A Letters Journal Exploring the Frontiers of Physics

August 2009

EPL, **87** (2009) 44006
www.epljournal.org
doi: 10.1209/0295-5075/87/44006

Transition on local temperature fluctuations in highly turbulent convection

F. Gauthier[1], J. Salort[1], O. Bourgeois[1], J.-L. Garden[1], R. du Puits[2], A. Thess[2] and P.-E. Roche[1]

[1] *Institut Néel, CNRS/UJF - BP 166, F-38042 Grenoble cedex 9, France, EU*
[2] *Technische Universität Ilmenau - Ehrenbergstraße 29, D-98693 Ilmenau, Germany, EU*

received 15 April 2009; accepted in final form 13 August 2009
published online 15 September 2009

PACS 47.27.te – Turbulent convective heat transfer
PACS 44.25.+f – Heat transfer: Natural convection
PACS 47.80.-v – Instrumentation and measurement methods in fluid dynamics

Abstract – In 1997, a new turbulent regime has been observed in a Rayleigh-Bénard cell and has been interpreted as the "Ultimate Regime" of convection. This observation was based on global heat transfer measurements at very high Rayleigh numbers (Ra). Using a set-up similar to the one used in 1997, we examine the signature of this regime from within the flow itself. A systematic study of probe-size corrections shows that the earlier local temperature measurements within the flow were altered by an excessive size of thermometer, but not according to a theoretical model proposed in the literature. Using a probe one order of magnitude smaller than the one used previously, we find evidence that the transition to the very-high-Ra regime is indeed accompanied with a clear change in the statistics of temperature fluctuations in the flow.

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In 1997, a new turbulent regime of thermal convection was observed by Chavanne *et al.* for Prandtl number of order unity ($Pr \sim 1$) and above a threshold Rayleigh number of order $Ra \simeq 10^{12}$ (the definitions of Pr and Ra are recalled later) [1]. Such conditions are found in environmental flows, including atmospheric and oceanic, giving a major practical importance to this result, beyond the theoretical challenge it raises. This new regime is characterised by an improved heat transfer, which is usually assessed by the dimensionless heat transport efficiency Nu of the flow. This Nusselt number Nu is defined as the total heat flux across the cell normalised by the diffusive heat flux that would settle in a quiescent fluid. Right above the reported transition, Nu scales like $Nu \sim Ra^{0.39\pm0.02}$ while the Ra exponent reaches at most 1/3 right below. A second signature of this regime was recently reported: fluctuations of the temperature drop across the boundary layer covering the plate used to force heat through the flow. This observation is consistent with an hydrodynamic boundary layer instability [2]. Both observations, as well as specific tests (in particular the observation of a $Nu \sim Ra^{1/2}$ heat transfer law in a corrugated surface cell [3]) are consistent with a 1962 prediction by Kraichnan [4]. This prediction states that an asymptotic or "Ultimate" convection regime will settle at high enough Ra once the boundary layer have undergone a laminar to turbulent transition. To the best of our knowledge, no alternative interpretation of all these observations is proposed any longer.

Despite the good agreement between observations and the theoretical prediction, two important issues still remain open. The first concerns the precise nature of the regime observed at very high Ra. In particular, what is the degree of overlapping between this observed regime and Kraichnan's prediction? Beside the experimental difficulty of reaching very high Ra in laboratory experiments, this comparison is delicate due to the ill-defined concept of laminar-to-turbulent transition in unsteady boundary layers, such as the ones present in turbulence convection (for example, see [5,6]) and due to Kraichnan's renouncement to treat the "join" between his asymptotic regime and the so-called "hard turbulence" regime present at lower Ra.

