TORSIONAL OSCILLATION OF THE LARGE-SCALE CIRCULATION IN TURBULENT THERMAL CONVECTION WITH VARYING PRANTDL NUMBER

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Summary We report measurements of the torsional oscillation of large-scale circulation (LSC) in turbulent thermal convection using the multi-thermal probe techniques. The experiment was carried out in a cylindrical convection cell with aspect ratio unity and the Rayleigh number Ra varies from 1.1×10^9 to 2.9×10^{11} and Prantdl number Pr varies from 5.3 to 19.4. The torsional oscillation was detected from the measured time trace of the phase evolution of the LSC. The Reynolds number Re scaling based on this oscillation frequency is $Re = 0.0236Ra^{0.48\pm0.02}$ which agrees very well with the prediction of Grossman and Lohse model for thermal convection.

INTRODUCTION

Turbulent Rayleigh-Bénard convection, a fluid layer confined between two horizontally paralleled conducting plate with top plate cooled down and bottom heated up has become an ideal model for the study of fluid turbulence [1]. One interesting feature of the turbulent thermal convection is the emerge of a coherent large-scale circulation, which is self-organised from thermal plumes erupted from the top and bottom thermal boundary layers [2].

It is not until recently that the dynamics of the LSC could be studied in detail with the multi-thermal probe technique [3,4,5]. Previous study with water as working fluid and Pr number from 4.3 to 5.3 has found that the LSC is meandering azimuthally with a Gaussian probability distribution of the azimuthal angle, which implies a stochastic process. The top and bottom parts of the LSC oscillate with a phase delay of π, while the middle part does not oscillate. Recently, Xi $et. al.$ find that the middle part of the LSC has the so-called sloshing motion [6]. This sloshing motion plus the torsional motion could explain the observed low-frequency oscillation of the temperature and velocity field [7]. According to our knowledge, only measurements of water, mercury and gas as working fluid with moderate and low Pr number are available for the properties of LSC. Dose the dynamics of LSC change if we go to the high Pr number regime? Our measurements shed light upon the this problem.

EXPERIMENTAL SETUP

The experiment was done in a cylindrical convection cell with aspect ratio one. Two copper plates with nickel coated surface were used as heating and cooling plates. A plexiglass cylindrical sidewall with three layers of tiny cylinders (each contains 8) located at $\frac{H}{4}$, $\frac{H}{2}$ and $\frac{3H}{4}$ (H is the height of the cell) of the convection cell and uniformly distributed azimuthally was used. We denote the three layer as bottom, middle, and top parts of LSC hereafter. A hole of diameter $2.5mm$ was drilled into each of the tiny cylinder and the sidewall but not penetrating it. 24 thermistors with precision 0.01^oC were put into the hole to measure the azimuthal temperature profile. The convection cell was covered by Styrofoam to prevent heat leakage and was carefully levelled to within 0.002 rad. Water and FC77(3M company) were used as working fluid with Pr number from 5.3 to 19.4. The experimental setup and the distribution of thermistors are sketched in (a) of Figure 1.

The azimuthal temperature profile of each layer (top,middle and bottom) was fitted to a cosine function $T_i = T_0 + \delta\cos(i\frac{\pi}{8} - \theta)(i = 1, 2, 3, ...8)$, where T_0 is the mean temperature of the azimuthal profile, δ is regarded as a measure of the flow strength and θ is the azimuthal position where the hot plumes of the LSC comes up. Since the LSC carries the thermal plumes, thus this method could measure the dynamics of the LSC.

RESULTS AND DISCUSSION

The torsional oscillation and it's Pr number dependence

The measured power spectrum of $\theta_{t,m,b}$ of the LSC is shown as inset in Figure 1(b) for $Ra = 1.99 \times 10^{11}$ and $Pr = 19.4$. The power of θ_m and θ_t is shifted upwards by a factor of 10 and 100 respectively for clarity. It is seen clearly that a peak exist in the power spectrum of top and bottom as indicating by the arrow in the figure. However this peak was not observed for the middle part. These prominent peaks of θ_m and θ_t mean that this frequency is a characteristic frequency above the decaying background. Since θ measures the azimuthal position of the hot ascending plumes and thus the phase of LSC, we see that the top and bottom part of LSC moves with a characteristic frequency. In order to clarify if the typical frequency of the top and bottom part are the same, we calculate the coherence spectrum C_p of θ_t and θ_b, which is shown in Figure 1(b). The peak in the coherence spectrum implies that the top and bottom part indeed oscillates with the same frequency. For the middle part, no oscillation was observed means that the middle part dose not oscillate. Since the top and bottom part oscillates out of phase with each other, as showing in Figure 1(c), thus in the middle part the motion of top and bottom of LSC will cancel each other, which leads to no oscillation in the middle. Using water as working fluid, by setting the bulk temperature at 30 ^oC and 15 ^oC respectively, the corresponding Pr number are 5.3 and 8, we observed

