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Large-scale flow properties of turbulent thermal convection

S. Ciliberto,* S. Cioni, and C. Laroche
Ecole Normale Supérieure de Lyon, Laboratoire de Physique, CNRS URA No. 1325, 46, Allée d'Italie 69364 Lyon Cedex 07, France
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The influence of large-scale flow on heat transport in turbulent thermal convection is experimentally investigated. Large-scale flow couples the upper and lower thermal boundary layers. This coupling produces a slow coherent oscillation of the temperature field and strongly influences the spatial distribution of temperature fluctuations. Moreover, when the large-scale flow is either suppressed or strongly modified no significant variation of the heat transport across the cell is observed. [S1063-651X(96)51012-3]

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Turbulent thermal convection in a fluid layer heated from below, that is, Rayleigh-Benard convection, presents several open problems which are not yet very well understood [1]. One of these is the role played by the mean circulation flow on the heat transport properties. This mean circulation flow consists of a large-scale convective roll which involves all the cell containing the convective fluid, thus it behaves like a large coherent structure of the turbulent flow. Its presence in turbulent Rayleigh-Benard convection was first noticed by Howart and Krishnamurty [2] but its importance on the heat flow has been pointed out only more recently [3–5]. There is now a general agreement that the large-scale flow strongly perturbs the thermal boundary layers [5]. However, it is not yet clear how this perturbation actually occurs. For example, one can ask whether the mean flow influences more either the mean temperature profile or the temperature fluctuations close to the boundaries. Furthermore, it is unclear whether the mean flow transports a relevant amount of heat and whether it couples the upper and lower thermal boundary layers, as recently proposed by Villermaux [6]. Several of these questions have been analyzed in a very smart experiment [7] in which one of the two boundary layers was perturbed by a large-scale horizontal flow. In another recent experiment [8] the boundary layers were instead perturbed by increasing the roughness of the horizontal plates. However, in those experiments, the large-scale vertical flow was always present; thus, a clear answer to the above mentioned questions could not be given. In this paper we report several results of an experiment in which the large-scale flow is directly perturbed in order to study its influence on the thermal boundary layer and on the heat transport properties. We find that the spatial distribution of the temperature fluctuations at the boundaries is strongly modified when the large-scale flow is suppressed near the boundaries and the two boundary layers are decoupled. However, no significant difference in the heat flow is observed. These features have been studied as a function of the Rayleigh number $\mathrm{Ra}=\alpha g d^3 \Delta T/(\nu\chi)$, where α is the thermal-expansion coefficient, g the gravitational acceleration, ΔT the temperature drop across the fluid layer, d the height of the layer, ν the kinematic viscosity, and χ the thermal diffusivity.

*Also at Department of Physics, University of Florence, Florence, Italy.

The experimental apparatus has been already described in Ref. [9], thus we mention here only the main characteristics. In Fig. 1 a schematic drawing of the cell is reported. The cell has horizontal sizes $L_x=40$ cm and $L_y=10$ cm and three different heights d equal to 40, 10, and 6.5 cm. With these three cells filled with water (at an average temperature of 45 °C corresponding to a Prandtl number, $\mathrm{Pr}=\nu/\chi$ of about 3) we were able to cover the interval $10^6<\mathrm{Ra}<10^{11}$ (specifically for $d=6.5$ cm $10^6<\mathrm{Ra}<10^8$, for $d=10$ cm $10^7<\mathrm{Ra}<10^9$, for $d=40$ cm $10^{10}<\mathrm{Ra}<10^{11}$). The bottom plate of the cell was made of a very thick copper plate heated with an electrical resistor. The top copper plate was cooled by a water circulation and its temperature was stabilized by an electronic controller. The vertical walls were made of plexiglass. All the apparatus was inside a temperature stabilized box. The temperature of the plates was measured in several locations indicated by Fig. 1(a)–1(h). Local temperature measurements of the turbulent flow were done with two

