COMPARISON BETWEEN ROUGH AND SMOOTH PLATES WITHIN THE SAME RAYLEIGH-BÉNARD CELL AT HIGH RAYLEIGH NUMBERS

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Summary In a Rayleigh-Bénard cell at high Rayleigh number, the bulk temperature is nearly uniform. The mean temperature gradient differs from zero only in the thin boundary layers close to the plates. Measuring this bulk temperature and the plates temperature allows to separately determine the thermal impedance of each plate. We present a high Rayleigh experiment in which the bottom plate is rough and the top plate is smooth; both interact with the same bulk flow. The Rayleigh number is varied between 10^9 and 10^{12}. We define a Nusselt number for the rough plate and a Nusselt number for the smooth one and we compare them. We show that the two Nusselt numbers follow different law as function of Rayleigh number, the rough plate being more efficient in exchanging heat as soon as the boundary layer thickness matches the roughness height.

INTRODUCTION

Because of the simplicity of the boundary condtions Rayleigh-Bńard (RB) systèmes (the hot bottom plate and the cold top plate are maintained at constant temperatures whereas the lateral sidewalls are adiabatic), are used as archetypal configuration for the study of natural convection and heat transfer mechanisms that occur in many industrial and natural processes. Indeed, RB convection displays most of the features observed in more complex systems: turbulence, viscous and thermal boundary layers, plumes, large scale circulation, a potential laminar-turbulent transition in the boundary layer beyond a critical Rayleigh number. However, to understand the high Rayleigh number behavior of a real RB cell, it becomes important to alter the boundary conditions and see how the plate roughness affects the heat transfer by the convecting fluid.

With smooth boundaries, the control parameters are those defining the shape of the cell, as the aspect ratio $\Gamma = D/H$, where H is the height and D the diameter of the cell, and two more specific ones, the Prandtl number Pr and the Rayleigh number Ra. $Pr = \nu/\kappa$, where ν is the kinematic viscosity, and κ the heat diffusivity, is characteristic of the fluid $Ra = \frac{g\alpha\Delta T H^3}{\nu\kappa}$ is the non-dimensional measure of the temperature difference $\Delta T = T_h - T_c$ between the hot (T_h) and cold (T_c) plates. g is the gravitational acceleration, and α the constant pressure thermal expansion coefficient. The thermal global response is given by the Nusselt number:$Nu = \frac{QH}{\lambda\Delta T}$ which compares the heat flux Q to the purely diffusive one $\lambda\Delta T/H$, where λ is the fluid thermal conductivity.

In the present work we examine a particular situation : the case of an asymetrical cell in wich the upper plate is smooth and the bottom plate is rough. In a Rayleigh-Bénard cell at high Rayleigh number, the bulk temperature is nearly uniform and the mean temperature gradient differs from zero only in the thin boundary layers close to the plates. The measure of this bulk temperature allows to separately determine the thermal impedance of each plate.

Experimantal set-up

The experiment is conducted using several cells filled with water. Details about the convection apparatus have been described in Tisserand et al. (2011) and here we mention only some key points. Two stainless steel cylinders of heights $H = 1m$(the tall one) and $H = 0.2m$ (the small one) are used as sidewalls of the convection cell. They have the same diameter $D = 50$ cm and thickness $2.5mm$. As the Rayleigh number (Ra) is proportional to the cube of the height H, measuring the Nusselt number in two different cylinders permits us to cover 4.5 decades of Ra (see figure 2). The top of the tall and small cells are provided by the same copper top plate. It is plated with a thin layer of nickel to prevent oxidation and it is cooled by temperature controlled water from a refrigerator circulator. The bottom plate, made of aluminium, differs from the top one in that it contains an embedded heater and the water-contact surface is rough. We have two kind of roughness consists in a square array of square plots, $d = 5mm$ of side, $h_o = 2mm$ in height, with a period of $2d = 1$cm (figure 1) and an omothethic one, with all the dimension multiplied of a factor 2.The measurement with the second kind of roughness are in progress. The height of the thermal boundary layers is equal to $h_o = 2$ mm when $Ra = 10^{11}$ for the tall cell and $Ra = 8.1^8$ for the small cell.

The temperatures of the two end plates are measured with type K thermocouples inserted in the plates and located at different points in order to check the temperature uniformity. The temperature of the bulk flow (Tb) is also measured (type K thermocouple) so that we can separately define $\Delta_r = 2\Delta_h = 2(T_h - T_b)$ and $\Delta_s = 2\Delta_c = 2(T_b - T_c)$. We can then assume that Δ_r is the temperature drop across a similar RB cell but with two identical rough plates, each of which behaves like the rough plate of our asymmetric cell. Likewise, Δ_s has the same behavior as the temperature drop across a symmetric cell with smooth cold and hot plates. Therefore we can define the rough and smooth Nusselt numbers as: $Nu_r = \frac{QH}{\lambda\Delta_s}$ and $Nu_s = \frac{QH}{\lambda\Delta_r}$. The main advantage of measuring Nusselt numbers in a non-symmetric cell is to test the influence of the bulk flow since the rough and smooth plates interact within the same large scale circulation.