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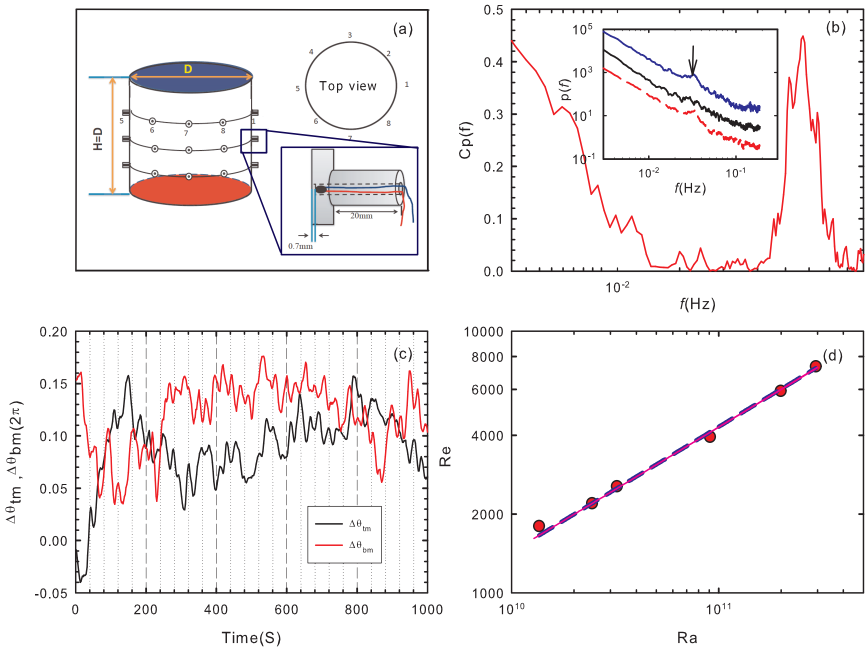

Figure 1. (a) Sketch of the convection cell and distribution of the thermistors. (b) The coherence spectrum of θ_t and θ_b. Inset is the power spectrum of θ_t (blue line), θ_m (black line) and θ_b (red dash line). The arrow indicates the characteristic frequency. (c) A segment of time trace showing the out-of-phase motion of the top (black line) and bottom (red line) part of LSC with the middle part as reference (arbitrary origin). (d) The measured Re as a function of the Ra for Pr=19.4. Experimental data are shown as red circle. A power law fit gives $Re = 0.0236Ra^{0.48\pm0.02}$(blue dash line). Prediction of Grossman and Lohse model for regime IV is shown as pink solid line.

the same phenomena. We conclude that the torsional motion of the LSC exsits in the high Pr number range.

Re number scaling

Based on the observed characteristic frequency f, we define a oscillation time $T_f = 1/f$, which is a characteristic time scale of the LSC. The Reynolds number is $Re = \frac{UL}{\nu} = \frac{2H^2}{\nu T_f}$, where T_f is the oscillation time of the LSC and ν is the viscosity of the working fluid. We plot the Re as a function of Ra in Figure 1(d) for Pr=19.4. A power law fit to the data results $Re = 0.0236 \times Ra^{0.48\pm0.02}$, which is shown as blue dashed line in (d) of Figure 1. In order to compare our experimental data with model prediction, we plot the Grossman and Lohse model [8] prediction of Re scaling for regime IV, which is $Re = 0.16 \times Ra^{\frac{4}{9}} Pr^{-\frac{2}{3}} + 0.0365 \times Ra^{\frac{1}{2}} Pr^{-\frac{1}{2}}$ in (d) of Figure 1. From the figure, we see that the measured Re and the model prediction are in good agreement with each other.

CONCLUSIONS

In conclusion, our study has revealed that the twisting oscillation also exists in the high Pr number regime. The measured Re number based on the oscillation frequency of LSC agrees very well with the GL model prediction for the regime IV.

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