The second important open issue is the experimental conditions for the triggering of this very-high-Ra regime, which is observed in some experiments but not in all. Indeed, if we consider heat transfer measurements reaching at least $Ra = 10^{13}$ and fulfilling the Boussinesq approximations, the litterature reports two sets of results in apparent contradiction: a clear transition is found in some [1,3,7–10] and not in others [11–14]. Adding to the complexity of the present situation, two "in-between" results evidenced some features of transitions at very high Ra but without increase in heat transfer. The first is a simulation showing that the friction coefficient on the thermal plates departs from the typical scaling of laminar boundary layers above $Ra \simeq 10^{12}$, "presumably marking the transition to turbulence" [14]. The second is an experiment which identifies two transitions for $Ra \simeq 10^{11}$ and $Ra \simeq 10^{13}$, based on statistical analysis of the temperature fluctuations in the flow [11,15]. We will come back on these observations, referred later as the "Chicago experiment".

The motivation of this paper is to answer the question: What is the signature of the transition to the very-high-Ra regime within the flow itself? Such a signature has already been reported by Chavanne *et al.* [16] but a finite-probe-size argument —proposed by Grossmann and Lohse (GL) to re-interpret the Chicago experiment [17]— should also apply for the fluctuations measurements reported by Chavanne *et al.* We note here that both of these two experiments were conducted using cryogenic helium as a convecting fluid in order to achieve very high Ra in Boussinesq conditions. This paper is organised in three sections. In the first, we present a systematic experimental study of the probe-size dependence of the measured temperature fluctuations, along with an analytical model. In the second section, we discuss two previous works related to transitions at very high Ra. On the one side, we find that a key hypothesis of GL model —on the scaling of the velocity boundary layer around the probe— is not satisfied, calling into question the conclusion of this theoretical work. On the other side, we find that the temperature signal recorded by Chavanne *et al.* is altered by a finite-size correction, calling for a confirmation of their results with a probe having a space–time resolution at least 3 times better. The third section of this paper reports on the temperature fluctuations obtained with a specially made 17 μm thermometer, nearly 12 times smaller that the ones used previously. These measurements are backed-up by a systematic study conducted in the Barrel of Ilmenau.

Finite size correction in local thermometry. –

Set-up. Five thermometers were made with typical sizes ϕ ranging from $\phi = 200\,\mu$m to 2 mm and aspect ratios close to 1. The 200 μm probe was a cube of As-doped Si, similar to the ones used previously in the Chicago experiment and by Chavanne *et al.* Probes of sizes 500 μm, 1 and 2 mm where assembled by tightly varnishing together $300\,\mu\text{m} \times 300\,\mu\text{m} \times 30\,\mu\text{m}$ AsGa substrate thermometers [18] and cylinders of annealed copper of various sizes. The probes were contacted and suspended by two 50 μm diameter low-conductivity constantan wires —thermalised to the copper block— with length of several mm to minimize the intrusion of the support. The upper inset of fig. 1 shows a probe of size 1 mm. To check reproducibility of results, two probes of size 1 mm were made. The probes were calibrated and operated in the well-mixed core region of a 20 cm height and 10 cm diameter cryogenic Rayleigh-Bénard cell, at equal distance

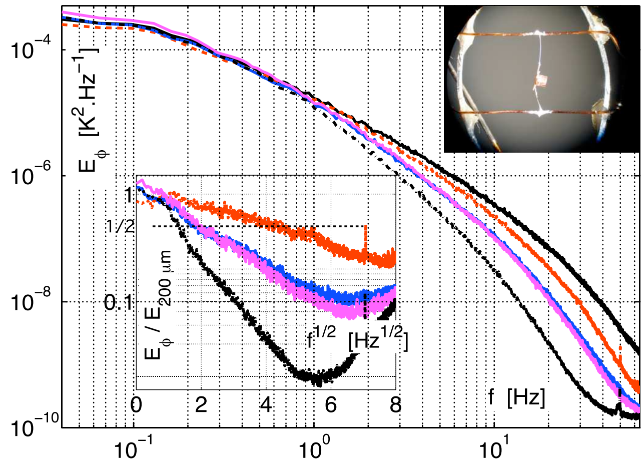

Fig. 1: (Colour on-line) Power spectral density E_ϕ of the temperature fluctuations sensed by probes of various sizes ϕ: from top to bottom (at 20 Hz), $\phi = 200\,\mu$m, 500 μm, 1 mm, 1 mm and 2 mm ($Ra = 2.0 \times 10^{11}$). Lower insert: spectral densities ratio $E_\phi / E_{200\,\mu\text{m}}$ *vs.* $\sqrt{f}$. From top to bottom, $\phi = 500\,\mu$m, 1 mm, 1 mm and 2 mm. Cut-off frequency $f'_{-3\,\text{dB}}$ is defined at ordinate crossing $y = 1/2$. Upper insert: top view of a 1 mm probe.

from the cell axis and vertical side wall. The unavoidable overheating due to the measuring current, corresponding here to a few hundreds of picowatt, was undetectable.

