

Measurement of flow velocity during turbulent natural convection in nanofluids



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HIGHLIGHTS

- As Ra increases, $\overline{|V|_{avg}}$ and $|V|_{max}$ for both water and nanofluid increase.
- $|V|_{max}$ for nanofluids is higher than for water in the field of view.
- $\overline{|V|_{avg}}$ for nanofluids is up to 6.1% higher than for water in the field of view.
- The addition of Al_2O_3 nanoparticles alters the mass transfer behavior of water.

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ABSTRACT

Increased cooling performance is eagerly required for many cutting edge engineering and industrial technologies. Nanofluids have attracted considerable interest due to their potential to enhance the thermal performance of conventional heat transfer fluids. However, heat transfer in nanofluids is a controversial research theme, since there is yet no conclusive answer to explain the underlying heat transfer mechanisms. This study investigates the physics behind the heat transfer behavior of Al_2O_3 - H_2O nanofluids under natural convection. A high spatial resolution flow velocimetry method – Particle Image Velocimetry – is employed in dilute nanofluids inside a Rayleigh-Benard configuration with appropriate optical access. The resulting mean velocity and flow structures of pure water and nanofluids are reported and their overall heat transfer performances are compared for Rayleigh numbers, Ra , of the order of 10^9 . This paper aims to identify the contribution of the suspended nanoparticles on the heat and mass transfer mechanisms in low flow velocity applications, as those occurring during natural convection. The outcome of this work is a first step towards the evaluation of the applicability of nanofluids in applications where more complex heat transfer modes, namely boiling and Critical Heat Flux, are involved that are of great importance for the cooling of Fusion reactors.

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1. Introduction

Natural convection is a ubiquitous heat transfer mode in nature but also in numerous engineering applications where both laminar and turbulent flows are established. Rayleigh-Benard (RB) convection is one of the most established models to study the associated heat and mass transport mechanisms, on the basis of the simplicity and controllability it offers. In the majority of these studies, traditional heat transfer fluids, such as air and water, are considered as working fluids. However, with the emergence of nanotechnology

and the development of a new category of coolants, called nanofluids, the interest in free and natural convection flow problems has been re-established [1,2].

Nanofluids are a new class of heat transfer fluids engineered by dispersing and stably suspending nanoparticles of the order of 1–100 nm in traditional heat transfer fluids (base fluids) [3]. A small amount of these nano-sized particles can provide a promising improvement in the thermal properties of the base fluid [4]. Based on a statistical analysis of data available in the literature, nanofluids offer an enhancement of 5–9% for the conductive heat transfer mode, 10–14% for the mixed conductive/convective, 40–44% for pool boiling and up to 200% for critical heat flux [5]. However, pure convection in nanofluids is considered to be a controversial heat transfer mode in terms of heat transfer performance. For instance,

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Nomenclature

q''	Applied heat flux [W/m ²]
g	Gravitational acceleration [m/s ²]
Gr	Grashof number [-]
h	Heat transfer coefficient [W/m ² K]
k	Thermal conductivity [W/mK]
L	Characteristic length [m]
Nu	Nusselt number [-]
Pr	Prandtl number [-]
Ra	Rayleigh number [-]
$Stdev$	Temporally and spatially averaged standard deviation of the turbulent velocity fluctuation [cm/s]
TI	Temporally and spatially averaged turbulent intensity [-]
V	Velocity [cm/s]

Greek characters

α	Thermal diffusivity [m ² /s]
Γ	Aspect ratio of the cell [-]
ΔT	Temperature gradient between the hot and cold plates [°C]
ν	Kinematic viscosity [m ² /s]

Subscripts

avg	Average
max	Maximum
nf	Nanofluid
w	Water
y	Y direction

while substantial enhancement of heat transfer is reported for forced convection [6,7], contradictory results are present between numerical and experimental studies for natural convection [8]. In the majority of the numerical works, heat transfer enhancement is reported, whereas in experimental investigations unexpected deterioration is observed.

