SIDEWALL EFFECTS IN RAYLEIGH-BÉNARD CONVECTION

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Summary We investigated the influence of the temperature boundary condition at the sidewall on the heat transport in Rayleigh-Bénard convection in simulations. For relatively low Ra the heat transport is higher when the sidewall temperature is kept at $\Delta/2$, where Δ is the temperature difference between the horizontal plates, than with an adiabatic sidewall. The reason is that then part of the heat current avoids the thermal resistance of the fluid by a heat flux through the sidewall, which is largest close to the horizontal plates. For higher Ra the bulk becomes more isothermal, which reduces the heat flux through the sidewall. Therefore the heat flux in a cell with a sidewall kept at $\Delta/2$ converges to the value obtained with an adiabatic sidewall for high Ra. However, an increase of the sidewall temperature leads to a lower heat transport at the bottom plate for all Ra.

INTRODUCTION

Rayleigh-Bénard (RB) convection is the classical problem to study heat transfer phenomenon [1]. The control parameters of the system are the Rayleigh number $Ra = \beta g \Delta L^3/(\kappa\nu)$, the Prandtl number $Pr = \nu/\kappa$, and the aspect ratio $\Gamma = D/L$. Here, L and D are the height and diameter of the sample, β the thermal expansion coefficient, g the gravitational acceleration, Δ the temperature difference between the bottom and top, and ν and κ the kinematic viscosity and the thermal diffusivity, respectively. Most experimental and numerical results on the Nusselt number Nu, i.e. the dimensionless heat transfer, agree up to $Ra \approx 2 \times 10^{11}$ and are in agreement with the description of the Grossmann-Lohse theory [1, 2]. However there are considerable unexplained differences between experiments performed at higher Ra [1].

Recent evidence suggests that the deviations might be related to the formation of different turbulent states in the high Ra number regime. Of particular interest are the experiments by Ahlers et al. [3–5], who found two different branches in one experiment and showed that the temperature difference between the average temperature inside and outside the the RB sample determines the state of the system. Also Roche et al. [6] found two different turbulent states in the high Ra number regime and they showed that the heat transport in the high Ra number regime can strongly depend on the characteristics of the sidewall and the aspect ratio. Thus both experiments indicate that the temperature boundary conditions at the sidewall can be important.

Therefore we investigate the difference between simulations with an adiabatic and an isothermal sidewall. This is an interesting comparison because in most experiments [4, 7, 8] the adiabatic temperature condition at the sidewall is obtained by placing a temperature shield that is kept at $\Delta/2$ around the sidewall with an isolation layer in between. As a completely isothermal sidewall is an oversimplification we will also consider the case in which only the bottom and top 1.5% of the sidewall is kept at $\Delta/2$ and the rest of the sidewall is adiabatic. This case is based on the design of the Göttingen setup [4] in which micro shields with a temperature of $\Delta/2$ are placed just above (below) the lower (upper) plate in order to prevent that the isolated region between the sidewall and the side shield is influenced by the temperature of the horizontal plates.

RESULTS

Figure 1a shows that the heat flux at the bottom plate is higher when the sidewall is kept at $\Delta/2$ than when the sidewall is adiabatic, even though the time-averaged heat flux through the sidewall is zero. This happens because part of the heat current avoids the thermal resistance of the fluid by going through the sidewall. Figure 1a shows that the difference between the heat transport measured with an adiabatic sidewall and with a sidewall that is kept at 0.5Δ decreases with increasing Ra. The reason is that with increasing Ra the temperature becomes more isothermal, i.e close to 0.5Δ, outside the thermal boundary layers (BLs). Since the thermal BL becomes much thinner for higher Ra this limits the fraction of the heat current that can avoid the thermal resistance of the fluid by going through the sidewall at high Ra and therefore the heat transport at the horizontal plates converges to the value obtained in simulations with an adiabatic sidewall. The figure also shows that a lower heat transport at the bottom plate is measured when the sidewall temperature is increased. In that case the heat transport does not converge to the value measured in a cell with an adiabatic sidewall, because the warmer sidewall generates a heat flux through the sidewall at all Ra.