Figure 1 shows typical temperature power spectra recorded by the different thermometers for $Ra = 2.0 \times 10^{11}$ ($Pr = 0.76$). We note a good collapse of the two spectra from the 1 mm thermometers as well as a reasonable superposition of spectra at low frequency. As expected, the larger thermometers have more pronounced roll-off at high frequency due to a larger space-time averaging.

Before presenting a model accounting for the size effect, we recall the definition of Rayleigh and Prandtl numbers:

$$Ra = \alpha \Delta g h^3 / \nu\kappa \quad \text{and} \quad Pr = \nu/\kappa, \tag{1}$$

where α is the isobaric thermal expansion coefficient, Δ the temperature drop across the cell, $h = 20$ cm the height of the cell, and ν and κ are the kinematic viscosity and molecular thermal diffusivity of the fluid. The range of Ra and Pr explored with these probes spans from 4×10^{10} to 2×10^{14} and from 0.7 to 7, respectively.

The mean velocity of the large circulation in the convection cell was estimated from the cross-correlation of the temperature fluctuations seen by different probes. For example, a maximum of the cross-correlation between 2 opposite probes for a time delay of 6 s was interpreted as resulting from a large-scale circulation with a typically velocity 20 cm/6 s $\simeq 3.3$ cm/s. These estimations were consistent with *local* velocity measurements at mid-height by Chavanne [16] in a similar cell. In this later work, the authors also derived a fit for the local velocity at mid-height, and we used it to estimate the characteristic velocity V seen by the thermometers.

Modelization. To account quantitatively for the finite resolution of a probe of size ϕ, we define its transfer functions, $H_\phi(f)$, in Fourier space, as the magnitude of the measured temperature normalised by the temperature that would have measured a ideal probe (*i.e.* infinitely fast and small).

The thermometers response involves several characteristic frequency scales. First, the frequency f_V associated with the spatial filtering of the probe:

$$f_V = V/\phi. \tag{2}$$

Second, the frequency f_κ associated with the thermal response of the velocity boundary layer surrounding the probe:

$$f_\kappa = \kappa/\lambda_\phi^2, \tag{3}$$

where λ_ϕ is the thickness of the probe's boundary layer (defined quantitatively later). Two other time scales associated with the probe are found to be significantly smaller than f_κ^{-1}: the thermal diffusion time inside the probe and the "*RC*" time scale, where R is the thermal resistance of the probe's boundary layer and C is the heat capacity of the probe. This special hierarchy of times scales is often found in cryogenic hydrodynamics and results from the very low heat capacity of material at low temperature, and accordingly from their high thermal diffusivity.

The velocity around the probe is time dependent and this reflects on the thickness of the velocity boundary layer with a typical viscous frequency response $f_\nu = \nu/\lambda_\phi^2$. This study is focused on fluids with intermediate Prandtl number ($0.7 < Pr < 7$) implying that $f_\kappa \sim f_\nu$ since the diffusivities ν and κ have the same order of magnitude. In the following, the dependence *vs.* f_ν will be accounted implicitly via the dependence *vs.* f_κ and Pr.

