

## THE HEAT TRANSPORT IN TURBULENT RAYLEIGH-BÉNARD CONVECTION: LOCAL SCALING EXPONENTS

Robert Kaiser & Ronald du Puits

*Technische Universität Ilmenau, 98693 Ilmenau, Germany*

**Abstract** Using infrared thermography, the dimensionless local wall heat flux  $Nu(x, y)$  has been measured with high spatial resolution. The measurements at the heating plate of a cubic Rayleigh-Bénard cell show that the scaling exponent  $\alpha$  in the  $Nu \propto Ra^\alpha$  scaling law depends on the position with respect to the surface. The results have been obtained in a small aspect ratio cell with  $\Gamma_x = 1, \Gamma_y = 0.26$  and clearly show an effect of the sidewalls on the local and therefore also on the global scaling of the heat transport.

### INTRODUCTION

Thermal convection is an omnipresent process in nature and industry. The Rayleigh-Bénard set-up is a model to study buoyancy driven flows actuated by a temperature difference. In this set-up, a fluid layer is confined between two horizontal plates, while the bottom plate is heated and the top plate is cooled. The entire set-up is fully described by three dimensionless parameters. The ratio of buoyancy and molecular diffusivity is given by the Rayleigh number. The fluid properties are characterized by the Prandtl number, which is the ratio between the kinematic viscosity and the thermal diffusivity. The aspect ratio defines the horizontal dimension of the convection cell with respect to the vertical dimension. In the present discussion, we are focussing on the heat transport, which is expressed as the Nusselt number and describes the convective heat flux compared to the case of pure conduction.

The local distribution of the heat flux plays a crucial role in understanding global processes. Therefore, Lui et al.[1] performed measurements of the local thickness of the thermal boundary layer near the heating plate, which can be interpreted as an inverse of the local heat flux. The conclusion is a strongly non-uniform distribution of the local thickness. Motivated by this work, du Puits et al.[2] conducted direct measurements of the local wall heat flux in the center of the heating and the cooling plates. A comparison with global heat flux measurements in cryogenic Helium reveals an enhanced local heat flux of up to 300 % [3].

It is obvious that an analysis of the two-dimensional distribution of the local heat flux is needed. In the following we will describe our convection facility and applied measurement technique. The measurement results are presented in the last section.

### EXPERIMENTAL SET-UP

The analysis of the local wall heat flux is performed in our large-scale convection facility, called the Barrel of Ilmenau. In order to confine the large-scale motion, a rectangular convection cell, made of acrylic glass, is assembled inside this facility. The working fluid is air at ambient pressure with a constant Prandtl number of  $Pr = 0.7$ . A detailed description of the convection cell is given in Kaiser et al. [4]

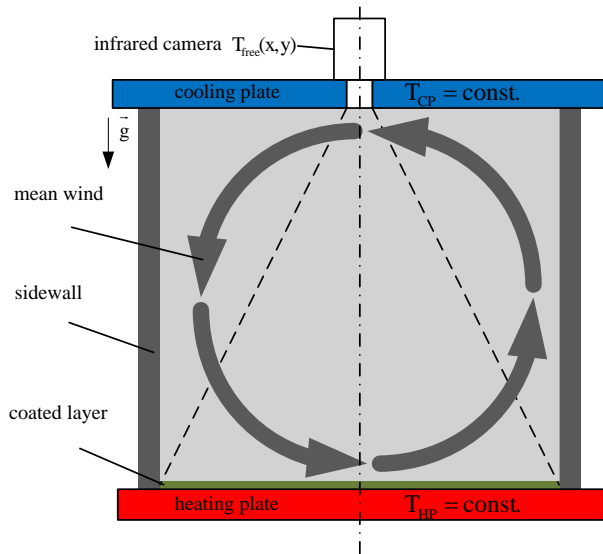
The measurements of the local wall heat flux  $Nu(x, y)$  at the bottom plate are conducted using infrared thermography. In order to visualize the thermal footprint of the near plate flow field, a thin layer of well-known heat conductivity  $\lambda_l$  is coated on the heating plate. While the lower surface of this layer is in perfect thermal contact with the temperature regulated heating plate  $T_{HP}$ , the free surface can follow the temperature of the flow. Using an infrared camera, the temperature distribution of the free surface  $T_{free}(x, y)$  is measured through a window in the cooling plate, see figure 1. Based on the material properties of the layer, a map of the local wall heat flux is computed:

$$Nu(x, y, t) = \frac{\lambda_l(T_{free}(x, y, t) - T_{HP})}{\lambda_{air}(T_{CP} - T_{HP})} \frac{H}{d} \quad (1)$$

