LARGE SCALE CIRCULATION IN TURBULENT RAYLEIGH-BÉNARD CONVECTION

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Abstract Statistical properties of turbulent Rayleigh-Bénard convection (RBC) are investigated experimentally in a cylindrical cell of aspect ratio one. We specifically analyze the large scale circulation of RBC based on measurements of temperature fluctuations by small Ge sensors placed inside the cell. The resulting dependencies of Reynolds numbers on Rayleigh number up to 2×10^{13} are compared to available theoretical and experimental results for similar geometries.

INTRODUCTION

The Rayleigh-Bénard convection (RBC) serves as a very useful model for fundamental studies of buoyancy driven flows. The large scale circulation (LSC) at high Rayleigh number, *Ra*, coexists with thermal plumes. The latter are emitted from the thermal boundary layers (BLs) that, together with heat diffusion over the BLs, drive the LSC [1]. At the highest *Ra*, with Prandtl number, *Pr*, near unity and in aspect ratio one containers, the LSC was studied in a number of experiments in water ($Ra = 2 \times 10^7 - 10^{11}$, [7, 8, 4, 12]) and in a cryogenic He experiment (up to $Ra = 10^{13}$, [6]).
During our experimental studies of the Nusselt number, *Nu*, dependence on *Ra* [11, 9, 10] we have also collected data on local temperature fluctuations aiming to investigate the LSC up to very high $Ra \approx 10^{13}$ and to study turbulent convection at small scales. We use cryogenic helium gas with *in situ* adjustable properties as working fluid, in a cylindrical container of height $L = 0.3$ m, with aspect ratio $\Gamma = 1$, i.e., the cell diameter is equal to *L*. Four small Ge temperature sensors were placed inside the cell, in pairs, positioned opposite each other, at half height of the cell, 1.5 cm from the sidewall and $d = 2.5$ cm vertically apart.

RESULTS AND DISCUSSION

The characteristic frequency, $f_0 = 1/T_0$, of plume detection, with period, T_0, ranging approximately between 6 s and 40 s, was obtained from the autocorrelation functions (or from the power spectra) of one-point temperature records and used for the calculation of the plume based Reynolds number, as defined in [1]: $Re(f_0) = 2f_0L^2/\nu$, where ν is the kinematic viscosity, see Figure 1.
From the cross-correlation function of temperature records at two neighboring points, positioned at the distance *d* between them, the time delay, τ, between both signals (ranging approximately between 0.2 s and 0.5 s) has been evaluated. This allows us to infer the corresponding LSC velocity, $U_0 = d/\tau$, and Reynolds number, $Re(U_0) = U_0L/\nu$, [6], assuming that the Taylor's frozen flow hypothesis holds, see Figure 1.
The elliptic model of space-time correlation, proposed in [3], can also be used for the characterization of turbulent flows. It has already been applied to RBC studies in water for velocity [12] and temperature fluctuations [4, 5]. The elliptic space-time correlation is specifically characterized by two velocities, *U* and *V*. In the case of frozen flow, $U = U_0$ and $V = 0$, while, in general, the sweeping velocity $V > 0$. We have calculated *U* and *V* in our case, from two-point measurements of temperature fluctuations, see Figure 1, where we also plot the corresponding Reynolds numbers, $Re(U) = UL/\nu$, $Re(V) = VL/\nu$ and $Re(U_{eff}) = \sqrt{U^2 + V^2}L/\nu$, as a function of *Ra*.
In order to better appreciate the emerging scaling of all deduced quantities plotted in Figure 1, we show them compensated by the scaling $Re \sim Ra^{4/9}Pr^{2/3}$, obtained for the *Ra*-*Pr* space of our experiment by the Grossmann and Lohse (GL) theory [2]. Additionally, the corresponding data of other pertinent experiments from different laboratories are also presented in Figure 1; they differ by less than 20 % from ours. Moreover, for *Ra* larger than ca. 10^{10}, all our data are consistent with the GL scaling $Re = \xi Ra^{4/9}Pr^{2/3}$ with $\xi \approx 0.40$ for $Re(f_0)$ and with $\xi \approx 0.45$ for $Re(U_{eff})$.
The velocity based Reynolds numbers derived from the two-point temperature measurements, right hand side of Figure 1, are more scattered than the $Re(f_0)$ data, left hand side of Figure 1. Longer records, precise synchronization and lower noise would be required to achieve higher precision. Moreover, the former data should be taken with caution due to the possible inhomogeneity of the flow between neighboring sensors. The reason lays in the fact that distinguishable differences between the skewness of the distributions of temperature fluctuations recorded at the neighboring sensors were observed, although this does not apply to the corresponding root mean square (rms) temperature. Nevertheless, our $Re(U_{eff})$ data agree quite well with relevant water experiments. The ratio of the characteristic velocities $U/V \approx 1$, i.e., $Re(U)/Re(V) \approx 1$, and this is consistent with recent visualization results [12], although poorly agrees with the result $U/V = 1.4$, reported in [4].
The threshold in the *Re* scaling at about 10^{10} has been observed also in the scaling of the distribution skewness, while no threshold was seen in the scaling of the rms temperature $T_{rms}/\Delta T = 0.36Ra^{-0.125}$, with $Ra = 10^8 - 10^{13}$, where ΔT is