We now compare the frequency scales f_V and f_κ with experimental data in order to determine which causes most of the observed roll-off at high frequency. Using decibels notations, we arbitrarily define the so-called $-3\,\mathrm{dB}$ cut-off frequency $f_{-3\,\mathrm{dB}}$ of a probe of size ϕ by

$$H_\phi(f_{-3\,\mathrm{dB}}) = 1/\sqrt{2}. \tag{4}$$

A first-order over-estimation of $f_{-3\,\mathrm{dB}}$, denoted by $f'_{-3\,\mathrm{dB}}$, is derived for the 3 larger probes using the approximated transfer function $H_\phi(f) \simeq \sqrt{E_\phi(f)/E_{200\,\mu\mathrm{m}}(f)}$, where E_ϕ is the power spectral density of temperature fluctuations measured by the probe of size ϕ. The lower insert of fig. 1 shows such spectral density ratio. The measured $f'_{-3\,\mathrm{dB}}$ can be compared with the $-3\,\mathrm{dB}$ cut-off frequency expected from the sole spatial filtering associated with f_V. If this spatial filtering is modeled in 1 dimension by a moving average performed over a flat-top smoothing window of size ϕ, the resulting transfer function will be $|\mathrm{sinc}\,(2\pi f\phi/V)|$ and the $-3\,\mathrm{dB}$ cut-off frequency will be $1.39\,V/2\pi\phi \simeq 0.2 f_V$. This spatial cut-off is found to be 6 times larger —on average— than the over-estimation $f'_{-3\,\mathrm{dB}}$ (and at least 3 times larger in all cases), showing that the response of the thermometers is more limited by the diffusion time across the boundary layer rather than by the spatial resolution of the probes. Surely, this statement will no longer be true for asymptotically smaller probes.

The boundary layer thickness λ_ϕ is defined by comparing the measured transfer function with a generic transfer function for a diffusion-limited process:

$$H_\phi = e^{-\lambda_\phi/\zeta}, \tag{5}$$

where $\zeta = \sqrt{\kappa/\pi f}$ is thermal skin depth of the quiescent fluid. The relevance of this analytical formula is supported by the reasonable linearity of the data plotted in the x-y representation chosen for the insert of fig. 1. If f_V had been the most relevant frequency scale instead of f_κ, we would have expected transfer functions with a steeper roll-off. Using eq. (5) and the definition of $f'_{-3\,\mathrm{dB}}$, we get:

$$\lambda_\phi - \lambda_{200\,\mu\mathrm{m}} = \beta/\sqrt{f'_{-3\,\mathrm{dB}}}, \tag{6}$$

where $\beta = \sqrt{\kappa/4\pi} \cdot \ln 2$. Can we now fit λ_ϕ/ϕ, as a function of the Reynolds number Re_ϕ of the probe?

$$Re_\phi = V\phi/\nu. \tag{7}$$

In the $Re_\phi \gg 10$ limit, the thickness of a boundary layer should be proportional to $\phi/\sqrt{Re_\phi}$ according to boundary layer literature [19]. In the $Re_\phi \ll 10$, the thickness should be of order ϕ. To accomodate the two limits, λ_ϕ is fitted by[1]

$$\frac{\phi}{\lambda_\phi} = A + B\sqrt{Re_\phi}Pr^\alpha. \tag{8}$$

According to literature [19], α is expected to be 1/2 for $Pr \ll 1$ and 1/3 for $Pr \gg 1$. In the intermediate Pr region of interest to us, we find that $Pr^{1/2}$ fits data slightly better than $Pr^{1/3}$, as shown in the insert of fig. 2. Choosing for convenience this former Pr-dependence, all experimental data can be well fitted with the parameters $A = 0.5$ and $B = 0.6$, as illustrated by fig. 2. The uncertainty on the value of A could be as large as $0 < A < 2$ but we recall that this positive parameter of order 1 was just introduced to have a physically sound limit for $Re_\phi \to 0$. Thus, we retain as a fit validated up to $Re_\phi \simeq 6000$ and for $0.7 < Pr < 7$:

$$\phi/\lambda_\phi \simeq 0.5 + 0.6\sqrt{Re_\phi Pr}. \tag{9}$$

Interestingly, from eq. (9) we find that the ratio f_V/f_κ is constant ($\simeq 3$) at large Re_ϕ ($Re_\phi Pr \gtrsim 100$ typ.), showing that the spatial and time filtering scale similarly with Re_ϕ.