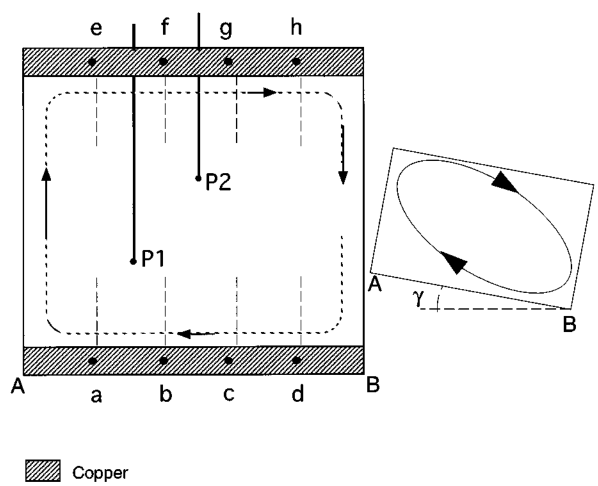

FIG. 1. Schematic drawing of the convective cell. The points $(a,\ldots,h)$ indicate the positions of the thermistors inside the copper plates. The thermocouples that can be moved vertically are indicated by $(P1,P2)$. The vertical dashed lines indicate the position of the thin plexiglass screens. The arrows schematically indicate the direction of the mean flow when the screens are not mounted. The mean flow is limited in the central region when the screens are mounted and it cannot extend till the two thermal boundary layers close to the horizontal plates.

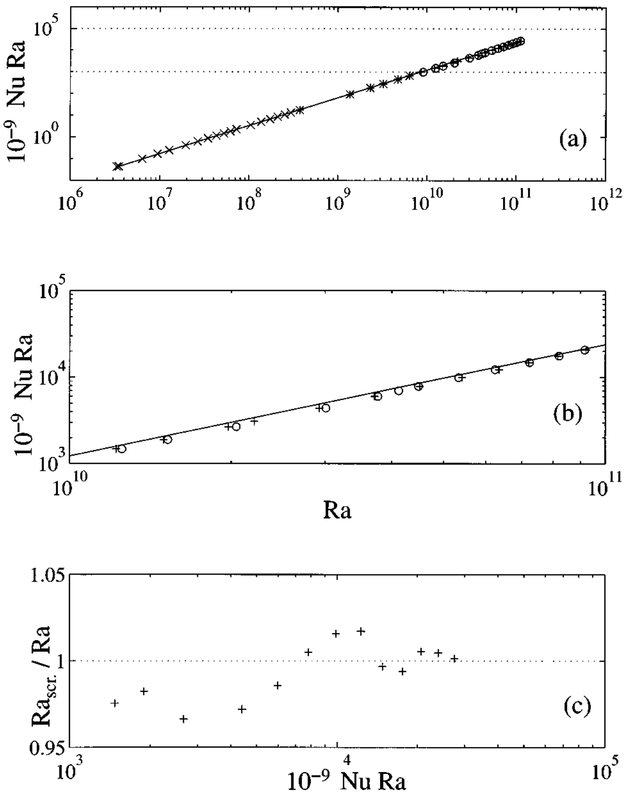

FIG. 2. (a) Dependence of the nondimensional heat flow NuRa as function of Ra in the range $(3.5\times10^{6}<\mathrm{Ra}<1.1\times10^{11})$: (x) data from Chillá *et al.* [9], (*) data from Cioni *et al.* [11]. Data of the present experiment (o) with screens, (+) without screens (see text). The fit represented in the figure corresponds to the ensemble of the data. The slope of the best fit line is 1.28 ± 0.01. The two horizontal dashed lines indicate the region where the properties of the mean flow have been studied. An expanded view of this region is shown in (b). (c) Ratio $\mathrm{Ra}_{scr}/\mathrm{Ra}$ as a function of NuRa. Here Ra_{scr} indicates the value of Ra measured with the screens.

small thermocouples ($P1$, $P2$) of 0.04 cm in diameter with a response time of 5 ms. The position of the temperature probes is indicated in Fig. 1. The probes $P1$ and $P2$ were located at $(L_x/4, L_y/2)$ and at $(L_x/2, L_y/2)$, respectively. Both probes could be moved along z with micrometric devices in order to measure, as a function of Ra, the profile of the mean temperature and of the temperature fluctuations. We have studied the influence of the large-scale flow on the following features of the turbulent thermal convection: the vertical mean temperature profile $T(z)$, the profile of the temperature fluctuation rms $\delta(z)$, and the nondimensional heat flow NuRa, where Nu is the Nusselt number (i.e., the total heat flux divided by the conductive one).

