Turbulent convective flows in a cubic cavity at high Prandtl number

A Vasiliev, A Sukhanovskii, P Frick
Institute of Continuous Media Mechanics - Academ. Korolyov, 1, Perm, 614013, Russia
E-mail: vasiliev.a@icmm.ru

Abstract. Characteristics of turbulent convective flows in a cubic cell is studied experimentally for high values of Prandtl number. The first set was carried out with propylene glycol (Pr = 64) and the second one with 25% water solution of propylene glycol (Pr = 24). It was found that increasing of Pr from 6.1 to 24 leads only to the slight change of intensity of the flow but during the next increasing of Pr from 24 to 64 the flow changes its structure.

1. Introduction
Turbulent free convection in closed cavities is a basic object for modeling convective processes in engineering applications but even in case of a simple geometry it is a complex problem. Convection in a cubic cavity with vertical temperature difference is characterized by number of regimes and was studied extensively for moderate values of Rayleigh number $Ra < 10^8$ [1]. Specific of convective flows under vertical temperature difference is their three-dimensional structure even at small supercriticalities. Experimental studies (these results were reviewed in [2]) showed that the case of strictly vertical temperature difference is characterized by a variety of large-scale flows.

Among the problems of large-scale dynamics of Rayleigh-Bénard convection we point out the studies of inversions of large-scale circulation in cavities of different geometry (mostly in cylinders) [3, 4, 5, 6, 7, 8]. Spontaneous inversions of large-scale circulation (LSC) for rectangular cavity with $\Gamma = 0.25$ were found in [9]. Regimes of LSC in rectangular tank of different aspect ratio was studied experimentally in [10], where it was shown that the LSC strongly depends on the small variation of the cavity thickness. Three-dimensional convective flows in a cubical cavity were experimentally and numerically studied in [11, 12], where the variety of dynamical regimes was observed.

This study is focused on the influence of physical properties of a fluid on the structure and characteristics of turbulent flows. Earlier, the influence of kinematic viscosity on turbulent characteristics was studied in [12]. Experiments were carried out for water at $T_0 = 25 \, ^\circ\text{C}$ and 50 $^\circ\text{C}$ and values of Prandtl number $Pr = 6.1$ and $Pr = 3.5$ respectively. Experimental results of [12] did not reveal strong dependence of the structure and characteristics of convective flows on Prandtl number. Here we present new experiments where we considered fluids at fixed values Rayleigh number but for substantially higher values of Prandtl number (64 and 24).
2. Experimental setup

Experimental studies of turbulent convection were carried out in a cubic cell with the side length $L = 250$ mm (Fig. 1,a). Vertical sides had been made of plexiglas of 25 mm thickness. The top and bottom walls were used as heat exchangers. The temperature in copper heat exchangers was kept constant by recirculation of fluid from a thermostatic bath and controlled by embedded thermocouples with accuracy $0.1 \, ^\circ\mathrm{C}$. Propylene glycol and its 25% water solution were used as working fluids.

In order to reduce the heat losses the side walls were heat-insulated by cellular polystyrene plates of 40 mm thickness, with a plexiglas window for PIV measurements.

Governing parameters are Prandtl and Rayleigh numbers

$$Pr = \frac{\nu}{\chi}, \quad Ra = \frac{g\beta L^3 \Delta T}{\nu \chi},$$

where $g$ is the gravitational acceleration, $\beta$ is the coefficient of thermal expansion, $\nu$ is the kinematic viscosity, $\chi$ is thermal diffusivity, and $\Delta T$ is the temperature difference between the hot and cold plates. Measurements of instantaneous velocity fields were carried out in the middle vertical cross-section (Fig. 1,b) by PIV technique using PIV system POLIS. Time shift between two consecutive PIV images were varied from 40 to 100 ms in order to get optimal tracers displacement for different values of Rayleigh number. Interrogation window was 32x32 pixels with 50% overlap. Spatial resolution for most of experiments was about 3 mm. The relative error of the velocity measurements was accurate to within 5%.

Temperature measurements were done by copper-constantan thermocouple array, located in the middle horizontal cross-section. Thermocouple module (NI 9213) was used to measure the voltage of the thermocouple at a sampling rate of 10 Hz.

Table 1 shows the characteristics of experiments that were realized.

3. Results

One of the main parameters which describes the structure and characteristics of convective flows is Prandtl number. At high Prandtl numbers heat transfer is provided by convection...
Table 1. Characteristics of experiments

| Experiment | $\Delta T$, °C | Pr | Ra          |
|------------|---------------|----|-------------|
| I          | 5             | 64 | $9.4 \cdot 10^8$ |
| II         | 8.6           | 64 | $1.6 \cdot 10^9$ |
| III        | 25            | 64 | $4.7 \cdot 10^9$ |
| IV         | 5             | 24 | $1.3 \cdot 10^9$ |
| V          | 10            | 24 | $2.7 \cdot 10^9$ |
| VI         | 25            | 24 | $5.2 \cdot 10^9$ |

Figure 2. Time-averaged velocity fields in central vertical cross-section, experiments I-III (from left to right).

when at low Prandtl numbers thermal conductivity is more efficient (for liquid metals). Earlier convection in a cubic cell for two values of Prandtl was studied in [12]. As a next step it is very interesting to study what would happen with a flow structure if we replace water with a fluid with substantially higher value of Prandtl number. Using propylene glycol (experiments I–III) and its 25% water solution (experiments IV–VI) as working fluids allowed us to carry out experiments for Rayleigh numbers comparable to the ones in [12] but for high Prandtl numbers (64 and 24). Time-averaged velocity fields in central vertical cross-section obtained for propylene glycol are shown in Fig. 2.

