Measurement of flow velocity during natural convection in nanofluids

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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\textsubscript{2}O\textsubscript{3} – H\textsubscript{2}O 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 $10^5$. 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.

Keywords: Natural convection, Rayleigh-Benard, Nanofluids, Particle Image Velocimetry, Cooling, Fusion

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 natural convection flow problems has been re-established [1].

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) [2]. It has been widely reported that even a small amount of these nano-sized particles (< 1 vol.%) can provide a significant improvement in the thermal properties of the base fluid. 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 [3]. However, pure convection in nanofluids is considered to be a controversial heat transfer mode in terms of heat transfer performance. For instance, while substantial enhancement of heat transfer is reported for forced convection [4, 5], contradictory results are present between numerical and experimental studies for natural convection [6]. 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 (~ $10^5$) and high $Ra$ (> $10^5$), 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, $\Gamma$, 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 $4 \times 10^7$ to $10^{12}$ [7]. At the “hard turbulence” state, there exists a coherent circulation that spans the height of the cell [8]. 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 [9]. Therefore, the existence of plumes makes

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turbulent convection unsteady over a range of time and spatial scales [10]. 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 [7, 8, 11]. 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. As a consequence, 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 $1 \times 10^{-3}$ m$^3$ 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. [12], 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 [49.5 x 49.5 mm$^2$] and 2 rectangular [10 mm x 36 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 thermostouples 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 40 mm x 40 mm and provides access to the flow field established in a square area located 25 mm above the cell’s lower free surface, 35 mm below the cell’s upper free surface and 30 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.

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

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 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/cm$^3$) hollow glass spheres (HGS) with 10 μm diameter 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.

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 x 32 pixels with a 75% overlap. Finally, the temporal average velocity vector field is calculated with a high spatial resolution of 0.46 mm. This method has been already employed for dilute nanofluid [13] inside a hypervapotron (HV) test channel.

2.4 Experimental procedure

Three different temperature gradients, $\Delta T$ (48, 55 and 63 °C) between the heating and the cooling plate
3. Results and discussion

In this part, results of 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 \( \text{Nu} = f(\text{Pr}, \text{Gr}) \), where \( \text{Nu} \) is the Nusselt number, \( \text{Gr} \) is the Grashof number, \( \text{Pr} \) is the Prandtl number. The product of the \( \text{Gr} \) and \( \text{Pr} \) numbers gives \( \text{Ra} \) that is commonly used in free convection applications. In our experiments, the system has two control parameters: \( \text{Ra} \) and \( \text{Pr} \) numbers and two response parameters: \( \text{Nu} \) and averaged velocities, \( \left| V \right|_{\text{avg}} \). In Table 2, the measured speed characteristics for water and nanofluid for all three \( \text{Ra} \) are presented. Firstly, it can be seen that the addition of nanoparticles into the base fluid alters the temporally averaged velocity field of the carrier fluid. More specifically, the presence of nanoparticles increases the time-averaged mean velocity \( \left| V \right|_{\text{avg}} \) of the base fluid by up to 6.1 %. Also, as \( \text{Ra} \) increases, the percentage of increase of the average velocity, \( \delta \left| V \right|_{\text{avg}} \) further increases. Except for the notable increase of the mean velocity, the maximum velocity of the temporally averaged field, \( \left| V \right|_{\text{max}} \), is also increased when nanoparticles are involved. Therefore, it can be concluded that for nanofluids the range of the time averaged velocity in the field of view (minimum to maximum value), is broader than for water.

3.1 Thermal study

The experimental conditions and the heat transfer performance for both fluids are presented in Table 1. As expected, when \( \text{Ra} \) increases, \( \text{Nu} \) increases for both fluids. However, due to the selected boundary conditions (constant \( AT \) instead of constant heat flux, \( q'' \)), the associated experimental uncertainty and the very 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 \( \text{Ra} - \text{Nu} \) dependency indicates a relationship of the type: \( \text{Nu} = c \text{Ra}^{\gamma} \) and more specifically, \( \text{Nu} \sim \text{Ra}^{0.28} \), with a mean deviation of 1.1 % for water, which is consistent with similar investigations in the literature [7, 8, 10, 14].

Table 1. Experimental conditions and heat transfer performance for water (w) and dilute nanofluid (nf).

<table>
<thead>
<tr>
<th>( \text{Ra} ) (x10^9)</th>
<th>Test</th>
<th>( \Delta T )</th>
<th>( \text{Pr} )</th>
<th>( q'' )</th>
<th>( \text{Nu} )</th>
</tr>
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<tr>
<td>2.2</td>
<td>w</td>
<td>47.72</td>
<td>3.8</td>
<td>19.5109</td>
<td>63.3</td>
</tr>
<tr>
<td></td>
<td>nf</td>
<td>47.86</td>
<td>18.7219</td>
<td>61.3</td>
<td></td>
</tr>
<tr>
<td>3.0</td>
<td>w</td>
<td>54.82</td>
<td>3.5</td>
<td>23.8625</td>
<td>67.7</td>
</tr>
<tr>
<td></td>
<td>nf</td>
<td>54.74</td>
<td>24.3328</td>
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<tr>
<td>4.0</td>
<td>w</td>
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<td></td>
<td>nf</td>
<td>63.50</td>
<td>30.0547</td>
<td>72.9</td>
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</tr>
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</table>

3.2 Visualization study

For the operating conditions employed in this study, the RB cell operates under the “hard turbulence” state. For all three \( \text{Ra} \), a single cellular structure with a preferential clockwise direction is observed to develop inside the RB cell. In Fig. 2, the direction of the velocity vectors (their length represents the velocity magnitude) indicates the existence of the LSC along with the preferential direction. In the same figure, the contours of the temporal averaged velocity in the y direction, \( \left| V \right|_{\text{avg,y}} \), 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, for water under \( \text{Ra} = 2.2 \times 10^9 \).

![Fig. 2. Contours of the temporal averaged velocity in the y direction, \( \left| V \right|_{\text{avg,y}} \), and velocity vector arrows according to the magnitude of the time-averaged velocity, \( \left| V \right|_{\text{avg}} \), for water under \( \text{Ra} = 2.2 \times 10^9 \).](image)
increases, the turbulent intensity, $T$, of the flow exhibits an increasing trend. However, this tentative finding cannot be verified due to the small nanoparticle concentrations and small range of $Ra$ used in this investigation.

![Fig. 3. Contours of the time-averaged velocity, $|V|_{avg}$, for (a) water and (b) nanofluid under $Ra = 4.0 \times 10^5$. The rectangle indicates the increase of the area of high velocities close to the heating surface.](image)

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 $Ra = 2.2 \times 10^7$, the fractional uncertainty in the mean $Nu$ was found to be less than 1.0% and in the mean temporal averaged velocity, $|V|_{avg}$, less than 0.8%, which is close to the uncertainty of the PIV measurements. 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. An important finding of this investigation is that the addition of a small amount of $Al_2O_3$ nanoparticles (~ 0.00026 vol.%) to pure DI water alters the heat and mass transfer behavior of the base fluid significantly (more than 6% increase of the time-averaged velocity in the mask). Even more, as $Ra$ increases the mean and maximum time-averaged velocities in the field of view, $|V|_{avg}$, and $|V|_{max}$ respectively are consistently increase. 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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References