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Investigation of convective heat transfer phenomena in differentially-heated vertical closed cavity: Whole field experiments and numerical simulations

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ABSTRACT

Natural convection in closed cavities has been a subject of intensive research in the past. Compared to numerical studies, the number of experimental works reported in this area have been relatively scarce. Of the limited number of experimental studies available in the literature, a majority have made use of invasive probes, which inherently disturb the flow. In the present work, real-time experimental measurements are carried out using one of the non-invasive techniques (Mach Zehnder interferometry), that provides the whole field temperature distribution of the fluid layer. Experiments are conducted in a differentially-heated vertical closed cavity of aspect ratio three with air as the working fluid. The vertical side walls of the cavity have been subjected to three temperature differences ($\Delta T = 10$, 20 and 30 °C) ($Ra = 9.7 \times 10^5$, 1.8×10^6 and 2.5×10^6). Transient numerical simulations have also been performed using COMSOL Multiphysics 5.2 and a detailed comparison of experimental and simulation results has been presented in the form of temperature contours, spatial distribution of Nusselt number and spatially-averaged heat transfer rates as a function of Rayleigh number. The interferometric measurements highlighted the importance of corner flows which affect the heat transfer rates between the two thermally active walls of the cavity. Buoyancy-induced flow patterns inside the cavity, as interpreted through interferometric measurements, have further been corroborated through smoke-based visualization technique as well as through the results of numerical simulations. Maximum heat transfer rates have been observed in the corners of the differentially heated cavity. Possible flow transitions have been captured by performing the spectral analysis of the interferometry-based transient data. Based on this analysis, $Ra = 1.8 \times 10^6$ was found to be greater than the critical Rayleigh number wherein the flow instabilities with two dominant frequencies were to be clearly seen.

1. Introduction

Buoyancy driven flows have been of great interest since the last several decades. Flow inside an enclosure has its own complexity due to the inherent interplay of buoyancy and viscous forces. Moreover, natural convection plays an important role for different applications in several areas. Hence, a large number of numerical and experimental studies have been reported in the literature to understand these flows. Natural convection is a buoyancy-driven flow, which arises due to density gradient, consists of boundary layer formation on the thermally active walls of the cavity. The overall work of fluid is to transport heat from hot wall to cold wall, the strength of the fluid movement is characterized by the Rayleigh number and Prandtl number of the fluid. This is a model problem for many industrial applications e.g. energy-efficient design of buildings and rooms, material manufacturing systems, solar collectors, cooling devices for electronic instruments, double glazed windows. In addition, there are applications in various other fields like chemical, mechanical, aeronautical, crystal growing industries and, cryogenic industries, cooling problems, etc. [1–7,32,33].

The available literature shows that the buoyancy-driven flow in differentially heated cavities has been studied (numerically and experimentally) for different shapes and sizes as well as different angles of inclination of the cavity for different working fluids. Natural convection in differentially heated cavity mainly has two types of boundary conditions. First, when both the vertical walls have different temperatures and horizontal walls are adiabatic, and second, when both vertical walls are adiabatic and horizontal walls are at different temperature (Rayleigh-Bernard convection with lower wall hot and upper wall cold). Davis [1] solved the problem numerically for a square cavity at different Rayleigh numbers ranging from 10^3 to 10^6, which is nowadays

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Nomenclature

Cp	specific heat capacity, J/kg K
g	acceleration due to gravity, m/s^2
h	heat transfer coefficient, $W/m^2/K$
k	thermal conductivity of fluid, W/mK
L, H, D	dimensions of the cavity, m
Nu	Nusselt number, hL/k
P_0	pressure, Pa
P	dimensionless pressure
Pr	Prandtl number, ν/α
q''	heat flux, $h\Delta T$, W/m^2
Ra	Rayleigh number, $g\beta\Delta TL^3/\nu\alpha$
t	time, s
ΔT	temperature difference, $T-T_c$
U, V, W	dimensionless fluid velocities, uL/α, vL/α, wL/α
X, Y, Z	dimensionless Cartesian coordinates, x/L, y/L, z/L
x, y, z	cartesian coordinate

Greek symbols

α	thermal diffusivity, m^2/s
β	volumetric coefficient of thermal expansion, 1/K
ν	kinematic viscosity, m^2/s
ρ	fluid density, kg/m^3
θ	dimensionless temperature, $(T-T_c)/(T_h-T_c)$
τ	dimensionless time, $\alpha t/L^2$

