5600	495	3

The *Pr* number of the considered monophasic Water-ZnO nanofluid is presented in Table 2

Table 2. Considered φ and Pr values

φ	0%	1%	5%
Pr	6.074	5.763	4.780

Its thermophysical characteristics considered as temperature independent are determined with [16,17].

$$\begin{aligned}
&\text{density } \rho_{\mathrm{nf}} = (1-\varphi)\rho_{\mathrm{f}} + \varphi\rho_{\mathrm{s}} \\
&\text{specific heat } C_{\mathrm{nf}} = \frac{(1-\varphi)(\rho C)_{\mathrm{f}} + \varphi(\rho C)_{\mathrm{s}}}{\rho_{\mathrm{nf}}} \\
&\text{volumetric expansion coefficient} \\
&\beta_{\mathrm{nf}} = \frac{(1-\varphi)(\beta\rho)_{\mathrm{f}} + \varphi(\beta\rho)_{\mathrm{s}}}{\rho_{\mathrm{nf}}} \\
&\text{effective thermal conductivity} \\
&\lambda_{\mathrm{nf}} = \left[\frac{\lambda_{\mathrm{s}} + 2\lambda_{\mathrm{f}} - 2\varphi(\lambda_{\mathrm{f}} - \lambda_{\mathrm{s}})}{\lambda_{\mathrm{s}} + 2\lambda_{\mathrm{f}} + \varphi(\lambda_{\mathrm{f}} - \lambda_{\mathrm{s}})}\right]\lambda_{\mathrm{f}} \\
&\text{dynamic viscosity} \\
&\mu_{\mathrm{nf}} = \frac{\mu_{\mathrm{f}}}{(1+\varphi)^{2.5}}
\end{aligned} \tag{5}$$

RESULTS

The calculated configurations are obtained by combining the 2 values of α (0 and 180°), 3 values of φ (0, 1 and 5%) and 8 Ra values ranging from $5.2\mathrm{x}10^7$ to $4.2\mathrm{x}10^{10}$. The dimensionless temperature T^* fields and the associated iso velocity u^* are presented in Fig. 3 for the half vertical cross section of the hemisphere represented in Fig. 2(a). These fields corresponding to the combination $\varphi = 1\%$, $Ra = 1.04\mathrm{x}10^9$ are representative of the free convective phenomena occurring in the enclosure.

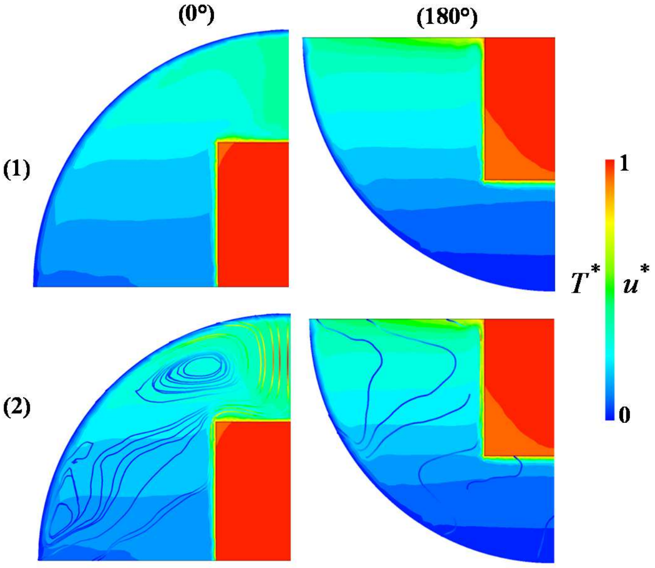

Figure 3. Dimensionless **(1)** T^* fields **(2)** T^* fields with iso velocity u^* in a vertical cross section of the hemisphere for $\varphi = 1\%$, $Ra = 1.04\mathrm{x}10^9$

When the dome is facing upwards $(\alpha = 0)$, the flow is axisymmetric. A convective cell is installed in the core of the cavity around the cube and the maximum temperature is reached at the center of the disk. The temperature of the latter is not uniform given the adopted thermal boundary condition. When the dome is facing downwards (α =180°), the fluid is stratified and the flow is limited to the immediate vicinity of the connection between the dome and the disk with a very reduced activity. In this case, the heat transfer is of the pure conductive type. The average global exchange between both cases is thus very different.

