MEASUREMENT OF THE LOCAL CONVECTIVE HEAT FLUX IN THERMALLY-DRIVEN TURBULENCE WITH ROUGH SURFACES

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Abstract We report experimental measurements of the local convective heat flux in a cylindrical Rayleigh-Bénard convection cell with rough top and bottom plates. The Rayleigh number Ra is from 6.1×10^8 to 5.3×10^9 and the Prandtl number is $Pr = 5.3$. Simultaneous measurements of velocity and temperature in the centre of the cell are made using a thermal probe and one-dimensional laser Doppler velocimetry (LDV). It is found that the normalised vertical heat flux J_z in the centre of the rough cell scales with Ra as $J_z = 0.46Ra^{0.18\pm0.01}$. The Reynolds number Re based on the rms velocity scales with Ra as $Re = 1.8 \times 10^{-2}Ra^{0.49\pm0.01}$. Compared to the smooth case, it is found that the enhancement of the convective flux in the centre of the rough cell is due to more thermal plumes passing through the centre.

INTRODUCTION

Thermally-driven turbulence is ubiquitous in both nature and industry. The Rayleigh-Bénard convection (RBC), which is a fluid layer confined between two horizontally parallel plates cooled from above and heated from below, has become an idealized model to investigate thermally-driven turbulence. One of the main issues in the study of turbulent RBC is how heat and momentum are transferred from the bottom to top. Xia, Lam and Zhou measured the global heat transfer efficiency, namely the Nussult number Nu, using four kinds of fluids with $2 \times 10^7 \leq Ra \leq 3 \times 10^{10}$ and $4 \leq Pr \leq 1350$ and found that $Nu = 0.14Pr^{-0.03}Ra^{0.297}$[5]. The local heat flux measurements by Shang, Tong and Xia found that in the cell center the local J_z scales with Ra as $J_z \propto Ra^{0.49\pm0.03}$ [2] , which is in good agreement with the Grossman and Lohse theory for thermal turbulence [1]. It is also found that using rough top and bottom plates, Nu can be enhanced [3]. To better understand this enhancement, measurements of the local heat flux in the rough cell are needed.

EXPERIMENTAL SETUP

The experiment is carried out in an upright cylindrical convection cell with a flat window for LDV measurement. The top and bottom plates with roughness used have been described in [4]. The sidewall used is described in [2]. The LDV together with an Argon laser are used to measure the vertical flow velocity V in the centre of the cell. A tiny thermistor with 300 μm in diameter is used to measure the temperature T in the centre of the cell. Using $V(t)$ and $T(t)$, we obtain the normalized vertical heat flux:

$$J_z = \frac{\langle V(t) \times \delta T(t) \rangle_t H}{\kappa \Delta T} \tag{1}$$

where $\delta T = T - T_0$ is the temperature deviation from the most probable temperature T_0, H height of the convection cell, ΔT temperature difference across the top and bottom plates and κ thermal diffusivity of the convecting fluid. The distance between the thermistor and the measurement point of the LDV is 0.5mm. For each Ra, the measurement lasts at least 13h.

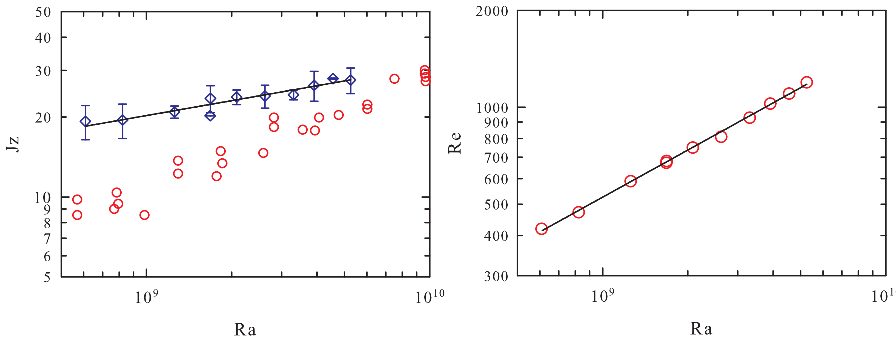

Figure 1. (a) The measured J_z at the centre of the cell as a function of Ra in the rough cell (blue triangles, present work) and smooth cell (red circles, from [2]). The solid line is a power law fitting to rough cell $J_z = 0.46Ra^{0.18\pm0.01}$; ($b$) The measured Re as a function of Ra in the rough cell. The solid line is a power fitting $Re = 1.8 \times 10^{-2}Ra^{0.49\pm0.01}$.