Subscripts

c	cold
h	hot

used as a benchmark solution. Further numerical studies of natural convection in closed square cavities have been performed for different conditions [2–5]. A numerical investigation has been performed by Paolucci and Chenoweth to understand the transition of flow from laminar to turbulent for a fluid having $Pr = 0.71$ in two dimensional closed differentially heated square cavity [6]. Critical Rayleigh number for the cavity considered in the simulations was identified as $Ra = 2 \times 10^8$. In their study, phenomena such as oscillatory instabilities, quasi-periodic flow, and turbulent flow were investigated. The authors discussed the flow instabilities in such systems which come in the flow when there is a transition from laminar to turbulent. Henkes and Hoogendoorn performed simulations to understand the stability of natural convection flow in a square cavity which was differentially heated [7]. The simulations were carried out for air and water as the working fluids with the horizontal wall being either conducting or adiabatic. It was concluded that, as the flow transition takes place from steady state to periodic with increasing Rayleigh number, air shows an exception. Air shows two frequencies instead of expected single frequency. Water flow was found more stable than air because of its high Prandtl number. In this study, the critical Rayleigh numbers for water and air were identified as 4×10^9 and 2×10^8 respectively. Further, the two-dimensional differentially heated closed cavity was numerically studied to analyze that at a particular Rayleigh number, boundary layer shows oscillatory behavior [8–10] and it was found that buoyancy layer is transverse in nature. Moreover, these layers are found to be most unstable. Later, Patterson and Imberger [11] found that horizontal intrusion at the far end causes internal wave activity. The authors investigated it for $Pr \geq 1$ and aspect ratio ≤ 1.

Ivey [12] performed an experimental study for high Rayleigh numbers (10^9) where the flow was found to be periodic and it was concluded that due to the inertia of the flow, the fluid which is entering in the core of the cavity from the vertical boundary layers, forms internal hydraulic jump in the cavity. The first bifurcation from a steady solution to an unsteady solution was first presented by Briggs and Jones [13,14]. Development of small disturbance in cubical cavity causes the flow to become unstable [15,16] and frequency of periodic flow in the differentially heated cubical cavity was calculated [17,18]. The transition of convective flow from its steady state to periodic motion and finally to the chaotic motion has also been discussed [19–22].

Experimental studies have also been reported in the differentially heated cavities. Srivastava et al. [23] used three different non-intrusive optical techniques, namely interferometry, schlieren and shadowgraph, to investigate Rayleigh-Bernard convection in a rectangular cavity. Water and air were taken as working fluids and results of all three techniques were compared. The comparative study showed that at low Rayleigh numbers, all the three techniques correlate well with each other. However, for applications involving strong temperature gradients (high Rayleigh numbers), the accuracy of interferometric measurements gets adversely affected by the presence of large number of closely-spaced fringes. Such high fringe density makes it difficult to clearly resolve the fringe patterns, which in turn leads to possible errors in the quantitative data. The authors reported that for such applications, schlieren and shadowgraph yielded better image quality. Saury et al. [24] conducted experiments on differentially heated cavity at large Rayleigh number (order of 10^{11}). The author analyzed the flow inside the cavity and temperature measurement was carried out and the effects of temperature difference and wall emissivity on vertical temperature gradients were discussed. Wright et al. [25] studied natural convection in a large vertical cavity using smoke pattern and interferometry. It was observed that for a given aspect ratio if Rayleigh number is greater than 10^4, the flow becomes unsteady and 3D flow of fluid starts in the cavity. The study of Rayleigh-Bernard convection by Gollub and Benson [26] also showed such types of instabilities. An experimental study was carried out for natural convection heat transfer in cavities of different aspect ratios by Arnold et al. [27]. The effect of angle of inclination on heat transfer was investigated as a function of cavity aspect ratio. Saury et al. [28] performed an experimental study in a cavity of aspect ratio four for different angles of inclination in the transition. The work proposed a unique modified critical Rayleigh number ($Ra = 8.5 \times 10^7$) using modified characteristics length for all angles of inclination. Temperature measurements were taken using probes in selected areas where the temperatures become unsteady first.

As discussed above, in literature, a large number of numerical investigations have been reported in the context of the differentially heated vertical closed cavity. However, experimental studies in such cavities are rather limited. Literature also shows that intrusive techniques have primarily been employed for experiments where the temperature is measured at a limited number of points using externally inserted physical probes e.g. thermocouples [28]. The non-invasive techniques have predominantly been used for flow visualization experiments and there is a complete lack of studies that are concerned with a quantitative aspect of heat transfer using these techniques [24,25]. Such studies, which are quite limited in number, primarily exist for the configuration of Rayleigh-Bernard convection where whole field temperature distributions are presented accompanied by heat transfer analysis [23,29–31]. Considering the scarcity of whole field experimental data pertaining to temperature distributions and local variations of heat transfer rates in configurations different from Rayleigh-Bernard convection, the need for developing a detailed understanding of the buoyancy-induced flow phenomena and their implications on the heat transfer rates in set-ups different from Rayleigh bernard configuration becomes important.

With this background, the present manuscript reports the non-invasive, real-time experimental investigations of natural convection in a