Results

The first result is that the temperature of the bulk Tb is larger than the mean temperature $(T_b + T_c)/2$ and this difference increases with the Nusselt number, so that the quantity $\chi = \frac{T_b - T_c}{T_h - T_b}$ becomes larger than 1 [1]. As consequence the behavoir of the Nu_s and Nu_r behavior as function of Rayleigh will be different.

We choose to show them in a reduced form (i.e. divided by $Ra^{1/3}$) as function not of the Rayleigh number but of $Ra^* = NuRa$ in order to compare them properly (it doesn't change for rough and smooth case) and to put on the same graph the small and the tall cell. The corrected values for the smooth plate are shown in figure 1 as ${}^{red}Nu_s = Nu_s Ra_s^{-1/3}$. They are in good agreement with previous measurements in the same cell, where both plates are smooth, shown as stars in the same figure. This agreement has many important consequences. It validates the usual approximation of two separate thermal resistances (the boundary layers) with a bulk between them approximately uniform in temperature. For clarity of the results, it will be interesting to define a reduced Nusselt:

$$ {}^{red}Nu = \frac{Nu}{Ra^{1/3}} = (\frac{Nu}{Ra_*^{1/4}})^{4/3} \tag{1} $$

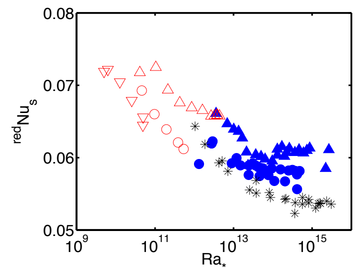

Figure 1. The reduced Nusselt number for the smooth plate. Open symbols: small cell. Full symbols: Tall cell. Up Triangles: $T = 70^o$C, $Pr = 2.5$. Circles: $T = 40^o$C, $Pr = 4.3$. Down Triangles: $T = 25^o$C, $Pr = 6.2$. Stars correspond to a previous work with symmetric smooth plates [2]. The shown error bars take into account our uncertainties on temperature and input power measurements.

In contrast, the rough plate results (figure 2) show a clear transition when the thermal boundary layer approximately matches the height of the grooves. It corresponds to a different value of Ra_* for each set of data, due to the different value of H in the tall cell (1m) and in the small cell (20cm). Note however, that we do not check the relative influence of the height and the period of the grooves. Before the transition, the Nusselt number is slightly reduced, compared to the smooth case, as in [**?**].

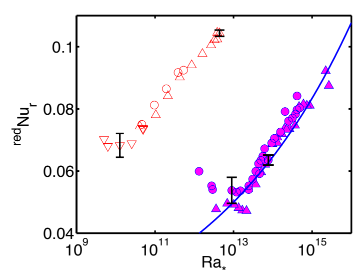

Figure 2. The reduced Nusselt number for the rough plate. The continuous line corresponds to $Nu \propto Ra^{1/2}$. Open symbols: small cell. Full symbols: Tall cell. Up Triangles: $T = 70^o$C, $Pr = 2.5$. Circles: $T = 40^o$C, $Pr = 4.3$. Down Triangles: $T = 25^o$C, $Pr = 6.2$. The shown error bars take into account our uncertainties on temperature and input power measurements.

CONCLUSIONS

We have carried out measurements of the Nusselt number as a function of the Rayleigh number in a Rayleigh-Bt'enard cell with a smooth upper plate and a rough lower plate. Measuring the temperature in the bulk flow permits us to define two Nusselt numbers separately: one for the smooth plate and one for the rough plate. Quite surprisingly, the Nusselt number based on the temperature of the smooth plate is perfectly consistent with previous measurements of Nu in a similar cell but with two smooth plates. In addition, the smooth plate seems insensitive to the rough plate behavior since the transition of the BL close to the rough plate is not detected in the results of the smooth plate. This confirms the poor influence of the large circulation flow on the behvior of both plates. The second main result reported in this paper is that the heat transfer enhancement observed in the case of a rough plate is not simply due to the increase of the wetted area, but grater.

References

[1] Tisserand, J.-C., Creyssels, M., Gasteuil, Y., Pabiou, H., Gibert, M., Castaing, B. Chill'a, F. 2011 "Comparison between rough and smooth plates within the same Rayleigh- Bt'enard cell". Physics of Fluids 23 (1), 015105?

[2] Chaumat, S. 2002 PhD thesis, Ecole Normale Suprieure de Lyon