the difference between the temperatures at the top and bottom of the convection container. In the $Nu \approx Ra^{\gamma}$ dependence we instead observed that the change of the power exponent, γ, from 2/7 to 1/3, occurs gradually, at larger values of *Ra*, within a broader interval of $Ra \approx 10^{11} - 10^{12}$, compared to the scaling of the *Re* numbers and distribution skewness reported here.

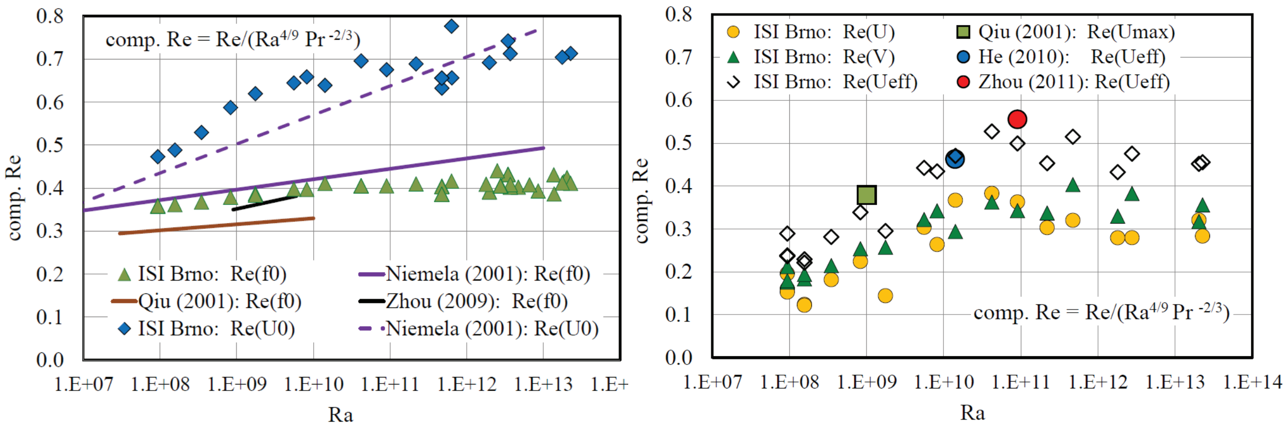

Figure 1. Compensated *Re* plotted as a function of *Ra*. Left: Our data, indicated as ISI Brno, obtained as explained in the text, are shown together with the data of Niemela (2001) [6], Qiu (2001) [8] and Zhou (2009) [13]. In our experiment, $Pr < 0.8$ up to $Ra = 10^{11}$, $Pr < 1$ up to $Ra = 10^{12}$ and $Pr \approx 2$ at $Ra = 2 \times 10^{13}$. Niemela (2001) [6] data are obtained from Péclet number dependencies and the corresponding compensated *Re* is calculated using a constant value of $Pr = 0.8$. Right: Our elliptic model data, as discussed in the text, are compared with the data of Qiu (2001) [7], He (2010) [4] (local temperature measurements) and Zhou (2011) [12] (PIV measurements). The Reynolds number data of Qiu (2001) [7] are evaluated for the flow velocity Umax, measured at the middle height of the cell, close to the wall, by LDV.

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