Studies in natural convection have been conducted for low, moderate ($\sim 10^5$) and high Ra ($> 10^7$), over a broad range of operating conditions. However, turbulent natural convection has mostly attracted the scientific interest. In turbulent convection, two different states have been identified and reported, depending on the Ra of the flow and the aspect ratio, Γ , of the configuration involved. In cells with a ratio close to unity, a “soft turbulence” state has been observed for $Ra < 10^7$ and a “hard turbulence” for Ra between 4×10^7 to 10^{12} [9]. At the “hard turbulence” state, there exists a coherent circulation that spans the height of the cell [10]. This characteristic structure of the resulting flow, known as large scale circulation (LSC) or mean wind, is self-organised from the thermal plumes that arise due to the buoyant forces in the system; warm plumes accumulate on one side of the cell and cold plumes on the opposite side [11]. Therefore, the existence of plumes makes turbulent convection unsteady over a range of time and spatial scales [12]. The way that the LSC evolves inside a natural convection cell depends mostly on the geometry, aspect ratio of the cell and Ra of the flow. For instance, for cube-shaped cell geometries under turbulent natural convection, the LSC is expected to be confined mainly within the diagonal plane of the cell, where the longer path length exists [9,10,13]. Up to date, the study of the LSC remains an attractive research topic, as it is characterized by complex heat and mass transfer phenomena. For instance, due to the mean wind, the two horizontal boundary layers in the Rayleigh-Benard cell are coupled and thus, the thermal fluctuations and the temperature profile close to the thermal boundary layers are significantly affected. The

current research focuses on the study of the flow structures during natural convection and the potential influence of nanofluids.

2. Methodology

2.1. Experimental rig

The natural convection chamber comprises a cubic cell with a volumetric capacity of 1×10^{-3} m³ with optical access through the insulated side walls. As depicted in Fig. 1(a), the RB cell consists of many subcomponents through which the heat losses are minimized and the flow is accurately developed inside. A detailed description of the rig can be found in Ref. [14], whilst a brief overview of its main components is included herein. The key part of the convection cell includes a heating plate, **A**, at the bottom, a cooling plate, **B**, at the top and lateral walls, **C**, all made by anodized aluminium. The cell incorporates also four quartz windows, **D**, (2 square [40 mm $\times$ 40 mm] and 2 rectangular [10 mm $\times$ 40 mm]), to allow visualization studies. Among the conductive components **A**, **B** and **C**, Teflon plates, **E**, are placed, to prevent their thermal connection. Finally, around the cell there are insulating pans, **F**, and a Plexiglas cover, **G**, to eliminate the heat losses from the sides. Towards this direction, a second set of heating elements, **H**, is placed underneath the main heating plate, to prevent any heat losses downwards. Several thermocouples are placed inside and outside the chamber to monitor in real time the temperature in various locations and evaluate afterwards the heat transfer performance of the working fluid.

2.2. Field of view

For the flow velocimetry studies, the applicable field of view (mask), where the velocity measurements are performed and processed, has slightly smaller dimensions than the square windows of the natural convection cell. The dimensions are set in such a way, to ignore the collected data close to the edges of the window, where light reflections could affect the reliability of our results. The applied mask, depicted in Fig. 1(b), has dimensions of 39 mm $\times$ 39 mm and provides access to the flow field established in a square area located 25.5 mm above the cell's lower free surface, 35.5 mm below the cell's upper free surface and 30.5 mm away from the vertical lateral walls. As shown in the same figure, the Cartesian coordinates for the experiment are defined such as the origin coincides with the mask's lower left edge.

2.3. Particle image velocimetry (PIV)

PIV is employed to measure the instantaneous flow velocity distribution in transparent and semi-transparent fluids with high spatial resolution. The method relies on the use of a laser source to illuminate micron-sized tracer (seeding) particles dispersed in the flow twice with a fixed time interval, on planes defined by a thin laser sheet. In the present investigation, a double-pulsed Nd-Yag laser (Nano T 135-15 PIV) is involved, along with a charge coupled device camera (LaVision Imager Intense) to record the displacement of the seeding particles during the time delay between the two laser pulses. More specifically, a very small quantity (~ 0.00045 vol.%) of naturally buoyant (density of 1.1 gr/cm³) hollow glass spheres (HGS) with 10 μ m diameter, supplied by Dantec Dynamics, is used. Due to the small size of the employed tracer particles, no drift velocities are expected between the particles and the liquid flow for the timescales of the experiments. For the operating conditions in this study and the resulting orientation of the LSC, the reported PIV images are projections of the diagonal flow field, as seen by the window depicted in Fig. 1.

