EXPERIMENTAL INVESTIGATION OF CRYOGENIC TURBULENT RAYLEIGH-BENARD CONVECTION IN CYLINDRICAL ASPECT RATIO ONE CELL

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Abstract The heat transfer efficiency and statistical properties of turbulent Rayleigh-Bénard convective flow are investigated experimentally in a cylindrical cell of aspect ratio one. We discuss the role of boundary layers asymmetry on the studied convective flow for Rayleigh numbers $10^6 < Ra < 10^{15}$ and statistical analysis of the RBC based on measurements of temperature fluctuations by small Ge sensors placed inside the cell interior. Resulting dependences of Nusselt and Reynolds numbers on Ra up to 10^{15} are analyzed and compared to available experimental results for similar geometry.

OVERVIEW

Rayleigh-Bénard convection (RBC) serves as an idealized model used for studies of thermally driven turbulent convection, which occurs on many length scales across the Universe, including geophysical and astrophysical flows as well as various industrial processes. The turbulent RBC, in a fluid layer confined between laterally infinite perfectly conducting parallel plates heated from below in a gravitational field, is characterized by the Rayleigh number $Ra = \alpha g \Delta T L^3/\nu\kappa$ and by the Prandtl number $Pr = \nu/\kappa$. Here, g stands for the acceleration due to gravity and ΔT is the temperature difference between the parallel bottom and top plates separated by vertical distance L. The working fluid properties are characterized by the isobaric thermal expansion α, the kinematic viscosity ν, and the thermal diffusivity κ. Efficiency of convective heat transfer is characterized by the Nusselt number $Nu = HL/\lambda$, where H is total heat flux, λ denotes the fluid heat conductivity. Under the so-called Oberbeck-Boussinesq (OB) approximation [1], Nu depends on Ra and Pr numbers only and is usually expressed in the form of the scaling law $Nu \sim Ra^{\gamma} Pr^{\beta}$. The value $\gamma = 1/3$ is predicted by a simplified physical model.

Available experimental results of worldwide laboratories on $Nu \sim Ra^{\gamma}$ dependence are contradictory at high Ra. We present experimental investigation of turbulent RBC at very high Rayleigh numbers, $Ra \leq 10^{15}$. We focus on a possibility of transition to the ultimate state of convection (so called Kraichnan regime) [2], where the efficiency of heat transfer, described by $Nu(Ra, Pr)$ dependence, should increase more steeply and eventually collapse to the scaling law $Nu \sim Ra^{1/2}$. Confirmation of existence of the ultimate regime is a great challenge in this field of study. Indeed, its existence and detailed knowledge of the ultimate scaling law would enable to get Nu values by extrapolation to extremely high Ra, which have not yet been achieved in any laboratory.

Another aim of our study is to get information about the structure of turbulent convection, to recognise large scale circulation (LSC) and its variations with Ra up to 10^{15} and to study turbulence at smaller scales, via time records of temperature fluctuations measured locally in the vertical stream of LSC. At high Ra, LSC coexists with thermal plumes which are emitted from the thermal boundary layers (BLs) and together with heat diffusion over BLs drive LSC [1]. We derive the characteristic period τ_{pl} of detection of plumes from the temperature fluctuation spectra (or from the autocorrelation function) and use the definition of the Reynolds number $Re = 2L^2/(\nu\tau_{pl})$ [1]. An approximate scaling law $Re \sim Ra^{1/2}$ has been theoretically predicted [1]. In another cryogenic experiment [3], Niemela et al. were able to detect the thermal plumes up to $Ra = 10^{13}$. Above this value the coherent structures were hard to distinguish [3].

RESULTS AND DISCUSSION

We use cryogenic helium gas as a working fluid with well-known and in situ tuneable properties. Our experimental cylindrical RBC cell of height $L = 0.3$ m, diameter $D = 0.3$ m (aspect ratio $\Gamma = D/L = 1$) is designed to minimize the influence of its structure on the convective flow [4], with the aim to resolve existing contradictions in Nusselt (Nu) versus Rayleigh number (Ra) scaling, at $Ra > 10^{11}$. In our previous work we have shown that for $7.2 \times 10^6 \leq Ra \leq 10^{11}$ our data (both uncorrected and corrected against various side effects) are consistent with $Nu \sim Ra^{2/7}$. Note that these data are obtained at experimental conditions satisfying the OB conditions very well. By applying suitable sidewall corrections, we show full agreement among cryogenic experiments of different laboratories performed with the cells of aspect ratio ~ 1 for Ra up to about 10^{11} [5]. In connection with our experiment we discuss tiny experimental details such as influence of the parasitic heat leak, additional corrections to finite heat conductivity and heat capacity of plates and so called chimney effects that might occur in thermally anchored venting tubes connected to the cell [6]. At higher $Ra > 10^{11}$, Nu data of various laboratories differ considerably. We claim that distinctly different $Nu(Ra)$ scaling as observed in various high Ra experiments can hardly be explained by the difference in Pr number. On approaching $Ra \sim 10^{11}$, our data display a crossover to $Nu \sim Ra^{1/3}$ [7]. Within OB approximation, the scaling law $Nu \sim Ra^{1/3}$ corresponds to the simple model where heat transfer is controlled by thermal diffusion across the BLs the thickness of which is defined by their critical Rayleigh number, all ΔT occurs over thin BLs adjacent to the plates and in the central turbulent region the working fluid is effectively mixed and isothermal.

In practice, the OB approximation is never exactly valid, especially for working fluids in the vicinity of their critical point, where the relevant fluid properties (α, ν, κ, λ) might vary over ΔT significantly, which results in asymmetry in boundary layers and in appreciable change of the mean temperature T_{mp} of the turbulent core with respect to the mean temperature of the top and bottom plates. According to our results, within our experimental resolution, the "1/3" scaling law holds up to $Ra \leq 10^{15}$, if the mean temperature of the working fluid - cryogenic helium gas - is measured directly, by small (0.2 mm) Ge sensors positioned inside the cell at about half of its height. On the contrary, if the mean temperature is determined in a conventional way as an arithmetic mean of the bottom and top plate temperatures, the $Nu(Ra)$ dependence displays spurious crossover to steeper scaling that might easily be misinterpreted as a transition to the ultimate state of convection. Our results, including the latter one, do not mean that this elusive transition does not happen, but suggest strongly that experimental investigation of this issue and observed departures from $Nu \sim Ra^{1/3}$ at very high Ra ought to be interpreted with extreme care [7].

Finally, we present statistical analysis of large scale as well as small scale properties of turbulent RBC based on measurements and statistical analysis of temperature fluctuations. Four small Ge sensors placed inside the cell interior, in pairs positioned opposite at half height of the cell, 1.5 cm from the sidewall and 2.5 cm vertically apart, were used. We discuss observation of coherent structures deduced by examining autocorrelation and cross-correlation of temperature signals. We determine the Péclet $Pe = Pr \cdot Re$ vs Rayleigh number Ra dependence, which approximately follows the dependence $Pe \sim Ra^{1/2}$ all the way up to $Ra = 2 \cdot 10^{14}$, while previously observed data are limited to $Ra \leq 10^{13}$ [3].

Together with the shape of turbulent spectra and probability distributions of temperature fluctuations we report results on scaling of temperature structure functions within the Bolgiano range of length scales and compare them with previous experiments performed in a larger experimental cell [8].

ACKNOWLEDGEMENTS

This work was supported by the GACR 203/12/P897 and MEYS CR (CZ.1.05/2.1.00/01.0017); work of LS by institutional support from the Charles University in Prague (UNCE).

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