Origin of the Temperature Oscillation in Turbulent Thermal Convection

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We report an experimental study of the three-dimensional spatial structure of the low-frequency temperature oscillations in a cylindrical Rayleigh-Bénard convection cell. Through simultaneous multipoint temperature measurements it is found that, contrary to the popular scenario, thermal plumes are emitted neither periodically nor alternately, but randomly and continuously, from the top and bottom plates. We further identify a new flow mode—the sloshing mode of the large-scale circulation (LSC). This sloshing mode, together with the torsional mode of the LSC, are found to be the origin of the oscillation of the temperature field.

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Thermal convection is a phenomenon occurring widely in nature and in many industrial processes [1]. A paradigm to study the generic convection phenomenon is the Rayleigh-Bénard (RB) system [2]. A fascinating feature of turbulent RB convection is the emergence of a well-defined coherent oscillation in the presence of turbulent background. This robust oscillation has been observed in both the temperature [3] and velocity fields [4], and in convection systems with different fluids [3,5,6] and different geometries [7–9]. Although much effort has been devoted to the study of this phenomenon in the past [3,10,11], the nature of this oscillation remains unsettled. It has been proposed that this oscillation is due to the periodic emission of thermal plumes from the top and bottom boundary layers of the system, which are coupled by the large-scale circulation (LSC) [10]. In this scenario, plume emission due to boundary layer instability in one plate is triggered by the arrival of thermal plumes from the other plate, which implies that plumes are emitted not only periodically but also alternately between the top and bottom plates. Some later experimental studies appear to support this picture and periodic plume emission has since been attributed to be the source of the observed temperature and velocity oscillations in the bulk fluid [12–15]. In addition to the apparent oscillations observed for temperature and velocity in the vertical circulation plane of the LSC, horizontal oscillations of the velocity field have also been observed [16–18] and it has been suggested that periodic plume emission is not necessary for the horizontal oscillation of the bulk fluid [16,18]. Recently, it is conjectured that the local temperature oscillations may be caused by the torsional motion of the LSC [2]. The conjecture, which could explain the oscillation near the top and bottom plate, is unable to explain that observed at the midheight plane, since, by symmetry, the torsional oscillations cancel out at the midheight plane. We also note that the experimental studies that appear to show evidence of periodic plume emissions are two-dimensional (2D) measurements [12–15]. With the LSC's twisting oscillation near the top and bottom plates and its azimuthal meandering [16,17,19], three-dimensional (3D) measurements become essential to unlock the intricate flow dynamics.

In this Letter, we present 3D measurements of the temperature oscillations in a cylindrical convection cell of aspect ratio unity. Local temperatures are measured simultaneously by 24 probes placed inside the convecting fluid and embedded in the top and bottom plates. These measurements reveal the origin of the temperature oscillation in the system and shed light on the driving mechanism of its flow dynamics. The experiment was conducted in a RB convection cell that has been described elsewhere [15]. Briefly, it is a vertical cylinder of height $H = 19.0$ cm and diameter $D = 19.0$ cm, with upper and lower copper plates and Plexiglas sidewall. Water was used as the working fluid and measurements were made at the Rayleigh number $\mathrm{Ra} = 1.7 \times 10^9$ and 5.0×10^9, with Prandtl number $\mathrm{Pr} = 5.3$. As the two measurements give the same qualitative results, only that for $\mathrm{Ra} = 5.0 \times 10^9$ will be presented. Local temperatures in the fluid are measured by 8 thermistors of 300 μm in diameter. As shown in Fig. 1(a), these thermistors are mounted on a star-shaped frame made of 1 mm diameter stainless steel tube. They have an equal azimuthal separation and have a distance of 1 cm from the sidewall, where the main ascending and descending flows are passing through [15]. The frame is soldered perpendicularly to a 1 mm diameter stainless steel tube and can thus traverse vertically along the central axis of the cell. The thermistors are labeled as $1, 2, \ldots, 8$, which also represent their azimuthal positions. The temperatures in the top and bottom plates were measured by 16 thermistors of 2.5 mm in diameter, which are embedded in the top and bottom plates, respectively, at half radius from the plate center and about 2 mm away from the fluid contact surface at positions TP1 to TP8 and at BP1 to BP8 [shown as solid circles in Fig. 1(a)]. To lock the azimuthal orientation of the LSC steadily, we tilted the convection cell with 2° at position 1. Temperatures of the 8 small thermistors and 16 large thermistors are measured simultaneously by a $6\frac{1}{2}$-digit multimeter at a data rate of 0.55/ sec.

