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Study of buoyancy driven heat transport in silicone oils and in liquid nitrogen in view of cooling applications

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ABSTRACT

Motivated by applications for cooling superconducting pellets with liquid nitrogen, we consider a source with a fixed heating rate per unit volume, immersed in a liquid pool and cooled through natural convection. In one recent experimental investigation (Dubois et al., 2016) carried on silicone oils and liquid nitrogen, we have demonstrated that the velocity field satisfies specific scaling laws with respect to the temperature increase in the liquid pool. In this work, we pursue the analysis by modeling the heat transfer in a parallelepiped enclosure for a steady laminar flow regime. The Navier-Stokes equations are solved using a finite volume approach to obtain the detailed three-dimensional flow and heat-transfer characteristics. A quantitative analysis of the velocity field over the temperature field shows that the experimental power laws are reproduced in simulations. Following Dubois and Berge (1978), a theoretical law originally introduced in the context of the classical Rayleigh-Bénard experiment is shown to be satisfied in the simulations over a wide range of Rayleigh numbers (Ra), assuming the definition of the characteristic convection length is adapted to the investigated geometry. Moreover, the simulations are shown to correctly reproduce the main features of the flow, including the characteristic convection length, for different heater lengths.

1. Introduction

High-temperature superconducting materials in the form of single grains of a few cm^3 are capable of trapping magnetic flux densities exceeding those of conventional permanent magnets. Magnetic flux densities in excess of 17 T were trapped in bulk superconductors at temperatures below 30 K [1,2], and densities up to 3 T were trapped at 77 K [3]. Bulk superconductors are thus very promising materials to be used in electrical systems such as motors, generators, magnetic bearings, and magnetic resonance devices [1,2].

The design of superconducting applications must include a cryogenic unit. First, the material must be maintained below its critical temperature, T_c, above which it becomes a normal material (typically, $T_c \sim 90$ K for YBCO, so that liquid nitrogen is a genuine cryofluid). Second, under time-varying fields, the material may undergo losses and self-heating, resulting in a reduction of the trapped magnetic flux [4]. To avoid a performance loss, the cryogenic system must then rapidly extract the generated heat and transfer it away from the superconducting material. As a result, it is of great interest to understand the flow and the heat transfer in cooling fluids in the presence of a volumic source with a fixed heat generation rate. Such a situation is also of interest in many practical and industrial applications implying a local heater immersed in a fluid.

As evidenced in our earlier investigation [5], in such a situation, one can expect the buoyancy to be the driving force of the convective flow in the considered device. An extensive bibliography on natural convection in cavities up to 1988 may be found in the review article by Ostrach [6]. The majority of the published studies can be classified into two groups: enclosures heated from below and cooled from above (Rayleigh–Bénard problem) and differentially heated enclosures. More recent literature on this topic show a large interest in the studies of convective phenomena in cavities heated from below and cooled with various boundary conditions [7–9]. Towards the effect of fluid properties on the process of heat transfer, Emery and Lee [10] studied the fluid property variations in a square cavity with different boundary conditions on the sidewalls. A comparison was made against constant property and it was observed that the overall heat transfer is unaffected by the variation of the fluid properties, although the flow and temperature fields in the cavity seem to be different. Chu and Hickox [11] studied localized heating in a horizontal enclosure of square platform. In their work, which was complemented by experiments,

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Nomenclature

Bi	Biot number (hL_c/k)
C_p	specific heat (J/kg-K)
g	acceleration due to gravity (m/s^2)
H	domain height
K	temperature in Kelvin
k	heater thermal conductivity (W/m-K)
K_f	fluid thermal conductivity (W/m-K)
L	liquid pool height above the heater (m)
L_c	heater Characteristics length
L_g	heater lengths
T_0	temperature of coolant at rest (K)
T_h	temperature of the heater surface
ΔT	$T_h - T_0$(K)
q''	heat generation ($Q/\rho C_p$)
Q	volumetric heat source (W/m^3)
Pr	Prandtl number
Ra	Rayleigh number
Ra_c	Critical Rayleigh number

Greek symbol

α	thermal diffusivity (m^2/s)
β	coefficient of thermal expansion (1/K)
μ	dynamic viscosity (kg/m-s)
v	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
τ_{wall}	wall shear stress (kg/ms^2)

a constant-temperature heated strip of fixed width was placed on the bottom wall of the enclosure. The effect of horizontal heated strips at the bottom wall of an industrial glass melting tank in two and three-dimensions was studied numerically by Sarris et al. [12]. To improve internal natural convection heat transfer, Ngo and Byon [13] studied the effects of heater location and heater size in a 2D square cavity using a finite element approach. Numerical results indicated that the average Nusselt number increases as the heater size decreases.

