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Onset of Horizontal Convection

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1. INTRODUCTION

Horizontal convection describes convection flow driven in an enclosure by non-uniform heating imposed across a horizontal boundary [1]. These flows are characterised by a Rayleigh number representing the strength of buoyancy over dissipative effects, a Prandtl number and aspect ratio of the enclosure. Numerous studies [2,3] focused on the dynamics of horizontal convection in thermal equilibrium where no net heat flux through the forcing boundary or through any horizontal level in the flow. Local [4] and global [5] linear stability analysis revealed that instability in horizontal convection is due to convective transverse-rolls in the thermal forcing boundary layer. However, the onset of this thermal instability, its early transient features and the dynamics of the transition to unsteady flow are not well understood.

More recently, Sanmiguel Vila *et al.* [6] investigated experimentally the onset of horizontal convection and proposed a scaling for the characteristic time of the transient flow. The current study aims to numerically investigate the onset of horizontal convection. The system considered is similar to the experimental setup used by Sanmiguel vila *et al.* [6]. However, the current investigation expands on the Rayleigh numbers to range from 10^6 to 10^{13}, accounting for the effect of Rayleigh numbers on the onset of horizontal convection.

2. METHODOLOGY

The system under consideration comprises a rectangular enclosure of width L and height H filled with an incompressible fluid where a Boussinesq model for buoyancy is employed. The incompressible Boussinesq Navier–Stokes equations are solved using a nodal spectral element method for spatial discretisation and a third-order operator-splitting scheme based on backwards-differentiation for time integration. Numerical simulations were performed with an aspect ratio $H/L = 0.5$ and a Prandtl number $Pr = 6.14$, representative of water, due to the motivating interest in global ocean circulation. Adiabatic boundary conditions were imposed on side and top boundaries, while a fixed cold temperature and a constant heat flux were imposed along left and right half of the bottom boundary respectively. The computational mesh used in the current study is carefully constructed to resolve thermal boundary layer as well as thermal plumes in the enclosure.

3. RESULTS

Figure 1(a) shows a time history of Nusselt number for $Ra = 6 \times 10^{11}$, the time τ is scaled by the boundary layer time τ_{bl} [6]. The Nusselt number first decreases monotonically as a stable thermal boundary layer develops on the heated half of the base. The thermal boundary layer grows and plumes begin to form near the centre and the bottom right corner of the enclosure, as shown in figure 1(b), which corresponds to a local minimum in the Nusselt number (figure 1(a)). The development of plumes (initially at the periphery of the heated part of the base) then causes an increase in Nusselt number. As the region of instability in the thermal boundary layer expands, the number of plumes increases as shown in figure 1(c). These vertical plumes resemble thermal characteristic of a Rayleigh–Bénard convection. Figure 1(d) shows the thermal boundary layer is completely replaced by thermal plumes. The Nusselt number attends its local maximum value, which signals the end of

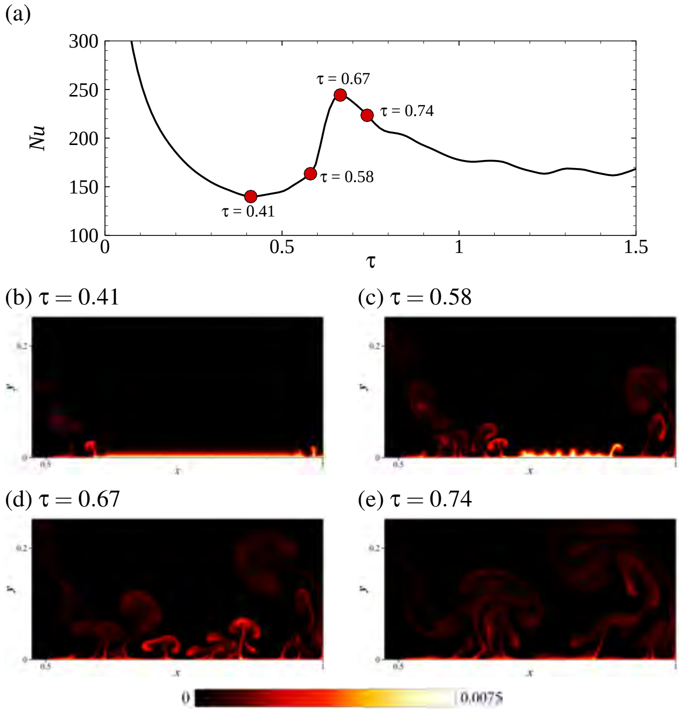

Figure 1. (a) Nusselt number time history with red symbols represent different time instant where snapshot of temperature contours are taken. (b)-(e) Contours plot of temperature field for $Ra_F = 6 \times 10^{11}$ at different time for the onset of horizontal convection as indicated.

the Rayleigh–Bénard convection. The effect of the Rayleigh–Bénard convection is to enhance heat transfer to the interior. As the plume rises, fluid from the cold boundary move horizontally to fill the void left by the rising plume. This horizontal movement of colder fluid stabilises the thermal boundary layer. This is shown in figure 1 where plumes coalesce and convect toward the right-hand corner of the enclosure. This creates segments of stable thermal boundary layer along the heated boundary. In addition, the plumes become slanted, which indicate formation of a horizontal convection regime.

4. CONCLUSIONS

High-order spectral-element simulations reveal transient features in horizontal convection at high Rayleigh number. It identifies the presence of Rayleigh–Bénard convection leading to the onset of horizontal convection.

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