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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.

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} 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. [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 × 40 mm] and 2 rectangular [10 mm × 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 × 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 ($\sim$0.00045 vol.%) of naturally buoyant (density of 1.1 gr/cm^3) hollow glass spheres (HGS) with 10 μm 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.

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