[1]It is interesting to note the similarity between the proposed fit function eq. (8) for local thermometers and King's law for cylindral hot wires. According to King's law, the heat transfer from an overheated wire to a flow can be fitted by $Nu = a + b\sqrt{Re_\phi}$, where a and b are of order one (for $Pr \sim 1$), and Nu is the Nusselt number of the hot wire. Writing that this Nu is limited by the thermal resistance of a λ_ϕ-thick boundary layer, we obtain a law similar to eq. (8).

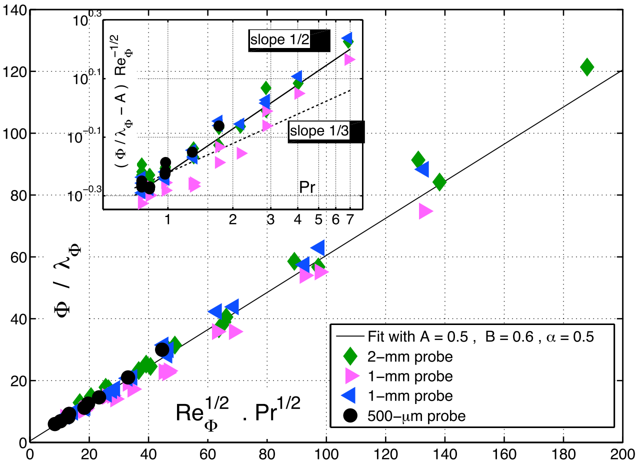

Fig. 2: (Colour on-line) Ratio between the size of the probe ϕ and the effective thickness of the probe's boundary layer, λ_ϕ. The parameters A, B and α are defined by eq. (8). Insert: Pr-dependence of this quantity compensated by $Re_\Phi^{1/2}$ (the offset $A = 0.5$ has a negligible contribution).

The exact value of this ratio results from arbitrary choices and definitions, but we showed previously that time filtering is the limiting process in our conditions. This hierarchy between the two filtering process could therefore be valid over a wider range of conditions that the ones explored in the present study.

As a summary, eq. (5) and eq. (9), enable to predict the typical finite-size correction for a local thermometer, or compare quantitatively the time response of different probes. In the next section, we apply these results to two published studies on flow transitions at very high Ra.

Consequences on the transition at high Ra. –

On Grossmann and Lohse's objection. The transitions observed in Chicago [15] for $Ra \simeq 10^{11}$ and $Ra \simeq 10^{13}$ have been re-interpreted as a probe-size artefact by Grossmann and Lohse (GL) [17]. In their model, GL first assume that the response of the probes is limited by thermal diffusion in the velocity boundary layer. This first assumption is in agreement with our findings. A second assumption states that the probe's boundary layer thickness is equal to the typical size of the probe for $Ra \leqslant 2 \times 10^{13}$ and equal to the thickness $\lambda = h/2Nu$ of the thermal boundary layer over the plates of the convection cell for $Ra > 2 \times 10^{13}$. For information, the probe Reynolds number in the Chicago experiment reaches $Re_\phi \simeq 400$ when $Ra = 2 \times 10^{13}$ [11].

The range of parameters Ra, Pr and Re_ϕ explored in the Chicago experiment overlaps significantly with the one of the present study. Our analysis is therefore expected to hold. Our experimental results and model disagree with GL model in several ways. First, for $Ra = 2 \times 10^{13}$, GL assumes that the probe's boundary layer thickness is comparable to the probe size ϕ while our analysis predicts a significantly smaller thickness[2], of order $\lambda \simeq \phi/13$, due to the large $Re_\phi \gg 1$. Second, we find that the thickness of the probe's boundary layer is proportional to the probe size ϕ. This differ from GL hypothesis of a boundary layer proportional to the convection cell height h and independent of the probe size ϕ in the high Ra limit. Third, the Ra-dependence of the boundary layer thickness differs significantly. GL model predicts two successive scalings: Ra^0 for $Ra \leqslant 2 \times 10^{13}$, (corresponding to $Re_\phi \lesssim 400$) and $Nu^{-1} \sim Ra^{-0.315 \pm 0.02}$ at higher Ra, while our measurements and model evidence a unique $Re_\phi^{-1/2} \sim Ra^{-1/4}$ scaling over nearly 4 decades of Ra up to $Ra = 2 \times 10^{14}$ and for Re_ϕ spanning the range 77 to 6000 (see fig. 2).

