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Lagrangian measurements in turbulent thermal convection: about the inhomogeneity of the velocity and temperature fields

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Abstract

Turbulent thermal convection is a complex problem: the flow is forced at almost all scales, because of the presence of both large scale circulation and small scale plumes. Moreover the difference of density induced by temperature adds an ingredient in the basic equations of the flow, so that turbulence could be different from the case of pure mechanical forcing. Mixing is in principle different and probably increased because of the structure of the plumes. Moreover the entire flow is not homogeneous (at least at large scales) and the statistical behaviour can be influenced by the large scale flow. One way to probe all these specific effects is to use a Lagrangian point of view, measuring, for example, Lagrangian transport of velocity and temperature, or heat flux. We will show how the inhomogeneity of the mean temperature and velocity fields affect the heat flux. Then the interactions between the mean fields and the Lagrangian fluctuations will be highlighted.

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Keywords: Turbulence; thermal convection; buoyancy-driven flows; heat flux; Lagrangian tracking; flow inhomogeneity.

1. Introduction and experimental set-up

1.1. Introduction

Turbulent thermal convection is ubiquitous in nature. Lots of geophysical (atmospheric circulation) or astrophysical (star convection) buoyancy-driven flows are due to natural temperature differences. Turbulent thermal convection has also a high industrial interest as for process cooling or in chemical reactors. Although this problem has been studied for several decades [1,2], understanding the global and local properties of this turbulent flow is still a challenge [3]. One of the model system used in laboratories is the Rayleigh-Bénard cell. A horizontal layer of fluid is confined between a hot bottom plate and a cold top one. The mixing induced by turbulence confines the temperature gradients in two thermal boundary layers close to the horizontal plates and the mean temperature field is quite homogeneous in the bulk. Coherent structures called thermal plumes form from instabilities of the boundary layers. The thermal

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forcing is measured with the Rayleigh number $Ra = g\alpha H^3 \Delta T/\nu\kappa$, where g is the acceleration due to gravity, H is the height of the convection cell, $\Delta T = T_h - T_c$ is the temperature difference between the two plates, α is the thermal expansion coefficient of the fluid, ν its kinematic viscosity and κ its thermal diffusivity. The Prandtl number compares the dissipative effects: $Pr = \nu/\kappa$. When the system is thermally forced, its response can be measured with the Nusselt number $Nu = QH/\lambda\Delta T$ where λ is the thermal conductivity of the fluid and Q the global heat flux. During the last decades, most of studies about turbulent thermal convection have adopted an Eulerian point of view to study the velocity and temperature distributions [4,5,6], trying to characterize the local heat flux. Because of the inhomogneity of both velocity and temperature distributions in Rayleigh-Bénard convection [5,7], the connection between space-domain predictions and time-domain measurements remains difficult. That is why, with the help of the computing resources increase, some Lagrangian experiments and numerical simulations have started to appear, both in classical turbulence [8,9,10,11,12,13] and convective turbulence. This approach can bring some significant advances to our comprehension of transport processes [14]. In turbulent convection Lagrangian studies are quite sparse. Schumacher's numerical simulation [15,16] have focused on thermal flux, acceleration statistics and pair dispersion. The first Lagrangian experiment were made using an instrumented particle [17] immersed in the convection cell [18]. This method allows to measure both Lagrangian velocity and temperature. Ni *et al.* [19,20] have performed the first particle tracking velocimetry in thermal convection using hundreds of sub-millimetric particle. This study is the development of recent works [21] using an improved instrumented particle with an increased autonomy. We have good enough statistics to have a good sampling of the cell (including the low-velocity center). The mean flow and temperature field appear to be largely inhomogeneous as shown by mean pseudo-Eulerian fields. This leads us to separate the flow in different specific zones to isolate different behaviours, particularly about the heat flux. Then we study the coupling between the large scale fields and the Lagrangian turbulent fluctuations.

1.2. Convection cell and measurement method

The convection cell consists in a parallelepipedic tank of 41.5 cm in width, 41.5 cm in height and 10.5 cm in depth filled with deionized water (see figure 1 (b)). More details are available in Liot *et al., JFM* (2016) [21]. We impose a constant heat flux of 300 W at the bottom plate with a Joule-heating system and the temperature of the top plate is regulated with a water circulation. The mean temperature is fixed at 38.4°C. The resulting Rayleigh number is 5.0×10^{10} and the Prandtl number is $Pr = 4.5$. The resulting Nusselt number reaches about 240. The thermal boundary layer thickness can be estimated by considering the heat flux conservation: $\delta_\theta = H/2Nu$. Here δ_θ is about 0.9 mm. Using the Prandtl-Blasius theory [22] we can estimate the viscous boundary layer thickness to about 1.4 mm.

Our Lagrangian sensor consists in a 2.1 cm in diameter particle with four thermistors embedded (see figure 1) whose density is matched with the water one with an error less than 0.005%. Considering the size of the boundary layers, the particle never goes into the boundary layers and explores only the bulk. The inner particle contains a radio-frequency transmitter, two industrial batteries and an electronic circuit which computes the mean temperature measured by the thermistors before modulating it for on-the-fly transmission. The thermistors consist in cylindrical temperature-sensitive resistors (length of 0.8 mm, diameter of 0.4 mm, response time of 0.6 s in water). The batteries act as a ballast so that the thermistors remain in a horizontal plane, the particle can rotate only around the vertical axis. The instrumented particle is the one described in Liot *et al.* (2016) [21] which is an improvement of the first instrumented particle used by Gasteuil *et al.* (2007) [18]. The battery life can reach more than twenty hours (about 1000 flow turnover times). The resulting statistics is enough to have a good sampling of the whole flow. The temperature signal is received on-the-fly by an antenna placed close to the cell. Simultaneously a digital camera captures the position of the particle in the cell. Since the cell depth is largely thinner than the other cell dimensions, the mean flow can be considered as quasi bi-dimensional. This justifies the use of only one camera in front of the large plane of the cell to track the particle. Finally the Lagrangian temperature can be measured along the particle trajectory.