To measure the heat flow we first estimated the heat losses of the cell [9]. These heat losses were then subtracted from the heating power to evaluate the fraction of heat Φ_c effectively transported by the convective water. The nondimensional heat flow NuRa is given by $\Phi_c \alpha g d^4/(\lambda \nu \chi)$, where λ is the thermal conductivity of water [10]. The values of NuRa, measured in different cells and geometries, are plotted versus Ra in Fig. 2(a). All the data are well fitted by a single power law, $\mathrm{Nu}\simeq(0.19\pm0.04)\mathrm{Ra}^{0.28\pm0.01}$, showing a negligible dependence on the aspect ratio. In Fig. 2(b), we report an expanded view of Fig. 2(a) in the range of Rayleigh, $1.5\times10^{10}<\mathrm{Ra}<1.1\times10^{11}$ ($d=40$ cm), where the influence of the mean flow has been studied. A direct measurement of the mean flow velocity V_0 shows that $V_0=2$ cm/s, at $\mathrm{Ra}\simeq5\times10^{10}$ and at $d/8=5$ cm from the bottom plate. We have studied in detail the influence of the mean flow on the thermal properties mainly in the highest cell (aspect ratio $\Gamma_x=L_x/d=1$, $d=40$ cm), but we have seen that the characteristics of the mean flow are similar also at larger aspect ratio ($\Gamma_x=6$, $d=6.5$ cm) [9] and in different geometries [11].

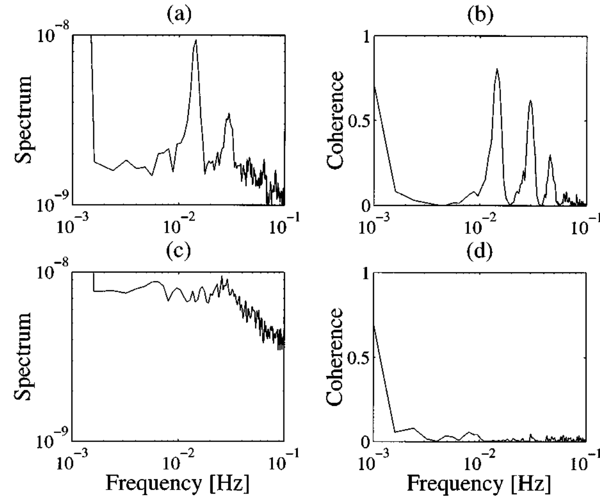

FIG. 3. Spectra (a),(c) and coherence functions (b),(d) of the temperature signals recorded at $\mathrm{Ra}=6.4\times10^{10}$ ($d=40$ cm) by the probes $P1$ and $P2$. $P1$ was located at $d/9\simeq45$ mm from the bottom plate, whereas $P2$ was 45 mm from the top. Only the low frequency part of the spectra is shown. The whole spectrum extends to roughly 10 Hz. (a) and (b) correspond to measurements done when the mean flow was present, whereas (c) and (d) correspond to measurements done when the mean flow was suppressed by the screens.

One of the main features, which is usually associated with the mean flow, is the presence of a coherent oscillation of the temperature field inside the cell [4]. The frequency of this oscillation can be measured using the power spectra of the local temperature signals detected by the probes $P1$,$P2$. As an example we show in Fig. 3(a) one of the spectra recorded at $\mathrm{Ra}=6.4\times10^{10}$ and $z=d/9\simeq45$ mm. We clearly see the presence of a very well defined peak at $f_p=15$ mHz. At a given Ra, the frequency f_p is related to the mean recirculation time, roughly $f_p\simeq V_0/d$ (see also Ref. [4]), and, it does not depend on the position inside the cell. We have also computed the coherence functions between the temperature signals measured by the probes $P1$ and $P2$ at two very distant points of the cell [12]. We find that at f_p the coherence can be larger than 0.8, even in the case [Fig. 3(b)] when the probe $P1$ is close to the upper boundary layer and $P2$ is near the bottom one. This indicates that this oscillation is related to a large-scale coherent motion involving all the cell. The nondimensional frequency $f_p'=f_p d^2/\chi$ is a function of Ra, specifically $f_p'\simeq B\mathrm{Ra}^{0.49}$ [13], which agrees to the dependence reported in Ref. [4]. We will see in the next part of the paper that this coherent oscillation is an important signature of the coupling between the two boundary layers produced by the mean flow.