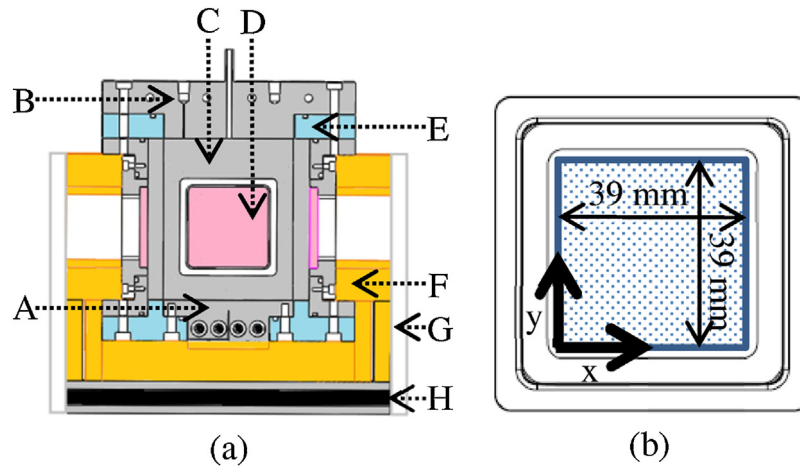


Fig. 1. Schematic drawing of the (a) natural convection chamber and (b) applicable field of view. The marked components are explained in the text.

This method has been already employed for dilute nanofluid inside a hypervapotron test channel [15]. The PIV technique employs measurements of scattered light from seeding particles in transparent media. The addition of nanoparticles and the subsequent Rayleigh scattering from them introduces optical noise on the images by obscuring the light scattered by the seeding particles (this is in the form of haze). In order for the PIV method to work reliably, a high signal to noise ratio for the intensity of the scattered light from seeding particles must be recorded. Thus, it is impossible to employ $\text{Al}_2\text{O}_3\text{-H}_2\text{O}$ nanofluids with much higher nanoparticle concentrations than the current ones for the optical studies. A feasibility study has been performed to define the limiting nanoparticle concentrations that can be employed so that the PIV method can be used reliably for the current study. The limiting concentration does not exceed the concentration used in this investigation.

Commercial software (DaVis 8.2.2) is used to perform the laser experiments and afterwards process the data. Each laser pulse pair is emitted at a rate of 1 Hz, with a time interval between the pulses ranging from 20–35 ms, depending on the flow velocity. For every operating scenario, 1000 independent pairs of images of the instantaneous flow are recorded – under steady state conditions – to reduce the statistical uncertainties of the reported data. Each 2D velocity vector is calculated from an interrogation window of 32×32 pixels with a 75% overlap. Finally, the temporally averaged velocity vector field is calculated with a high spatial resolution of 0.49 mm.

2.4. Experimental procedure

Three different temperature gradients, ΔT : 48, 55 and 63°C between the heating and the cooling plate were imposed, while the temperature at the cooling plate was maintained constant. Each of these temperature gradients corresponds to a certain Ra for the flow that varies between 2.2×10^9 and 4.0×10^9 . Dilute $\text{Al}_2\text{O}_3\text{-deionised (DI) H}_2\text{O}$ nanofluids with a mean concentration of 0.00026 vol.% were synthesized and tested for all three Ra . The employed nanoparticles were supplied by Alfa Aesar (44931), with an average particle size of 45 nm (quantified by TEM) and a particle density of 3965 kg/m^3 . All the results presented herein, were calculated under steady state conditions, reached about 3 hrs after the placement of the fluid in the cell [14].

3. Results and discussion

In this part, results of a thermal and visualization study under natural convection for water and a dilute nanofluid are presented. In such applications, the heat transfer correlations are of the form of $Nu = f(Pr, Gr)$. The product of the Gr and Pr numbers gives Ra that is commonly used in free convection applications. In our experiments, the system has two control parameters: Ra and Pr numbers and two response parameters: Nu and temporally averaged velocities, $|V|_{avg}$.

3.1. Thermal study

The experimental conditions and the heat transfer performance for both fluids are presented in Table 1. As expected, when Ra increases, Nu increases for both fluids. However, due to the selected boundary conditions (constant ΔT instead of constant q''), the associated experimental uncertainty and the small concentration of nanoparticles used in this study, there is no consistent trend concerning the alteration of the heat transfer performance of the base fluid. The observed $Ra\text{-}Nu$ dependency indicates a relationship of the type: $Nu = cRa^\gamma$ and more specifically, $Nu \sim Ra^{0.28}$, with a mean deviation of 1.1% for water, which is consistent with similar investigations in the literature [9,10,12,16].

Pr , Ra and Nu are given by,

$$Pr = \frac{\nu}{\alpha},$$

$$Ra = \frac{g\beta\Delta TL^3}{\nu\alpha},$$

$$Nu = \frac{hL}{k}$$

The heat transfer coefficient, h , is given by,

Table 1

Experimental conditions and heat transfer performance for water and nanofluid.