As a conclusion, our experimental results and analysis disagree with an important hypothesis of GL model. Consequently, the question about the possibility of a finite-size artefact in the measurements reported in Chicago [15], and consequently in those of Chavanne *et al.* [16] —of interest to us— remains fully open. This question is addressed in the following sections.

On Chavanne et al. temperature fluctuations transition. To test if the change in the temperature statistics reported in [16] results from a finite-size artefact, one needs to compare the magnitude of the reported observation with the magnitude of the finite-size correction. Unfortunately, this comparison is delicate because the transfer function associated with the finite size correction is not fully known, in particular its analytical dependence at small $f/f_{-3\,\mathrm{dB}}$. Nevertheless, we can test if the magnitude of the observed transition is the same when measured with a 200 μm and 500 μm probes.

Following Chavanne *et al.*, we consider the exponent ξ_2 of the 2nd-order structure function of the temperature fluctuations $T(t)$:

$$\xi_2 = \frac{\mathrm{d} \log \left\langle (T(t+\tau) - T(t))^2 \right\rangle_t}{\mathrm{d} \log \tau}, \qquad (10)$$

where the brackets represent time averaging. The dependence of ξ_2 *vs.* the time increment τ (or *vs.* space increment $V \cdot \tau$) contains the same mathematical information as a temperature power spectrum. In fig. 15 of ref. [16], the authors observed that the inflexion of $\xi_2(V \cdot \tau)$ differs below and above $Ra \simeq 10^{12}$, in particular for spatial increments in the window $0.5 < V \cdot \tau < 2$ cm. As shown in the insert of fig. 3, a similar qualitative change of shape is also present on our data, as illustrated with $Ra = 3.6 \times 10^{10}$ and $Ra = 2.0 \times 10^{12}$. But in the window of increments of interest, we also find that the measured ξ_2 depends of the size of the probe, here 200 μm *vs.* 500 μm. This probe-size dependence reveals some finite size effects at least on the 500 μm probe, and up to increment $V \cdot \tau \simeq 4$ cm. To safely clear the increments window 0.5–2 cm from visible finite

[2] B. Castaing already pointed the surprising large boundary layer thickness assumed in the GL model during the *Conference on High Rayleigh Number convection* at the ICTP in 2006.

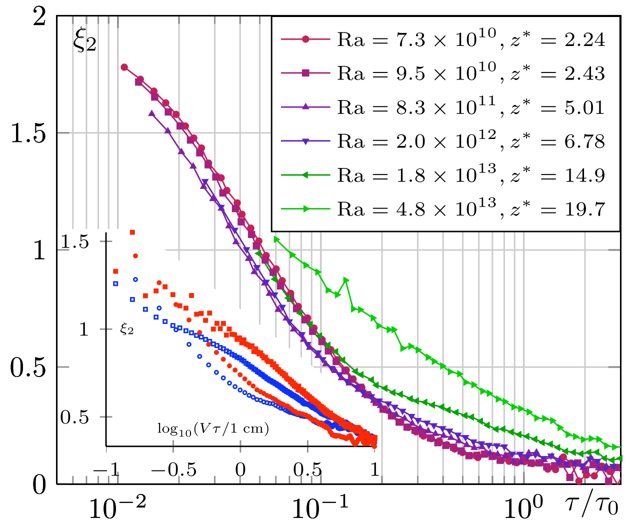

Fig. 3: (Colour on-line) Structure function exponent ξ_2 *vs.* the time increment τ/τ_0 (see text) from the $17\,\mu$m thermometer. For the 2 highest Ra, the shape of the curve changes. Insert: ξ_2 at $Ra = 3.6\times10^{10}$ (circles) and $Ra = 2.0\times10^{12}$ (squares) from probes of size 200 (open symbols) and $500\,\mu$m (filled symbols). For direct comparison with fig. 15 of ref. [16], the increments on the x-axis are in cm.

size correction, the resolution of the $500\,\mu$m probe should be improved by a factor $4\,\text{cm}/0.5\,\text{cm} = 8$, corresponding to a reduction in size by a factor 8 according to the probe-size model. The $200\,\mu$m probe is therefore not small enough to be free from finite size effect in the range of increments of interest. A probe of typical size $500/8 \simeq 60\,\mu$m is required.