As a completely isothermal sidewall is an oversimplification of the experimental situation we also consider the case in which an isothermal region of $0.015L$ close to the bottom and top plate is kept at 0.5Δ and the rest of the sidewall is adiabatic. This model is based on the design of the Göttingen RB setup [3–5], in which micro shields kept at 0.5Δ are

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placed just above (below) the bottom (top) plate in order to prevent that the temperature of the plates influences the isolated region between the sidewall and the side shield. Figure 1b shows that the result from this model is almost the same as for the case in which the entire sidewall temperature is kept at 0.5Δ. The reason for the agreement is that the temperature of the fluid close to the sidewall only differs significantly from $\Delta/2$ outside the thermal BL and therefore the heat flux through the sidewall is only large in the thermal BL region. A comparison between the height of the isothermal region of the sidewall ($0.015L$) and the thermal BL height λ_θ reveals that the isothermal region is larger (or equal to) than λ_θ for all Ra, i.e. we find that λ_θ is $0.017L$ at $Ra = 2 \times 10^7$, $0.0106L$ ($Ra = 2 \times 10^8$), $0.0054L$ ($Ra = 2 \times 10^9$), $0.0029L$ ($Ra = 2 \times 10^{10}$). From this we conclude that the sidewall region close to the horizontal plates is crucial. We note that this is a particularly challenging region in experiments as the sidewall and the horizontal plates meet in this region and therefore it is impossible to complete prevent all heat currents in this region.

DISCUSSION AND CONCLUSIONS

We used direct numerical simulations to investigated the influence of the temperature boundary conditions of the sidewall on the heat transport in Rayleigh-Bénard convection. We show that at low Ra the heat transport is higher when the sidewall temperature is fixed at $\Delta/2$ than with an adiabatic sidewall, because then part of the heat current prevents the thermal resistance of the fluid by going through the sidewall. However, this effect disappears at higher Ra where the bulk becomes more isothermal and the heat flux through the sidewall decreases. In agreement with experimental results we find that an increase of the sidewall temperature leads to a lower heat transfer at the bottom plate. Just as in experiments this effect is visible over a large Ra number regime; in the simulations from $2 \times 10^6 \leq Ra \leq 2 \times 10^{10}$. In addition, we show that the sidewall region close to the horizontal plates is crucial, while this is particularly challenging region in experiments. In future simulations we will also model the effect of the physical properties of the sidewall.

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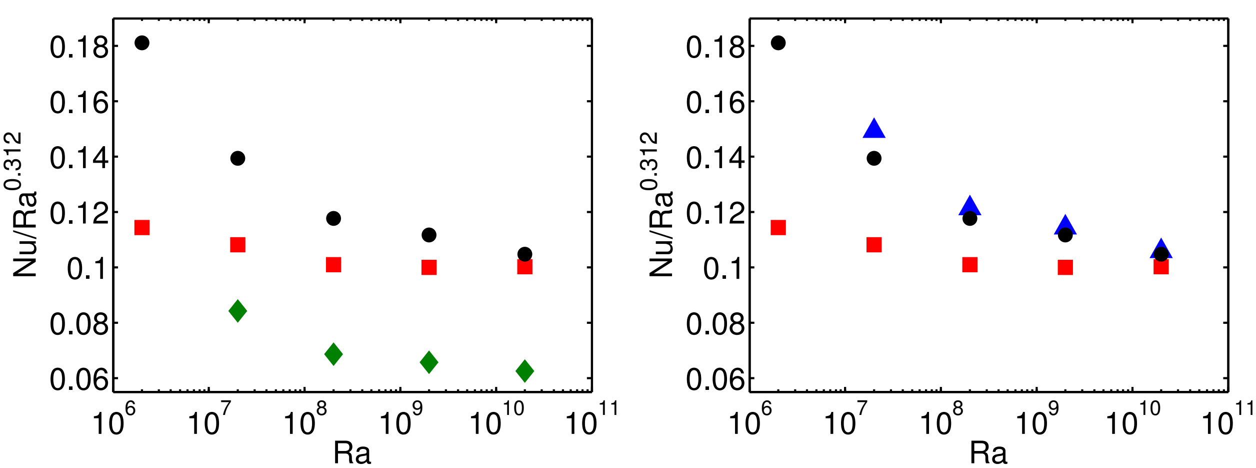

Figure 1. Nusselt versus Ra. The heat transport in simulations with an adiabatic sidewall [9, 10] is indicated by the red squares. The results of simulations in which the sidewall is kept at 0.5Δ is given by the black circles. Panel a compares these results with simulations in which the sidewall temperature is 0.75Δ (dark green diamonds) and panel b shows the results for the simulations in which the lower and upper 1.5% of the sidewall are kept at 0.5Δ and the rest of the sidewall is adiabatic (blue upward pointing triangles).