Near-wall heat transport in turbulent Rayleigh-Bénard convection in air

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Simultaneous measurements of velocity and temperature in a convective boundary layer have been undertaken to characterize the near-wall heat transport in turbulent thermal convection. In a large-scale Rayleigh-Bénard experiment, known as the ‘Barrel of Ilmenau’, Laser Doppler Velocimetry (LDV) was used in combination with an ultra-small microthermistor of 125 μm size to measure the diffusive and the convective fraction of the near-wall heat flux \( q = q_d + q_v = -\lambda \frac{dT}{dz} + c_p \varphi (w^+ T^-) \) (\( q_d \) – diffusive heat flux, \( q_v \) – convective heat flux, \( \lambda \) – heat conductivity, \( T \) – temperature, \( z \) – wall-normal coordinate, \( c_p \) – specific heat capacity at constant pressure, \( \varphi \) – density, \( w \) – wall-normal velocity component). Time series of the wall-normal velocity component and the temperature have been measured at various distances from the wall and the profile of the wall-normal heat flux component \( q(y) \) has been analyzed. The measurements clearly show that, even at a very moderate Ra numbers as low as Ra = 3 \times 10^{10}, convection dominates the heat transport adjacent to the wall.

Experimental set-up and measurement technique

We study the convective heat transfer in a large-scale Rayleigh-Bénard (RB) experiment which is called the ‘Barrel of Ilmenau’. It meets two important criteria, a very high Rayleigh number of \( Ra_{max} = 10^{12} \) and a large size of 7.15 m in diameter and 6.30 m in height. The particular advantage of this extra-large facility is the fact that the boundary layer is of the order of tens of millimeters (depending on Ra) which permits a maximum of spatial resolution of all measurements compared to any other RB facility in the world. A 1-d Laser Doppler Velocimeter and a microthermistor have been used to measure the wall-normal velocity component \( w \) and the temperature \( \theta \) simultaneously at various distances \( z \) from the lower surface of the cooling plate.

Fig. 1 Set-up of the simultaneous measurements of the wall-normal velocity component and the temperature

The measurement volume of the LDV (about 70 μm x 500μm in size) was aligned beside the thermistor with respect to the orientation of the mean wind. The distance between the centers of the LDV measurement volume and the temperature sensor is adjusted to be smaller than 300 μm which is about one third of the minimum Kolmogorov length scale in our experiment.

Results

We have measured profiles of the diffusive and the convective fraction of the total wall-normal heat flux in the fluid layer adjacent to the cooled top plate. According to eq. 1 in Figure 2 the profiles of the diffusive heat flux \( q_d(z) \) and the convective heat flux \( q_v(z) \) at the maximum Rayleigh number \( Ra = 9 \times 10^{11} \) are plotted.

Beyond the viscous sub-layer \( y^+ > 10 \) convection dominates the heat transport inside the boundary layer. The reason for that is the fact that a multitude of coherent structures like vortices, spirals, sheet-like and mushroom-like plumes etc. are contained in the, highly turbulent, mean wind. Moving along the plate surface they penetrate into the boundary layer, mix it, and carry heat either away from or towards the plate surface. This phenomenon has also been shown in flow visualization that has been published in the Gallery of Fluid Motion recently [2].

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