ROUGHNESS-ENHANCED HEAT-FLUX IN TURBULENT THERMAL CONVECTION

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Turbulent thermal convection is an ubiquitous phenomenon in nature (atmosphere, ocean) and in industrial systems (heat exchanger, ventilation in buildings). To study this phenomenon, model systems can be used. One of the most extensively studied is the Rayleigh-Bénard cell. It consists in a fluid layer between two horizontal plates, heated from below and cooled from above. When the thermal forcing is strong, the flow induced by the temperature difference becomes highly turbulent. In this limit, the dynamics of the system is controlled by the thermal boundary layers where most of the temperature difference is located. For moderate thermal forcing with smooth plates, all experimental heat-flux measurements are consistent and relatively well understood.

For larger thermal forcing, the experimental heat-fluxes seem to highly depend on the details of the cell geometry and on the precise boundary conditions. To figure out how the boundary conditions act on the system, new experiments, in which a controlled roughness has been added, have been run recently in Lyon [1] and Hong Kong [2, 3]. They exhibit new heat-transfer regimes in which the heat-flux is enhanced. But the mechanisms are not well understood and there are quantitative variations between experiments that lack an interpretation.

To go beyond those discrepancies and find a model, we have been carrying out systematic measurements with various square-stud roughnesses in two cylindrical cells (height $H = 1\,\mathrm{m}$ and $H = 20\,\mathrm{cm}$ and diameter $D = 50\,\mathrm{cm}$). Those cells are asymmetric: the hot plate is rough and the cold plate smooth. The independence of both plates, which is experimentally verified, then allows *in situ* comparison of the heat-transfer regimes of the rough and the smooth cases.

The new roughnesses have the same proportions as the ones previously used [1], with dimensions twice larger (the new height is $h_0 = 4\,\mathrm{mm}$ versus $h_0 = 2\,\mathrm{mm}$ in the previous setup). Our aim is to compare the results obtained in those setups. The little roughnesses show a transition for the heat-transfer of the rough plate, whereas no transition appears with the smooth one. The transition occurs when the height of the thermal boundary layer reaches the height of the roughness. This transition is independent of the aspect ratio of the cell.

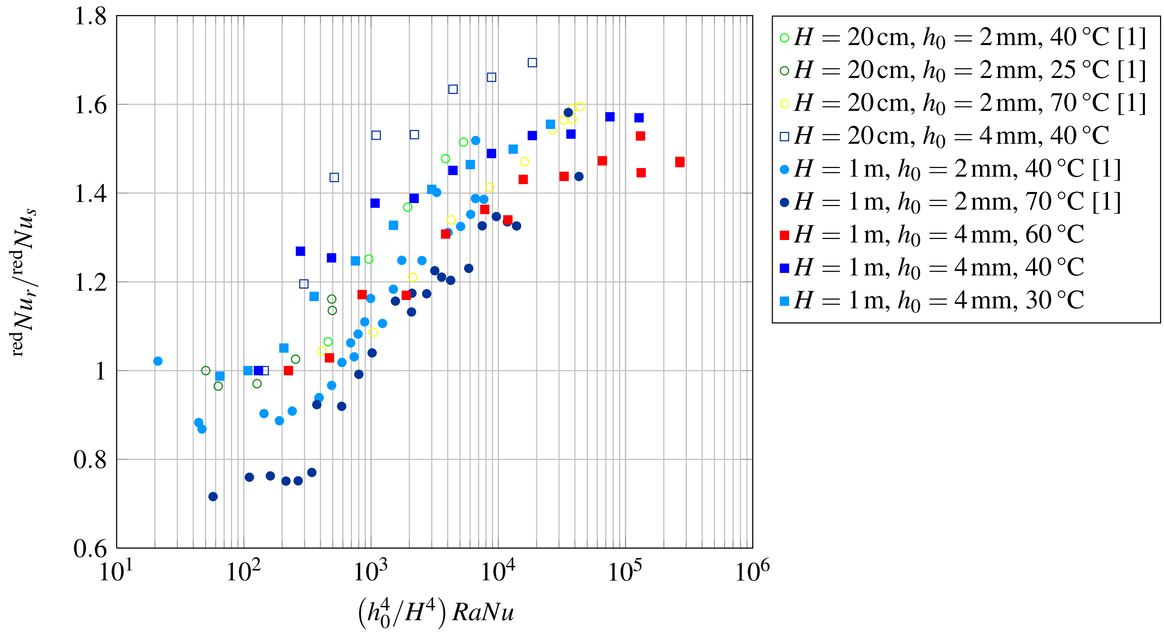

Figure 1. Heat-transfer enhancement versus dimensionless power normalized by h_0. In these units, the transitions to the enhanced regime fairly collapse.