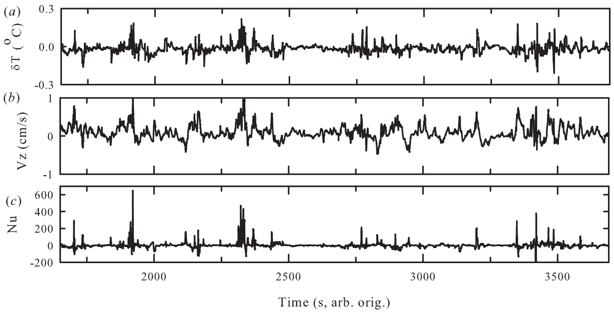

Figure 2. Arbitrary chosen time series of (a) temperature, (b) velocity and (c) vertical heat flux ($Ra = 8.2 \times 10^8$).

RESULTS AND DISCUSSION

We show in figure 1(a) the measured J_z in the centre of the rough cell as a function of Ra. The data in rough cell (blue diamonds, present results) can be fitted by a power law relation as $J_z = 0.46Ra^{0.18\pm0.01}$. Also shown in the figure are data from Shang et al. [2] (red circles), which is measured in the centre of a smooth cell. It is obvious that the vertical heat flux in the centre of the rough cell is larger than the smooth case over the range of Ra of the experiment. Especially for Ra smaller than 2×10^9, J_z in the rough cell is roughly twice that in smooth cell. Shang et al. reported that $Jz = 3.5 \times 10^{-4}Ra^{0.49}$ in the centre of a smooth cell [2]. Compared with smooth case, the heat flux in the centre of the rough cell behaves quite differently.

Since the time-averaged velocity in the centre of the cell is almost zero, we define Re in the way that $Re = V_{rms}H/\nu$, where V_{rms} is the velocity fluctuation. The measured Re vs Ra is shown in figure 1(b). As it is seen that the data can be well represented by a power law $Re = 1.8 \times 10^{-2}Ra^{0.49\pm0.01}$. Comparing the present results of the scaling exponent of Ra in the rough cell with that in the smooth cell, which is 0.49 ± 0.03 as reported by Shang et al. [2], we see that the Re scaling with Ra for the rough and smooth cell are in good agreement with each other.

In order to investigate the reason for the enhancement of vertical heat flux in the centre of the rough cell, we show the time series of the measured temperature derivation from the most probable temperature, velocity and vertical heat flux in figure 2. From the figure, the signatures of the thermal plumes are very clear (the spikes of the temperature derivation). Because both hot and cold thermal plumes will give a positive heat flux, the measured J_z always skewed towards the positive side. The flatness of the normalized velocity $(V - \langle V \rangle)/V_{rms}$ changes from 4.7 to 3.3 when Ra changes from 6.1×10^8 to 5.3×10^9, which indicates that the velocity at lower Ra has more frequent large spikes corresponding to thermal plumes. It is also noticeable that with the increase of Ra, the probability distribution function of the normalized velocity becomes more like a normal distribution. Thus present results convincingly show that it is the thermal plumes, which give rise to the heat flux in the centre of the rough cell within the resolution of the present experiment.

In conclusion, we carried out simultaneous measurements of the temperature and vertical velocity in the centre of a Rayleigh-Bénard convection cell with rough top and bottom surfaces. The measured vertical heat flux $J_z = 0.46Ra^{0.18\pm0.01}$ and the Reynolds number $Re = 1.8 \times 10^{-2}Ra^{0.49\pm0.01}$. It is found that the vertical flux in the centre of a rough cell enhances and the enhancement is caused by more thermal plumes passing through the centre.

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