First remarkable difference from experiments with water is the large-scale flow structure. All experiments in [12] had large-scale circulation (LSC) oriented along one of the diagonals. Fig. 2 shows that for experiment I there is no LSC which occupies the whole cell. We can assume that for this experiment the upward convective flow is mainly located in the center and downward flows are near the side walls. Increasing of Rayleigh number leads to the change of the flow structure and in experiment III we can see LSC which occupies the whole cell. The structure of LSC in a central vertical cross-section is asymmetric.

The distribution of turbulent pulsations (Fig. 3) is also very different in comparison with water experiments ([12]). In water experiments the maximums of turbulent pulsations are located near corners of the cell. In experiments with propylene glycol the turbulent pulsations are located mostly in the central part of the cell with dominance of pulsations of vertical velocity. It means that turbulent flow of substantially more viscous fluid are strongly anisotropic. Even when LSC is formed (experiment III) the level of turbulent pulsations in a center of the cell is still high. We assume that thermal plumes is the source of these intensive turbulent pulsations.

For description of the temporal evolution of the large-scale circulation we decompose the
vertical component of the velocity into Fourier series

\[ v_z(t, x, z) = \sum_n \sum_m B_{nm}(t) \cos\left(\frac{\pi nx}{L}\right) \sin\left(\frac{\pi mz}{L}\right) \]

and we analyze the time variations of the amplitudes of lowest modes, assuming that the intensity of LSC is characterized by \( B_{11}(t) \). Time variation of \( B_{11}(t) \) is shown in Fig. 4. It is clear that LSC exist only in experiment III at relatively high Rayleigh number but time variation of LSC is non-periodic without reversals (change of LSC direction).

Second series of experiments (IV-VI) was carried out with 25% water solution of propylene glycol (Pr=24). The goal was to consider the case when Pr is still high in comparison with water but substantially less than for pure propylene glycol (Pr=64). The general structure of mean
velocity fields (Fig. 5) are similar to the ones in water experiments [12]. Increasing of Pr from 6.1 to 24 leads only to the slight change of intensity of the flow but during the next increasing of Pr from 24 to 64 the flow changes its structure.

4. Results
The main goal of this study was revealing the influence of the variation of Prandtl number on characteristics of turbulent convective flows in a cubic cell. The first set of experiments was carried out with propylene glycol (Pr = 64) and the second one with 25% water solution of propylene glycol (Pr = 24). It was found that increasing of Pr from 6.1 to 24 leads only to the slight change of intensity of the flow but during the next increasing of Pr from 24 to 64 the flow strongly changes its structure. This result deserves special attention because it proves that variation of Prandtl number for fluids with relatively high values of Pr leads to the remarkable evolution of the flow. It can be important for description of thermal convection in different technological processes with highly viscous fluids.

The financial support of grant RFBR No.16-41-590406 is gratefully acknowledged.

References
[1] Valencia L, Pallares J, Cuesta I and Grau F X 2007 International journal of heat and mass transfer 50 3203–3215
[2] Zimin V D and Frick P G 1988 Turbulent Convection (Nauka)
[3] Funfschilling D and Ahlers G 2004 Physical Review Letters 92 194502
[4] Xi H D and Xia K Q 2007 Physical Review E 75 066307+
[5] Xi H D and Xia K Q 2008 Physical Review E 78 036326+
[6] Funfschilling D, Brown E and Ahlers G 2008 Journal of Fluid Mechanics 607 119–139
[7] Brown E and Ahlers G 2009 Journal of Fluid Mechanics 638 383+
[8] Xi H D, Zhou S Q, Zhou Q, Chan T S and Xia K Q 2009 Physical Review Letters 102 044503+
[9] Sugiyama K, Ni R, Stevens R J A M, Chan T S, Zhou S Q, Xi H D, Sun C, Grossmann S, Xia K Q and Lohse D 2010 Physical Review Letters 105 034503+
[10] Vasiliev A Y and Frick P G 2011 JETP Letters 93 330–334 ISSN 0021-3640
[11] Bolshukhin M A, Vasiliev A Y, Budnikov A V, Patrushev D N, Romanov R I, Sveshnikov D N, Sukhanovsky A N and Frick P G 2012 Computational continuum mechanics 5 469–480
[12] Vasiliev A, Sukhanovskii A, Frick P, Budnikov A, Fomichev V, Bolshukhin M and Romanov R 2016 International Journal of Heat and Mass Transfer 102 201 – 212 ISSN 0017-9310