Horizontal convection in very shallow enclosures

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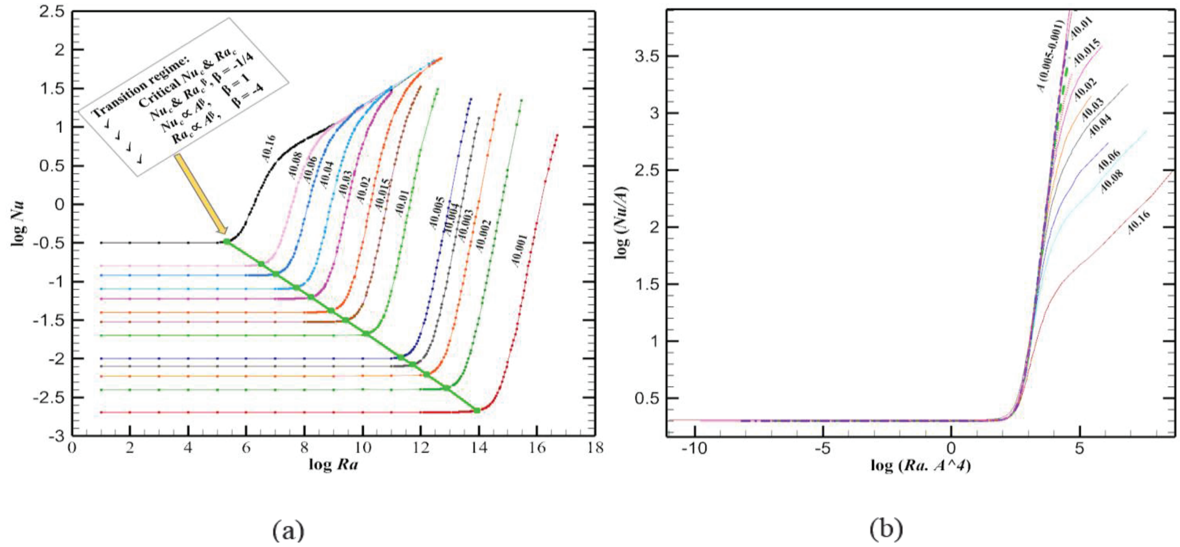
1. INTRODUCTION

Horizontal convection is a distinctive mode of convective heat transfer where heating and cooling happens along the same horizontal boundary. The inspiration for research in the field originates from the need to understand geophysical flows [1] and also process engineering, e.g. glass melting [2]. Previous studies of horizontal convection in rectangular enclosures [1, 3, 4] investigated either with a fixed or a small range of aspect ratios to report scaling of the Nusselt (*Nu*) and Rayleigh (*Ra*) numbers. Despite these works, further research concerning horizontal convection is required to better understand the effect of decreasing aspect ratio on the transition of the flow from diffusive to convective regimes and to determine the bound of the *Nu*-*Ra* scaling. Thus, our study aims to provide insights about horizontal convection in the context of different regimes and their respective scalings of significant quantities towards the limits of small aspect ratios.

2. METHODOLOGY

A water-filled rectangular enclosure with internal dimensions of length L, height, H (aspect ratio, $A = H/L$) is studied. The flow with buoyancy modelled using a Boussinesq approximation was driven by imposing a linear temperature profile on the bottom boundary of the enclosure, and insulating temperature conditions on the remaining boundaries. The 2D incompressible Navier–Stokes equations augmented by a buoyancy term in the momentum equation and a scalar advection-diffusion transport equation for temperature were solved by a high-order in-house solver, which employs a spectral-element method for spatial discretisation and a 3rd-order time integration scheme based on backwards-differencing.

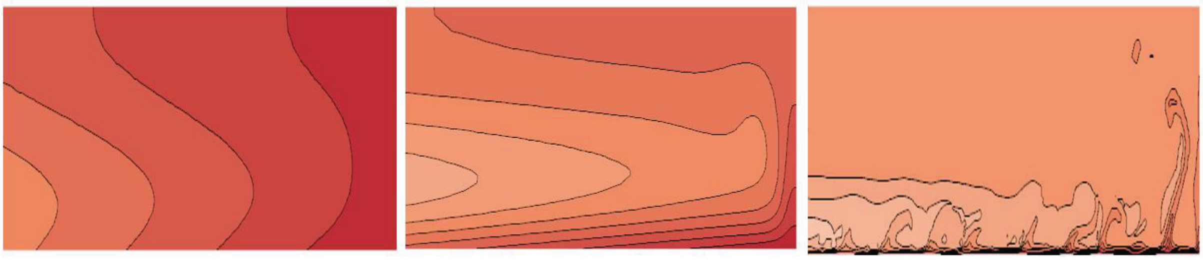


(a) (b)

Figure 1. Plots of (a) log *Nu* against log *Ra* and (b) log (*Nu*/*A*) against log (RaA^4), for various aspect ratios between A=0.001 to 0.16.

3. RESULTS

Numerical simulations were conducted for thirteen aspect ratios (*A*=0.001 to 0.16) for Prandtl number of water (*Pr*=6.14) to acknowledge the role of horizontal convection in oceanic circulations. All simulations were time-evolved to a statistically steady state to measure the time-averaged *Nu.* Figure 1(a) shows *Nu* vs *Ra* plots, which depicts that increasing *Ra* governs the flow from a diffusion-dominated regime to a steady-state convection-dominated regime, before subsequently developing an unsteady flow. The unsteady activity is concentrated in the vicinity of the vertical plume rising from the hot end of the heated boundary as presented in figure 2. *Nu* is independent of *Ra* but varies linearly with *A* values in the diffusion-dominated regime, and is visible at the left side of the green line in figure 1(a). Beyond this regime, *Nu* increases and the formation of plumes can be observed at the hot end of the enclosure. It is marked as the transition regime, where *Ra* scales with *A* with a gradient of -4. The critical *Ra* and the corresponding *Nu,* where the transitions occur for all *A* values are marked in figure 1(a). Once the flow passes through transition regime, the *Nu* for most *A* values appear to collapse onto a single trend with a ¼th gradient of *Ra*, and this is termed as the convective regime. The fully-developed plumes are evident at this stage as seen in figure 2(iii), and an overturning circulation commences to complete the flow. Based on this scaling of the transition regime, figure 1(b) plots log (*Nu*/*A*) against log (RaA^4) and illustrates a collapse for all *A* values into a single line. It provides the evidence that the flow is dominated by enclosure height at low *Ra.*



(i) (ii) (iii)

Figure 2. Temperature contours focused on the hot-end of the enclosure for *A*=0.04 (i) diffusive $Ra=10^8$, (ii) transition $Ra=10^{10}$ and (iii) convective $Ra=10^{12}$ regimes. The darker colour sheds refer to higher temperatures.

4. CONCLUSIONS

This study identifies the critical values of *Ra* and *Nu* for the flow transition and also *Ra~A* and *Nu~A* scalings for different regimes of horizontal convection with a broad range of shallow enclosures. These are beneficial to understand the impact of enclosure confinement of horizontal convection and further research in this regard.

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