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Ultimate states of turbulent thermal convection and shear flow

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Abstract. Turbulent heat transfer is reviewed for thermal convection (or shear flow) between horizontal (or parallel) permeable walls. It is shown that wall permeability can lead to the so-called ultimate state in which a wall heat flux is independent of thermal diffusivity or kinematic viscosity. In the ultimate state of thermal convection (or shear flow) between permeable walls, large-scale thermal plumes (or spanwise rolls) are induced even in the vicinity of the walls. These large-scale thermal and flow structures fully extend in the fluid layers, yielding the ultimate heat transfer.

Keywords: Turbulence, Thermal Convection, Wall-Bounded Shear Flow, Heat Transfer

If there is a difference in temperature between bulk fluid and a wall surface in wall-bounded turbulent flows, heat will be transferred between the fluid and the wall. Such heat transfer is dominated by thermal conduction on the wall where turbulent heat flux is null, although it highly depends on turbulence characteristics. In this talk, turbulent heat transfer in wall-bounded thermal convection and shear flow is discussed with emphasis on the so-called ultimate state in which a wall heat flux is independent of thermal diffusivity, i.e. conduction anomaly (or anomalous thermal dissipation), while energy dissipation is independent of kinematic viscosity, i.e. the Taylor dissipation law implying the inertial energy dissipation or anomalous energy dissipation.

In the first part of this talk, the classical scaling widely observed in turbulent Rayleigh-Bénard convection is reviewed to differentiate the ultimate state from the classical state. Feasibility of the ultimate heat transfer is then explored numerically [1]. Wall permeability, which can be implemented on a porous wall, is introduced in Rayleigh-Bénard convection. It is found that in thermal convection between the horizontal permeable walls, the ultimate heat transfer can be achieved at high Rayleigh numbers. We discuss the reason why the wall permeability can lead to the ultimate scaling in wall-bounded convective turbulence. In the ultimate state large-scale thermal plumes are induced by buoyancy in the close vicinity of the walls, yielding intense transpiration velocity. The ultimate heat transfer is attributed to such large-scale significant fluid motion.

In the second part, we further pursue the ultimate heat transfer numerically in turbulent channel flow by introducing the wall permeability [2]. The ultimate heat transfer can be accomplished even in shear flow between the parallel permeable walls at high Reynolds numbers. In the ultimate state large-scale spanwise rolls appear from the Kelvin-Helmholtz instability [3], significantly enhancing near-wall heat transfer without flow separation. The large-scale turbulence structures with similarly strong velocity and temperature fluctuations bring about the ultimate heat transfer.

In the last part, it is demonstrated that the ultimate heat transfer can be achieved in realistic configurations by numerical simulation and experiment of turbulent thermal convection between horizontal porous walls. At low Rayleigh numbers, vertical (wall-normal) fluid motion is not excited in the near-wall region despite wall permeability, so that the classical state can be observed. At high Rayleigh numbers, however, large-scale thermal plumes appear even near the walls from convective instabilities of near-wall thermal conduction layers to intensify the vertical heat flux, leading to the ultimate state. In between these two distinct scaling ranges of the Rayleigh number, we have found super-ultimate behaviour represented by the heat flux significantly exceeding that in the ultimate state. This super-ultimate scaling is considered to be a consequence of full excitation of large-scale thermal plumes comparable with those in the ultimate state at the high Rayleigh numbers and of less energy dissipation in the flow through porous walls than in the ultimate state at the high Rayleigh numbers.

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