$Ra (\times 10^9)$	Test fluid	$\Delta T (^\circ\text{C})$	Pr	$q'' (\text{kW/m}^2)$	Nu
2.2	w	47.72	3.8	19.5109	63.3
	nf	47.86		18.7219	61.3
3.0	w	54.82	3.5	23.8625	67.7
	nf	54.74		24.3328	69.1
4.0	w	63.37	3.1	30.5906	74.3
	nf	63.50		30.0547	72.9

Table 2

Velocity characteristics for water and nanofluid.

$Ra (\times 10^9)$	Test fluid	$\overline{ V _{avg}}$ (cm/s)	$Stdev$ (cm/s)	$\delta \overline{ V _{avg}} $ (%)	TI (%)	$ V _{max}$ (cm/s)
2.2	w	0.2321	0.1868	3.1	80	0.6853
	nf	0.2393	0.1906		80	0.7289
3.0	w	0.2461	0.2034	5.5	83	0.6968
	nf	0.2596	0.2140		82	0.7777
4.0	w	0.3243	0.2469	6.1	76	0.9566
	nf	0.3440	0.2483		72	1.0123

$h = \frac{q''}{\Delta T}$. The thermophysical properties of water were obtained from Rohsenow et al. [17], while for nanofluids, empirical correlations and formulas were used as in Ref. [14]

3.2. Visualization study

For the operating conditions employed in this study, the RB cell operates under the “hard turbulence” state. For all three Ra , a single cellular structure with a preferential clockwise direction, upflow to the west and downflow to the east (cardinal points), is observed to develop along a diagonal of the RB cell. This is in agreement with similar studies, where it is reported that the LSC evolves in one of the diagonals [18] or it may undergo reorientations between them [19]. An explanation for the preferred direction of the LSC in a cylindrical cell with $\Gamma = 1$ is given by Brown and Ahlers, who attributed this to the effect of the earth's Coriolis force [20]. However, in a similar study that involved a cylindrical cell with $\Gamma = 0.5$, the orientation of the LSC was found to be rather randomized [21,22]. Other factors reported to influence the orientation of the LSC are construction imperfections of the rig, including the heating and cooling plates or a possible minor tilt of the cell relative to gravity. Yet, there is no conclusive answer for the orientation of the LSC plane, neither in cylindrical cells, in which there is rotational symmetry, nor in cubic ones, where the LSC is pinned to a diagonal set. In Fig. 2, the direction of the velocity vectors (their length is proportional to the pixel displacement) indicates the existence of the LSC along with the preferential direction, for water under $Ra = 2.2 \times 10^9$. In the same figure, the contours of the temporally averaged velocity in the y direction, V_{avg-y} , are depicted. It can be seen that the maximum values are at the upper left and lower right side of the cell, where warm plumes (red) rise along the left side of the cell and cold plumes (blue) fall along the opposite side.

In Table 2, the calculated temporally and spatially averaged velocity characteristics, $\overline{|V|_{avg}}$, $Stdev$, $\delta|\overline{|V|_{avg}}|$ and TI for water and dilute nanofluid for all three Ra are presented. It is noted that the spatially averaged velocity is calculated over the applicable field of view in Fig. 1(b). Firstly, it can be seen that the addition of nanoparticles into the base fluid alters the temporally averaged velocity field of the carrier fluid in the field of view. More specifically, the presence of nanoparticles increases the temporally and spatially averaged velocity, $\overline{|V|_{avg}}$, of the base fluid by up to 6.1%. Also, as Ra increases, the percentage of increase of the velocity, $\delta|\overline{|V|_{avg}}|$, further increases. Except for the notable increase of $\overline{|V|_{avg}}$, the temporally averaged maximum velocity, $|V|_{max}$ also increases in the field of view when nanoparticles are involved. Therefore, it can be concluded that for nanofluids the range (minimum to maximum value) of $|V|_{avg}$ in the field of view is broader than for water.

In Fig. 3, contours of $|V|_{avg}$ for water and nanofluid for $Ra = 4.0 \times 10^9$ are depicted. It can be seen that the area close to the heating surface, where the maximum velocities (>0.64 cm/s) are reported (as indicated with a black coloured rectangle that was added by the authors), is notably larger for the nanofluid than for water. Finally, concerning TI , there is an indication that it decreases