As a conclusion, in the previous observations of Chavanne *et al.*, the interesting range of scales is not fully exempt of probe-size effects. The signature of the transition could remain partly significant, but a confirmation with a much smaller probe would be desirable.

Measurements with a micron-size thermometer. – To test directly the statistical signature of transition within the flow, we designed and micro-machined a thermometer which is one order of magnitude smaller than the ones used in the previous cryogenic convection experiments and 3.5 times smaller than the conservative $60\,\mu$m requirement defined above. The main characteristics of the probe are the following. The temperature-sensitive area is a $\simeq 1\,\mu$m large layer of annealed NbN [20] deposited across a 3 mm long, $17\,\mu$m diameter glass fiber. On each side of the temperature-sensitive area, a 150 nm thick layer of gold is deposited along 1.5 mm of fiber, to provide electrical contacts with limited lateral heat conduction. The fiber is suspended at its ends by two $50\,\mu$m diameter wires, themselves suspended on $220\,\mu$m Cu wires glued across a thin ring of diameter 15 mm. This web-like structure —already validated with micron-size hot wires [21,22]— was chosen to minimize the non-invasive character of the support. The temperature sensitivity was $\partial \ln R/\partial \ln T \simeq 0.7$ at 5 K (where R is the resistance) and the performance were limited by a resistance noise of spectral density $1.5\times10^{-6}/f$, corresponding to a rms noise of order 1 mK. This noise prevented operation above $Ra = 5\times10^{13}$ in order to maintain Boussinesq conditions. It also deterred us from putting the micro-thermometer in the middle of the cell as previously, due to the smaller temperature fluctuations here. The measuring current ($0.5\,\mu$A) produced no detectable overheating [23]. This micro-thermometer was suspended 2 mm above the bottom plate of a 43 cm high, 10 cm diameter convection cell. In the range of Ra explored ($7\times10^{10} < Ra < 5\times10^{13}$), the estimated thermal boundary layer above the plate is always smaller than 1 mm and the probe can be considered to be outside of it. We will come back on this point later with a systematic study *vs.* the plate-probe distance.

In fig. 3, ξ_2 is plotted *vs.* the dimensionless time increment τ/τ_0, where $\tau_0 = \lambda^2/\kappa$ is a caracteristic small time scale of the boundary layer. This normalisation of τ is chosen for convenience, the typical local velocity being unknown in this conditions. Changes in the spatial arrangements of the large-scale circulation inside the cell can induce offsets of the typically velocity seen by the probe and of the heat transfer Nu, up to a few tens of %, which would result in a offset along the x-axis of this figure. Thus, the exact abscisa values result from an arbitrary normalisation and they are expected to be less universal than the general shape of the curve itself, which is robust to such offsets. A central result is that —for $5\times10^{-2} < \tau/\tau_0 < 2$ typically— the shape of $\xi_2(\tau/\tau_0)$ changes above $Ra \simeq 10^{13}$, corresponding also to the Ra for which the heat transfer transition is found in this elongated cell [23]. The observed change in shape is qualitatively consistent with Chavanne *et al.*'s [16], confirming *a posteriori* that their observation was not an artefact although it may have been partly altered by a finite-size effect.

Effect of the plate-probe distance. Effective distance between the micro-thermometer and the bottom plate in units of plate boundary layer thickness is Ra dependent. One could object that the probe may not be fully outside the boundary layer till $Ra = 10^{13}$ and that the observed transition corresponds to the exiting from some hypothetical outer boundary layer.

As a first comment, we note that such an artefact had no reason to appear for the same Ra as the heat transfer enhancement, unless unlikely coincidental circonstances.

