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STATISTICAL PROPERTIES OF THERMAL PLUMES IN TURBULENT RAYLEIGH-BENARD CONVECTION WITH A ROUGH PLATE

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<u>Summary</u> A comparative study of the plume dynamics near the rough and smooth horizontal plates of a water-filled asymmetric Rayleigh-Bénard cell is presented. Direct numerical simulations are performed over a large range of Rayleigh numbers (from 10^5 to 10^{10}) in order to cover the three heat transfer regimes. Several techniques of plume feature description are used to highlight how roughness changes the dynamics of plume emission and the energetic content of plumes.

MOTIVATION

In a real thermal system, the underlying surfaces involve specific topographies or small-scale roughness which have a significant impact on the heat transfer. Particularly, in the case of turbulent convection, the addition of wall roughness results in a global heat transfer enhancement and in some cases, in an increase of the exponent of the heat transfer scaling law ($Nu \sim Ra^{\beta}$, Nu Nusselt number, Ra Rayleigh number) [1, 2]. It is commonly admitted that the heat transfer enhancement originates from an intensification of the thermal plume emission at the tips of roughness elements [3].

In classic turbulent Rayleigh-Bénard convection, previous studies have shown the role of thermal plumes in the heat transport within the cavity [4]. Several techniques of plumes description have been proposed to characterize plumes in terms of geometry, number, intensity or velocity. They can be based on the post-processing of a temperature field determined from thermochromic liquid crystal microspheres [5], on the identification of temperature threshold in numerical snapshots [6], on the analysis of cliff-ramp structures in local time series [7], or on shadowgraph treatment [8].

In the present numerical study, we consider convection over a regularly roughened plate in a Rayleigh-Bénard cell. The three successive heat transfer regimes, previously observed in this kind of configuration (see for example [1]), are modelled from inactive roughness (regime I) to a regime (called III) where the relative heat transfer increase is larger than the relative surface increase induced by roughness addition. The objective of this work is to identify how roughness changes the plume features and their dynamics, depending on the regime.

NUMERICAL SET-UP

We study the fluid flow occurring in an asymmetric 3D Rayleigh-Bénard rectangular cell filled with water. The cell is heated from below by an isothermal rough plate, modeled by a set of square-based obstacles as sketched on figure 1. Sizes of the roughness elements share some common geometric features with the Lyon's experiments [9, 2] such as aspect ratios or distribution, but we retain a larger roughness height ($H_r/H = 0.03$, H cavity height) in order to trigger the first transition between the heat transfer regimes I and II to a lower Ra.

The Navier-Stokes equations are solved under the Boussinesq approximation. The parallel numerical solver (SUN-FLUIDH code) uses a finite volume discretization on staggered grids. The time marching is treated by a semi-implicit scheme combined with a prediction - correction scheme for the velocity - pressure coupling, with a global second-order accuracy. The code has been validated for the classic turbulent Rayleigh-Bénard convection by comparison with the DNS data [10]. Numerical simulations are performed for a large range of Rayleigh numbers in order to cover the three heat transfer regimes ($10^5 \le Ra \le 10^{10}$). We use meshes from $1.3 \cdot 10^6$ to $5 \cdot 10^8$ cells in order to ensure a sufficient space resolution. The computational domain is decomposed into 256 to 2048 subdomains depending on the considered *Ra* number. The convergence in space and time has been *a posteriori* checked by testing the convergence of several formulations of the time-averaged Nusselt number.

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Figure 1: Instantaneous flow vizualisation at $Ra = 10^6$, $5 \cdot 10^7$ and $2 \cdot 10^9$, respectively belonging to regimes I, II and III. Colour indicates the thermal dissipation field.

RESULTS

Taking advantage of the cavity asymmetry, we conduct a comparative study of the plume dynamics near the rough and smooth horizontal plates within the same Rayleigh-Bénard cavity for the three regimes of heat transfer.

First, we consider more specifically three particular Ra numbers, each belonging to a different regime (figure 1). The time monitoring of a set of probes recording temperature or vertical velocity, and located near the rough and smooth plates, shows how roughness alters the statistical properties of thermal plumes. In agreement with the experiments (see for example [3, 4, 9]), intense temperature fluctuations are observed more frequently near the rough plate than near the smooth plate, especially in the intermediate regime II. Concurrently, the largest vertical velocity fluctuations are found near the smooth plate rather than around the rough one. In addition, instantaneous characteristics of thermal plumes such as amplitude (in terms of local increment) or width (equivalent to a transit time) can also be calculated from the time series, following the [7] methodology. As expected, log normal distributions are generally recognized in the PDFs of the plume features. However, a noticeable change is observed in regime II, with a more frequent detachment of high energy plumes close to the rough plate, both in terms of potential and kinetic energy.

Finally, we make use of space-time diagrams [8] to quantify the spatio-temporal dynamics of the thermal plumes. An increase of the plume number with Ra is observed on both sides of the cavity for all regimes. Although a similar plume distribution near the smooth and rough plates is found in regime I and III, we show that a strong asymmetry between the two horizontal plates is established in regime II with a significant increase of the number of plumes close to the roughness. Moreover, we note in this regime the presence of highly dissipative structures not only near roughness but also within the bulk of the cavity (as seen on figure 1).

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