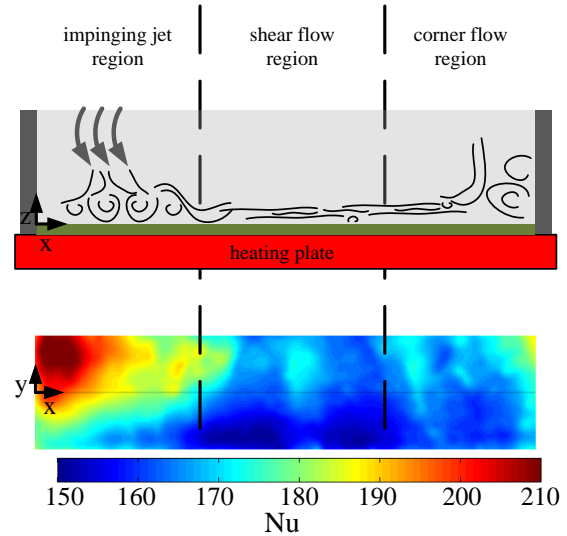
$\lambda_{air}$  is the heat conductivity of the fluid at the averaged temperature of the heating and the cooling plate.  $T_{CP}$  is the temperature of the cooling plate.  $H$  is the height of the fluid layer and  $d$  is the thickness of the coated layer on the heating plate. Due to an *insitu* calibration using thin-film heat flux sensors, the total measurement uncertainty amounts to 7%. Further information is given in [4].

### RESULTS

The local wall heat flux distribution is investigated in a parameter domain of  $10^{10} \leq Ra \leq 5.5 \cdot 10^{10}$ . Figure 2 shows the time averaged distribution of the Nusselt number  $\langle Nu(x, y) \rangle_t$  at  $Ra = 4.09 \cdot 10^{10}$ . The strong variation of the local Nusselt number of up to 30% of the spatial and temporal mean value is a typical feature in the investigated parameter range. It is a direct consequence of the flow field at the surface of the bottom plate which was recently investigated by



**Figure 1.** Experimental set-up of the two-dimensional heat flux measurement inside the rectangular convection cell  $\Gamma_x = 1$  and  $\Gamma_y = 0.26$



**Figure 2.** Sketch of the near plate flow field and the time averaged distribution of the wall heat flux on the heating plate in a rectangular convection cell measured at  $Ra = 4 \cdot 10^{10}$

Willert et al 2014 [5].

In the region of downward motion, a strong impingement of the mean wind on the heating plate becomes visible, which mixes the fluid close to the plate surface very well. This mixing enhances the heat flux, see figure 2. Again, on the path of the large-scale circulation, the boundary layer flow in the shear flow region alternates between laminar and turbulent phases. At the opposite corner the flow rises due to the deflection at the sidewall and one or, sometimes two corner vortices develop. Based on this observation, the heating plate is divided into three subdomains with an inherent flow characteristic. The global heat transport, in terms of the local Nusselt number scalings, can be written as:

$$Nu_{global} = \frac{1}{3}Nu_{jet} + \frac{1}{3}Nu_{shear} + \frac{1}{3}Nu_{corner} \quad (2)$$

The measurements are still in progress and final results will be presented during the conference.

## References

- [1] S.L. Lui, K.Q. Xia. Spatial structure of the thermal boundary layer in turbulent convection. *Phys. Rev. E* **57**: 5494-5503, 1998.
- [2] R. du Puits, C. Resagk, A. Thess. Measurements of the instantaneous local heat flux in turbulent Rayleigh-Bénard convection. *New. J. Phys.* **12**, 2010.
- [3] J.J. Niemela, K.R. Sreenivasan. Confined turbulent convection. *J. Fluid Mech.* **481**:355-384, 2003.
- [4] R. Kaiser, R. du Puits. Local wall heat flux in confined thermal convection. *Int. J. Heat Mass Tran.* **73**:752-760, 2014.
- [5] C. Willert, R. du Puits, C. Resagk. Investigation of the turbulent boundary layer in high Rayleigh number convection in air using long PIV sequences. In *Proceedings of the Int. Symp. on Applications of Laser Techniques to Fluid Mechanics*, Lisbon, Portugal, 07-10 July, 2014.