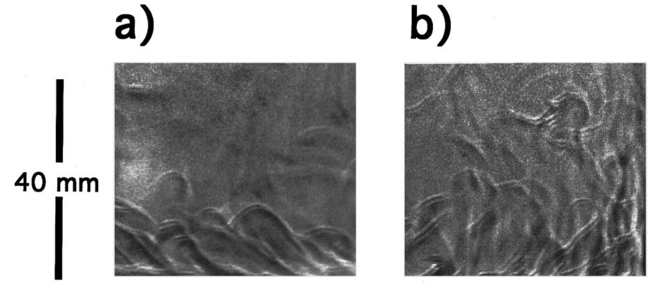

FIG. 4. (a) Shadowgraph of the plumes detaching from the lower thermal boundary layer in the cell with $d=40$ cm. The plumes start inclined because they are pushed by the mean flow. (b) The same as (a) but when the screen are mounted. Now the plumes start vertically as the mean flow is confined in the central region of the cell.

The large-scale flow also has an important effect on the transport of thermal fluctuations. For example, the plumes detaching from the lower boundary layer are inclined because they are pushed by the large-scale flow. This effect can be seen in Fig. 4(a) where the shadograph image of the thermal plumes is shown. The horizontal direction of the mean velocity is always parallel to the longest side of the cell (AB in Fig. 1). Keeping RaNu constant, we perturbed the large-scale flow by tilting the cell of an angle γ of $\pm 10°$ with respect to the horizontal. This tilt was obtained by lifting the cell either at side A ($\gamma=-10°$) or at side B ($\gamma=+10°$). The tilt of the cell imposed the direction of the large-scale flow, which was moving from the lowest side of the bottom plate toward the highest one; that is, from B (A) to A (B) for $\gamma=-10°$ ($\gamma=10°$). Furthermore, when the cell is tilted the large-scale flow remains close to the plates for a much shorter distance than when the cell is horizontal. This is schematically indicated in Fig. 1.

In Fig. 5(a) we compare $T(z)$, measured by the probe $P1$ at three different angles of tilt, $\gamma=0°$, 10°, and $-10°$. The

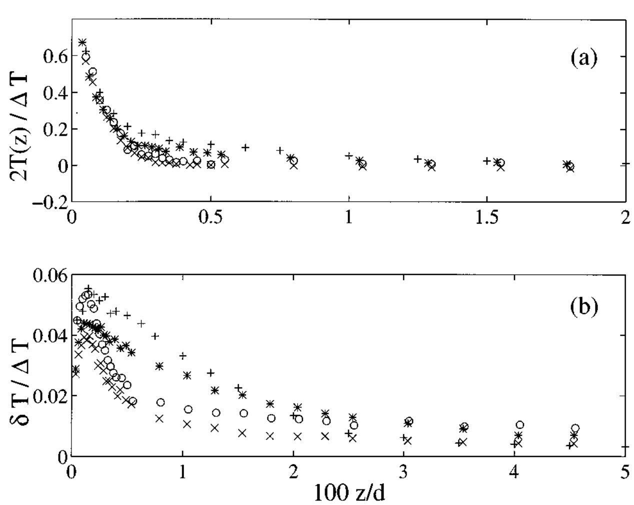

FIG. 5. Vertical profiles of the mean temperature (a) and of the rms of the temperature fluctuations (b). +, ×, * correspond to measurements done without the screen with γ equal to 0°, −10°, and +10°, respectively. ○ correspond instead to measurements done with the screens at $\mathrm{Ra}=5\times 10^{10}$ and $d=40$ cm.

corresponding $\delta T(z)$ is plotted in Fig. 5(b) as a function of z close to the wall for $z/d<0.002$, $T(z)$ does not change as a function of γ. This is consistent with the fact that, in spite of the important changes of the large-scale flow structure, the measured values of heat transport did not change by tilting the cell. Also the value of f_p was not influenced by the tilt of the cell. In contrast $T(z)$ and $\delta T(z)$ change by about 40% as a function of γ for $0.002<z/d<0.008$, as can be observed in Fig. 5. Thus, one concludes that the perturbation of the local properties of the mean flow have the only effect of changing the local temperature fluctuations outside the thermal boundary layer. These results agree with those found for $\gamma=90°$ (horizontal heating) [15], where it is observed that Nu is still proportional to $\mathrm{Ra}^{2/7}$. Here we are showing that not only the dependence is the same but also that the proportionality constant does not depend on γ, for $\gamma<10°$. This is rather surprising, because on the basis of the Siggia and Shraiman model [1,5], which correctly predicts the boundary layer shape [9,14], one would expect to observe a variation of $T(z)$, even for very small z, when the mean flow is modified.