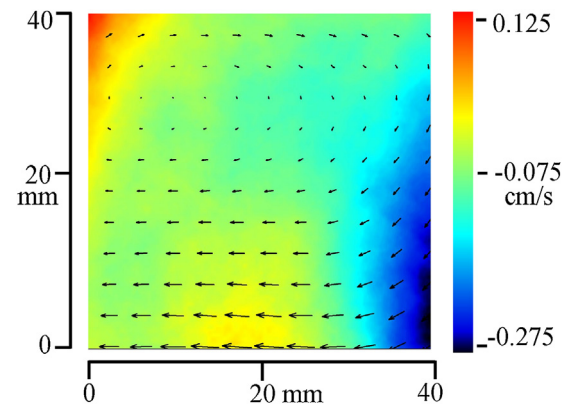


Fig. 2. Contours of the temporally averaged velocity in the y direction, V_{avg-y} and velocity vector arrows according to the magnitude of the temporally averaged velocity, $|V|_{avg}$, for water under $Ra = 2.2 \times 10^9$.

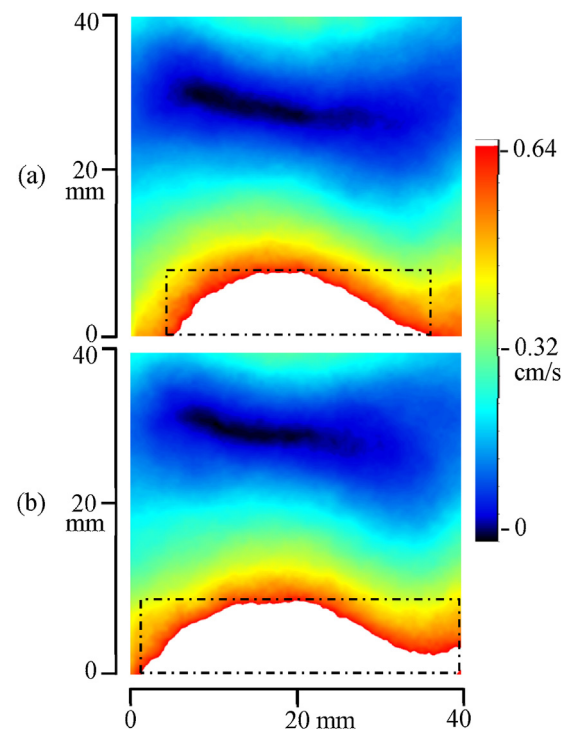


Fig. 3. Contours of the temporally averaged velocity, $|V|_{avg}$, for (a) water and (b) nanofluid under $Ra = 4.0 \times 10^9$. The rectangle indicates the increase of the area of high velocities close to the heating surface.

when nanoparticles are involved. However, no certain finding can be extracted due to the small nanoparticle concentrations and the employed operating and measuring conditions.

3.3. Repeatability test and error analysis

To ensure reliability of the reported results, a repeatability test was performed for water and nanofluid. From a set of three repeated experiments for $Ra = 2.2 \times 10^9$, the fractional uncertainty in the mean Nu was found to be less than 1.0% and in $\overline{|V|_{avg}}$, less than 0.8%, which is close to the uncertainty of the PIV measurements. More specifically, the maximum uncertainty in the measured velocity is 0.0007 cm/s, which corresponds to the minimum detectable pixel shift according to the employed camera and the selected calculation parameters. Therefore, the results presented herein are considered precise.

4. Conclusions

This study examines experimentally the heat and mass transfer characteristics of a dilute Al_2O_3 –DI H_2O nanofluid under turbulent natural convection. Heat transfer measurements simultaneously with a high spatial resolution velocimetry method (PIV) were obtained in a Rayleigh–Benard cell with optical access. Firstly, as Ra increases $\overline{|V|_{avg}}$ and $|V|_{max}$, consistently increase for both test fluids. Interesting enough, both velocities for nanofluids are higher than for water in the field of view. Therefore, we report that the addition of a small amount of Al_2O_3 nanoparticles, 0.00026 vol.% to DI water alters the mass transfer behavior of the base fluid significantly (more than 6% increase of $\overline{|V|_{avg}}$ in the field of view). Concerning the effect of the suspended nanoparticles on the heat transfer performance of the base fluid, there is no consistent trend. However, in a past experimental study of the authors [14] the thermal performance of Al_2O_3 –DI H_2O nanofluids with concentrations up to 0.12 vol.% is reported. In the literature, the majority of the relevant research considers constant q'' instead of constant ΔT between the hot and cold plates of the RB cell. In two highly cited articles [12,23] a comparison is performed between the results obtained under these two operating conditions. The outcome is that for $Ra \sim 10^9$ the heat transport in the two cases is essentially the same. This work is a step towards the understanding of the contribution of the nanoparticles on the heat and mass transfer mechanisms in low flow velocity applications, such as natural convection.

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