Evolution of $\overline{Nu}$ versus φ presented in Fig. 4 for two Ra values shows that $\overline{Nu}$ increases as φ and Ra increase for both treated positions. The influence of φ on $\overline{Nu}$ is moderated for low values of Ra when the dome is oriented upward $(\alpha = 0)$ but is sensitive throughout the Ra range when the dome is oriented downwards $(\alpha = 180°)$.

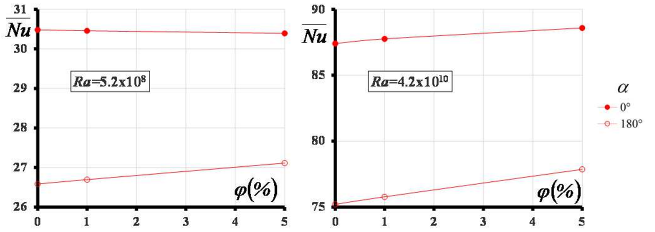

Figure 4. Evolution of $\overline{Nu}$ versus φ for two Ra values

Evolution of the average Nusselt Number $\overline{Nu}$ versus Ra in the logarithmic scale presented in Fig. 5 is linear.

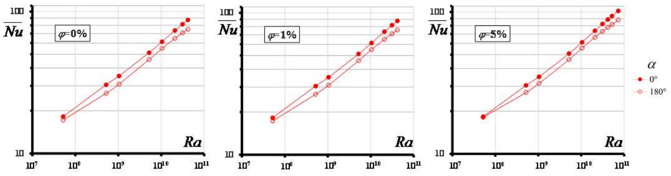

Figure 5. Evolution of $\overline{Nu}$ versus Ra

Taking into account the Prandtl number representing the nanofluid volume fraction, the relationship is clearly of the

$$\overline{Nu}(\alpha) = k.Ra^b\, Pr^m \qquad (6)$$

type. The analysis of the $\overline{Nu}$ results by means of the least square optimization method allows the determination of the coefficients (k,b,m). Their values are presented in Table 3, obtained with coefficients of determination higher than 0.998. These results highlight the relative influence of the volume fraction depending on the dome orientation. The average value of the factor Pr^m is close to 1 (1.04 and 0.90 for α =0 and 180° respectively).

Table 3. Values of (k,b,m) for the correlation $\overline{Nu}(\alpha) = k.Ra^b\, Pr^m$

α	k	b	m
0	0.40	0.223	0.023
180	0.43	0.212	-0.080

It clearly appears that the results presented are partial and cannot be interpolated or extrapolated for tilt angle and volume fraction values other than those considered here. Further calculations are needed to examine the influence of the three parameters (Ra, Pr, α) on the natural convective heat transfer with the considered Water-ZnO nanofluid in larger ranges. This work is in progress.

CONCLUSION

This work qualifies and quantifies the natural convective phenomena occurring in a hemispherical enclosure. An active cube centered on the disc of the enclosure generates a power leading to Rayleigh number ranging from 5.2x10^8 to 4.2x10^{10}. The disc remains horizontal while its isothermal dome is oriented either upwards or downwards. The enclosure is filled with a water-ZnO nanofluid, being its volume fraction of 0% (pure water), 1% and 5%. The 3D numerical solution is obtained by means of the volume control method based on the SIMPLE algorithm. Thermal and dynamic fields presented here are consistent with the results obtained for the convective heat transfer represented by the mean Nusselt number. The results confirm a conventional correlation of the Nusselt-Rayleigh-Prandtl type. The presented results are partial and only concern the considered configurations. The study is currently still continuing in order to extend the correlations to larger ranges of tilt angle, power generated by the cube (Rayleigh number) and volume fraction (Prandtl number). The results will allow to optimize the thermal design of these cavities for applications in electronic engineering.

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