Starting from these observations we checked if the whole heat flow could be affected when the mean flow is suppressed close to the boundary. In order to get this result we modified the cell as follows. Close to the bottom and top plates we put four thin vertical screens (see Fig. 1), 1 mm thick, $d/4$ high, and as long as the cell width. The distance between two consecutive screens was $d/4=10$ cm. Notice that the heat transported by these screens is less than 10^{-4} the total heat transported by turbulent thermal convection, even if these vertical screens would be high d. Thus, the vertical screens have just a very robust mechanical effect on the mean flow, which is completely suppressed close to the boundaries. The effect of this perturbation can be seen in Fig. 4(b), where the plumes detaching from the boundary layer are now vertical. Furthermore, the frequency f_p is not detected in any part of the cell, as can be observed in Fig. 3(c), where we report the temperature spectrum, measured between two screens at $z=d/9\simeq 45$ mm. By comparing this spectrum with that of Fig. 3(a), measured at the same z without screens, we clearly see that the frequency f_p does not exist anymore and the spectrum does not present any other well defined lines. Furthermore, the coherence function between the two probes $P1$ and $P2$, reported in Fig. 3(d), is 0. This means that the screens not only have the effect of suppressing the mean flow close to the thermal boundary layer but they also destroy the coherence of this large-scale flow. These results show that the coupling between the two boundary layers, produced by the mean flow, is an essential ingredient in order to generate the coherent oscillation. These experimental observations agree with the main hypothesis of a simple model [6], which explains these oscillations in terms of the coupling between the upper and lower boundary layers by means of the mean flow.

The dependence on z of the temperature fluctuation rms is perturbed by the presence of the screens, as can be seen in Fig. 5(b). The mean temperature profile $T(z)$, plotted in Fig. 5(a), is influenced by the screens for $0.002<z/d<0.008$, whereas for $z/d<0.002$, $T(z)$ is equal to that measured without screens. This is confirmed by the fact that no significant variation of the heat transport is produced by the screens.

The heat flow measurements, done with the screens, are compared with those done without screens in Figs. 2(a) and 2(b). It is important to notice that the heat flow did not change by putting the small screens. A more sensible way of showing this is to measure at constant NuRa (i.e., at constant heating power) the ratio $\mathrm{Ra}_{scr}/\mathrm{Ra}$, between the Rayleigh number Ra_{scr}, measured with screens, and Ra measured without screens. The ratio $\mathrm{Ra}_{scr}/\mathrm{Ra}$ is plotted as a function of the applied heat flow NuRa, in Fig. 2(c). We clearly see that the ratio is close to one within ± 0.02, showing that the heat transport is not affected, within experimental errors, by the mean flow suppression.

In conclusion, we have demonstrated that in turbulent thermal convection the mean flow plays a very important role in coupling the two horizontal boundary layers. When it is suppressed, the two boundary layers are decoupled and the coherent oscillation of the temperature field disappears. This result is in agreement with the recent model of Ref. [6]. Furthermore, we have shown that the large-scale flow strongly influences the thermal fluctuations and the temperature profile close the thermal boundary layers. In spite of this important changes produced by the perturbation of the mean flow, the mean temperature profile, close to the walls, remains equal with and without the mean flow. As a consequence the Nu values are not affected. Finally the experiment clearly indicates that, when the thermal boundary layers are decoupled, the old models which predict Nu $\propto \mathrm{Ra}^{1/3}$ are not jet correct.

On the basis of these experimental results one can conclude that changes in the heat transport produced by the mean flow are compensated by changes in turbulent transport. This means that the coupling of the thermal fluctuations with the mean flows cannot be neglected in order to construct a reliable theory of the heat transport. For example the model of Ref. [5] considers that inside the boundary only the horizontal component of the velocity field is important whereas our measurements clearly indicate that also the temperature fluctuations and their coupling with the vertical velocity play an important role. This feature, which has been recently taken into account [16], can explain the discrepancies of the model predictions with the experimental results [17,11]. However other models [3] do not need to invoke the presence of a mean flow in order to explain the observed dependence of Nu versus Ra. We believe that these models are more appropriate to describe the present observation.

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