The large roughness cells show a saturation plateau at high thermal forcing for the rough plates. But, again, there is no transition on the smooth plate. The plateau seems to be independent of the aspect ratio. The comparison between those two sizes of roughness seems to reveal the existence of a characteristic length which is the height of the roughness. However, this length does not seem to be enough to fully collapse all data. It seems likely that the horizontal length scales may also play a role.

The common point of all the measurements is an enhancement of the thermal heat-transfer more than what is expected by the surface increase. In the large roughness case the heat-transfer enhancement reach 70%, with only 40% of surface increase (see figure 1).

To go beyond the global heat-flux discrepencies, we turned to local features of the flow. We use a miniature thermistor (400 μm diameter), located on the central vertical axis, of a cubic 40 cm × 40 cm × 10 cm PMMA half-rough convection cell ($h_0 = 2$ mm), to characterize the high flux regime. In particular, we investigate the amplification mechanism: does it originate from a buoyancy instability inside the notches or from changes in the boundary layer structures? This analysis is carried out through the measurement of the local temperature at several locations near the roughnesses: above a roughness, inside a notch or along the groove, compared to the temperature statistics on the smooth plate.

The boundary layer thickness in our system is very thin, less than 500 μm. It is therefore not possible to measure profiles nor to directly measure its thickness. One alternative is to use the evolution of the shape of the local temperature histograms [4]. This shows that the boundary layer is much thinner on top of a plot than it is on the smooth plate. One possible explanation is that the boundary layer does not have enough length to develop on the plots. This could lead to a smaller temperature impedance.

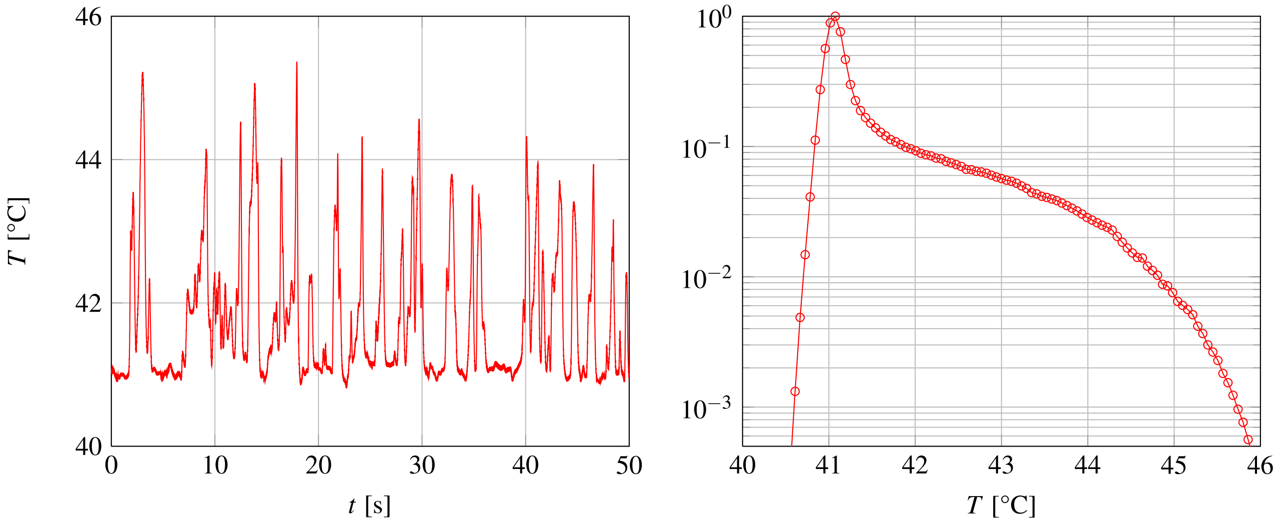

Figure 2. Temperature signal and temperature histograms recorded 3 mm above a plot. The Rayleigh number is $Ra \approx 5 \times 10^{10}$. The shape of the histogram is typical of a position close but above the boundary layer.

References

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