As a second comment, we consider the quantity $z^\star$ in the legend of fig. 3, which represents the remoteness of the probe from the plate in units of plate boundary layer thickness $\lambda = h/2Nu$. We find that the estimated plate's boundary layer thickness represents less than 15% of the plate-probe distance when the transition is observed. *A priori*, when the transition is seen, the probe is already well outside the plate's thermal boundary layer.

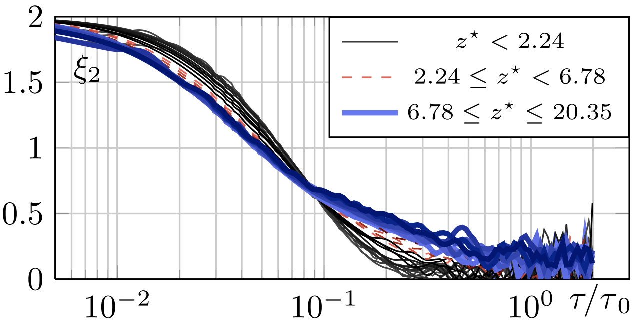

Fig. 4: (Colour on-line) The exponent $\xi_2(\tau/\tau_0)$ is plotted at a different distance $z^\star = \frac{2Nu}{h}z$ from the bottom boundary layer for $Ra = 3.2 \times 10^{11}$ in the "Barrel of Ilmenau".

To rule out directly the possibility of such an artefact, we carried a systematic analysis on the structure function exponent ξ_2 for different plate-probe distance. This study was carried in the "Barrel of Ilmenau", a Rayleigh-Bénard cylindrical cell filled with air ($Pr = 0.7$) with an height set to 6.3 m, corresponding to an aspect ratio Φ/h of 1.13 [5]. The local temperature fluctuations have been recorded using a temperature probe of size 150 μm that was moved along the central axis of the cell above the bottom plate at $Ra = 3.2 \times 10^{11}$. Figure 4 illustrates that the $z^\star$-dependence of $\xi_2(\tau/\tau_0)$ between $z^\star = 6.78$ and $z^\star = 20.35$ is significantly smaller than the magnitude of the change of $\xi_2(\tau/\tau_0)$ observed between $z^\star = 6.78$ and $z^\star = 19.7$ in fig. 3. Therefore, a plate-probe distance artefact can't explain the observed transition.

Concluding remarks. – Thanks to a systematic study of probe-size corrections, we showed that earlier measurements of temperature fluctuations in the core of a high Rayleigh number flow [16] were altered by finite-size effects, but not according to the scenario proposed in [17]. An important conclusion from [16] was therefore questioned: is there really a visible qualitative change in the statistic of temperature fluctuations in the core of the flow when the flow enters the very-high-Ra regime? The main result of the present study is a "yes" answer to this question, thanks to a specially designed micro-thermometer.

What can we learn about this very-high-Ra regime? As shown in fig. 3, the transition is associated with an increase of ξ_2 for time increments $\tau/\tau_0 \sim 1$, corresponding to the space increment $x = V \cdot \tau = V\lambda^2/\kappa$. The boundary layer thickness λ corresponds to the balance of diffusive and advective transport. Outside of it —where our measurement are done— advection is stronger ($V > \kappa/\lambda$), implying $x = V \cdot \tau > \lambda$. Thus, the transition manifests itself on scales x larger than the thermal boundary layer thickness λ, which could suggest an instability mechanism affecting extended pieces of boundary layers.

In addition to the enhancements of heat transfer [16] and boundary layer fluctuations [2], the regime observed at very high Ra is thus characterised by a third signature, but more work is needed to understand the basic mechanism of the associated instability. Without better understanding of this *terra nova*, we remain unable to extrapolate measurements and models of convection to flows of geophysical and astrophysical interests.

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We thank B. Hébral, B. Chabaud, Y. Gagne, F. Chillà, A. Tilgner and more especially B. Castaing for discussions. The assistance of T. Fournier, P. Diribarne and P. Lachkar in micro-machining is gratefully acknowledged. Financial support was provided by Région Rhône-Alpes (301491302), Procope program (17858YD and D/0707571) and by Deutsche Forschungsgemeinschaft (TH 497/22-1).

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