The interplay between horizontal heat transfer and large scale circulation in turbulent Rayleigh-Bénard convection

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We derive the following generalized expressions of the vertical and horizontal Nusselt numbers to describe the instantaneous heat transfer efficiency in turbulent Rayleigh-Bénard convection (RBC):

$$Nu_V(t) = -\oint z\frac{\partial T}{\partial z}dS - \sqrt{PrRa}\iiint z\frac{\partial T}{\partial t}dV \tag{1}$$

$$Nu_H(t) = -\oint x\frac{\partial T}{\partial z}dS - \sqrt{PrRa}\iiint x\frac{\partial T}{\partial t}dV \tag{2}$$

For RBC in a statistical steady state, ensemble averages of Eqs. 1 and 2 reduce to the expressions given by Zhang *et al.*[1] With the definitions above, we obtain the time series of the Nusselt vector (*i.e.* Nu_V and Nu_H) by conducting two dimensional numerical simulations (see figure 1a). It is found that its trajectory shows a cardioid pattern (see figure 1b) for the case with Rayleigh number $Ra = 10^8$ and $Pr = 4.38$. Moreover, the evolution of heat transport is highly coupled with the dynamics of large scale circulation (LSC), with its extreme values (the third and fourth quadrants in figure 1b) being preludes to LSC reversal events (which can be identified as the global averaged angular momentum L changes its signs).

Finally, we propose a novel experimental method to measure both the vertical and horizontal components of the Nusselt vector using quantitative shadowgraphy (see figure 1c), and show our preliminary results.

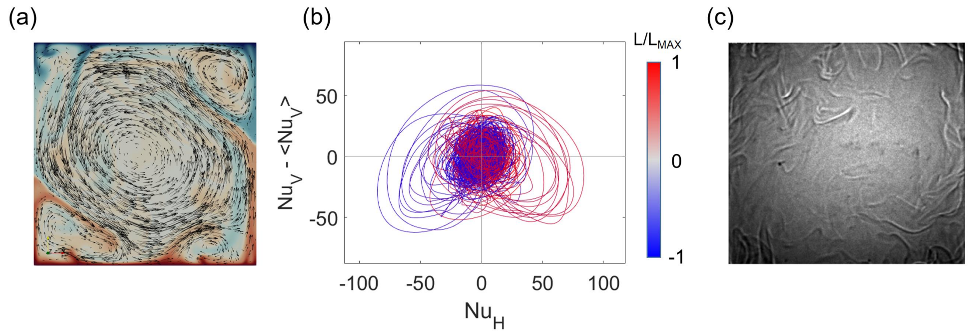

Figure 1: (a) Snapshots of the velocity and temperature fields in a 2D RBC domain at $Ra = 10^8$ and $Pr = 4.38$. (b) The corresponding Nusselt vector trajectory in the Nu_H-Nu_V plane. (c) A shadowgraphy image of RBC using water as the working fluid.

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[1] Zhang, Ding and Xia, *J. Fluid Mech.* **914**, A15 (2021).