THE EFFECT OF VELOCITY BOUNDARY CONDITIONS ON $2D$ RAYLEIGH-BÉNARD TURBULENCE

R. Ostilla Monico[1], E. P. van der Poel[1], R. Verzicco[1,2] and D. Lohse[1]
[1]*Physics of Fluids, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands*
[2]*Dipartimento di Ingegneria Meccanica, University of Rome "Tor Vergata", Via del Politecnico 1, Roma 00133, Italy*

Abstract Rayleigh-Bénard (RB) convection, the flow between a cold top plate and a hot bottom plate, is commonly used to model natural convection. Experimental realizations of RB usually consist of low aspect-ratio geometries and are limited to no-slip velocity boundary conditions. This is not representative of most geo- and astrophysical systems we wish to model. In this contribution, the effect of aspect-ratio and velocity boundary conditions on a 2D RB system have been studied by varying the sidewall boundary conditions between no-slip, stress-free and periodic, and the differences in the heat transport are measured. Heat transport is found to be larger for stress-free and periodic cells than for the no-slip case. Aspect ratio plays a small role in periodic cells, as long as the aspect ratio is larger than a certain threshold. For stress-free and no-slip cells, aspect ratio plays opposing roles. Thinner cells have larger heat transport than square cells when the sidewalls are stress-free. In contrast, for cells with no-slip walls, square cells have a larger heat transport than thin cells.

INTRODUCTION

The flow between a cold top plate at temperature T and a bottom hot plate at temperature $T + \Delta$ separated by a distance L is called Rayleigh-Bénard (RB) flow. The temperature difference can be expressed non-dimensionally as the Rayleigh number, $Ra = g\beta\Delta L^3/(\nu\kappa)$, where g is gravity, β is the thermal expansion coefficient of the fluid, ν is the kinematic viscosity of the fluid and κ is the thermal conductivity of the fluid. Here we focus on the turbulent case, i.e.., large Ra. The other non-dimensional control parameter of the system is the Prandtl number $Pr = \nu/\kappa$, which gives the ratio of viscosity to thermal conductivity and is a fluid property.

RB is commonly used for modelling natural convection, both in engineering flows and natural flows in geo- and astrophysics. However, these are predominantly systems with very large aspect-ratios and stress-free boundary conditions. Recent studies on RB convection focused on the so-called ultimate regime [1], where the BLs are expected to become turbulent. This regime is of interest as it is expected that the scaling of the integral quantities in this regime can be extrapolated to the very high Ra present in geo- and astrophysical natural convection. In DNS, the velocity boundary conditions are commonly taken as no-slip in both horizontal and vertical plates [2]. This has a strong effect on the resulting thermal and kinetic boundary layers (BLs). Therefore it is of interest to know how these velocity boundary conditions affect both the transition to the ultimate regime and the ultimate regime itself.

Here a systematic study of the effect of velocity boundary conditions is carried out in a 2D RB cell of varying aspect ratio $\Gamma = D/L$, where D is the width of the cell. Pr is fixed to unity and the Bousinessq approximation is used to compute the buoyancy forces. The velocity boundary conditions on the sidewalls were taken to be either periodic, stress-free or no-slip, and the velocity boundary conditions on the top plate were taken to be either stress-free or no-slip. In the case of stress-free and no-slip sidewalls, an adiabatic boundary condition is used for the temperature.

RESULTS

The global response of the system is quantified through the non-dimensional heat transport, i.e., the Nusselt number $Nu = Q/\Delta\kappa L^{-1}$. In figure 1 an overview of the results is given.

Figure 1a shows the compensated Nu against Ra for a thin cell with $\Gamma = 1/3$ and for a square cell with $\Gamma = 1$ for both stress-free and no-slip sidewalls. Heat transfer is always larger for the stress-free boundaries, and it can be a factor three larger for the thin cell. The effect of Γ is reversed for stress-free cells, as the thinner cells have a larger heat transport, while for no-slip cells, the thinner cell has a smaller heat transport.

Figure 1b shows the compensated Nu against Ra for a wide cell with $\Gamma = 2$ for both stress-free and no-slip sidewalls. Heat transport is about 10% larger for the case with stress-free sidewalls. The difference here is much less significant than the difference between the no-slip and the stress-free case.

Figure 1c shows Nu against Γ in a periodic cell for three different values of Ra. The effect of the periodic length on heat transfer becomes neglible as long as $\Gamma > 2$, independently of the value of Ra.

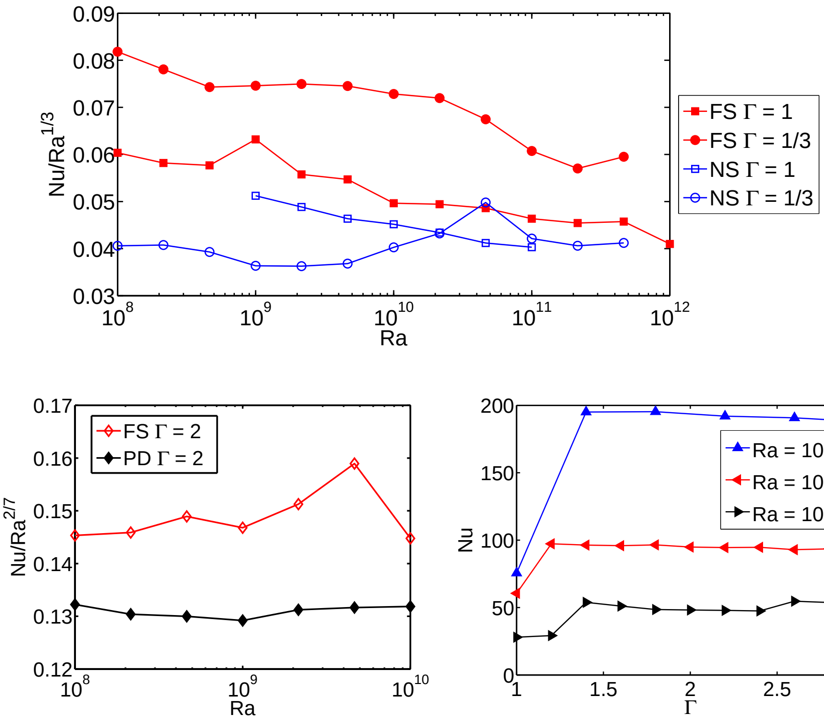

Figure 1: The top panel shows $Nu/Ra^{1/3}$ against Ra for two aspect ratios and two sidewall velocity boundary conditions. On the bottom-left panel, $Nu/Ra^{2/7}$ is plotted against Ra for an aspect ratio of $\Gamma = 2$ and two sidewall velocity boundary conditions. Finally, Nu against Γ in a periodic cell for three values of Ra is shown on the bottom-right panel.

CONCLUSION

The effect of different velocity boundary conditions on Rayleigh-Bénard turbulence is analysed. Simulations have shown that sidewall velocity boundary conditions have a large impact on the resulting heat transport. The heat transport for periodic and free-stress sidewalls is higher than for no-slip transport. However, different velocity boundary conditions show different properties. While thin cells have a higher heat transport for stress-free side walls, short cells have a higher heat transport for no-slip side walls.

References

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