Closer to the situation considered in this work, numerous studies focused on the convection induced by a local heater attached on one of the liquid pool walls [14,15]. Considerable attention has been given to classical Rayleigh-Bénard convection from vertical/horizontal enclosures specified either with constant temperature or heat flux [16]. However, a very limited number of studies [17] considered convective heat transfer from a local source, which is specified with a constant volumic heat generation rate and is located away from the liquid pool walls. This situation is different from the classical Rayleigh-Bénard problem where periodic convective cells appear.

This work is focused on the buoyancy driven heat transfer in cooling fluids, in the case of an immersed volumic source with a fixed heat generation rate.

Obtaining accurate measurements, for instance by means of particle imaging velocimetry, may be difficult and is particularly challenging for liquid nitrogen. A well-controlled and uniform temperature must be obtained in the cryostat, as small local temperature variations (0.1–1 K) may cause parasitic boiling or evaporation. This condition is particularly difficult to achieve for cryostats where windows using different materials are required to observe the flow. The cryostat enclosure also limits the field of view and thus the size of the region which may be investigated (in commercial cryostats this field of view is typically of a few cm^2).

In this context, we make the choice to focus on a numerical analysis. It comes as a very useful complementary approach, with ideal environmental parameters, where the 3D distribution of both velocity and temperature can be determined over the entire system (which is difficult to achieve experimentally even with a non-cryogenic fluid). Through an analysis of the flow as a function of the physical properties of the liquid and the geometry of the system, numerical simulations also help to understand the underlying physical mechanisms and identify their relevant parameters.

Prior to the present work, we have recently studied numerically the convective flow induced by a heater immersed in a 10 cst silicone oil [18]. It was shown that the characteristics of the flow depend on the length of the heater and that longer heaters lead to lower average Nusselt numbers thereby extending the predictions of [13] to the geometry of an immersed heater.

In parallel, we have studied experimentally the laminar convection flow induced in a similar system with silicone oils and liquid nitrogen, for Rayleigh numbers (*Ra*) ranging from 10^4 to 10^7 [5]. A flow pattern with two counter-rotating cells, reminiscent of the classical Rayleigh-Bénard cells, was observed. The maximal vertical velocity between the two cells, v_z, was studied as a function of the temperature difference between the heater and the liquid pool, ΔT, and was found to nearly follow a square root law, as $v_z \sim \Delta T^m$ with $m \sim 0.5$. Moreover, after having adapted the definition of the characteristic wavelength to the studied geometry, the maximum vertical velocity was shown to follow the theoretical law of Normand et al. [19] for silicone oils. Normand's law was originally derived for a system of convection rolls in a container with horizontal dimensions much larger than its height, and for a regime near the onset of the convection instability. In fact, it was found that the law faithfully reproduced the experimental data over a fairly large range of Rayleigh numbers, including regimes far from the instability threshold. Both these findings and the new definition of the characteristic wavelength shed light on the mechanisms underlying the convective flows which are relevant for engineering cooling applications.

The purpose of this paper is to further analyze the characteristics of the convective flow away from the convection threshold, by means of a 3D numerical model and as a function of the fluid properties and the heater geometry. More specifically, we are seeking to determine whether the velocity-temperature correlations observed in [5] are satisfied in the simulations. Simulation results for different heater lengths are also compared to new data acquired with the same experimental setup.

The paper is organized as follows: The experimental and the modelling methodologies are discussed in Section 2. Fluid flow characteristics inside the domain are presented in Section 3. The discussion is reinforced through an analysis on different coolants (liquid nitrogen, silicon oils) and a comparison with the experimental data. More specifically, the relevance of defining a new characteristic wavelength for analyzing the maximum velocity as a function of the Rayleigh number is confirmed. The convection flow is also investigated for different heater lengths both experimentally and numerically, and it is shown that the predicted characteristic wavelength is consistent with the measured one. Finally, a summary and conclusions are presented in Section 4.

2. Experimental procedure and solution methodology

2.1. Investigated fluids

In both the experimental and numerical investigations, several cooling fluids are considered in order to cover a wide range of