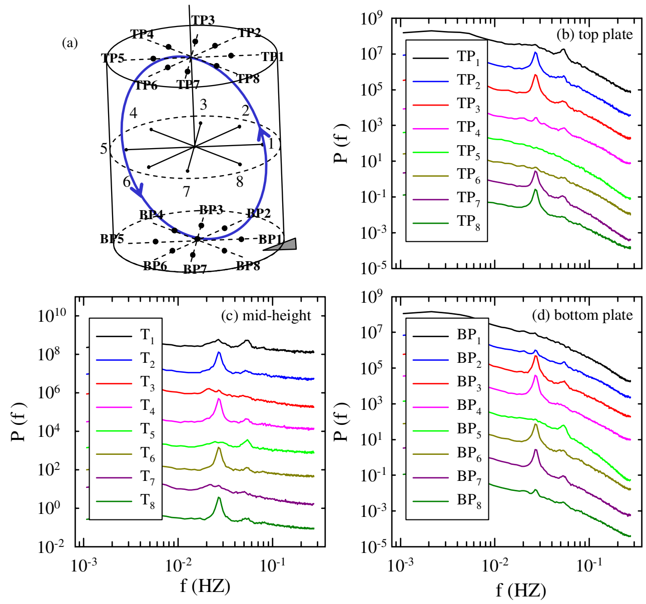

FIG. 1 (color online). (a) Sketch of the convection cell and thermistor configurations. Power spectra of temperatures measured by thermistors (b) embedded in the top plate at positions TP1 to TP8 (from top to bottom); (c) at midheight positions T1 to T8 in the bulk fluid; and (d) embedded in the bottom plate at positions BP1 to BP8. For clarity, each data set is shifted up from its lower neighbor by a factor of 20.

Figures 1(b) and 1(d) plot the frequency power spectra of the temperatures measured by the embedded thermistors in the top and bottom plates, respectively. Because of the finite thermal diffusivity of the plates, when a hot (cold) plume is emitted from the bottom (top) plate, it leaves a cold (hot) spot there for a finite time before the temperature recovers to the previous value by conduction. Similarly, when a hot (cold) plume impinges the top (bottom) plate, it will heat (cool) fluid in the boundary layer and leave a thermal imprint there. It has been shown in previous experiments that thermistors embedded in the plates are able to capture signatures of these plume departures and arrivals [11,20]. The prominent peaks in the power spectra near $f_0(\simeq 0.028$ Hz) correspond to the same oscillation frequency (for the same Ra) measured in many previous studies both in the fluid and in the plates [3,5,11–13]. It is seen from the figures that strong oscillations are observed at positions TP2, TP3, TP7, and TP8, where the hot ascending flow arrives at the top plate, and at positions BP3, BP4, BP6, and BP7, where the cold descending flow arrives at the bottom plate. On the other hand, no significant oscillation is observed at positions TP4, TP5, and TP6, where cold plumes are emitted, and at positions BP1, BP2, and BP8, where hot plumes are emitted. These results show clearly that there is no temperature oscillation at positions where plumes are emitted. Furthermore, if the plumes are not emitted periodically, then the oscillations observed at positions where plumes arrive from the opposite plate must originate in the bulk.

An important feature of the model that attributes the origin of temperature oscillations to the periodic emission of thermal plumes from the boundary layer is that emission of the hot (cold) plumes is triggered by arrival of cold (hot) plumes and thus hot and cold plumes are emitted alternately from the bottom and top plates with a time separation equals to half of the oscillation period [10]. To test this, we examine the phase relationships between the temperatures measured in the plates, which can be obtained from the cross-correlation function of the measured temperatures: $C_{T_i,T_j}(\tau) = \langle [T_i(t+\tau) - \langle T_i \rangle][T_j(t) - \langle T_j \rangle] \rangle / \sigma_{T_i}\sigma_{T_j}$, where σ_{T_i} and σ_{T_j} are the corresponding standard deviations. Figure 2 shows the cross-correlation function between temperatures measured at the positions BP1 and TP5, where hot and cold plumes are emitted, respectively. If the hot and cold plumes are shed alternately from the bottom and the top plates, the cross-correlation function $C_{\mathrm{BP1,TP5}}(\tau)$ should have strong negative peaks at $\tau = \pm\tau_0/2$, with $\tau_0/2$ the approximate time for plumes to traverse the height of the cell (here $\tau_0 = 1/f_0 = 36$ sec). As shown in the figure the correlation is very weak and there is no negative peaks at $\tau = \pm\tau_0/2$, but a negative peak at $\tau = 0$. A negative peak at $\tau = 0$ means that the hot and cold plumes are shed simultaneously. Also plotted in Fig. 2 is the cross-correlation function between temperatures measured at BP1 and BP5, the positions where in the bottom plate hot plumes depart and cold ones arrive, respectively. If the arrival of the cold plumes at BP5 triggers the emission of the hot plumes at position BP1, the cross-correlation function will have a strong positive peak near $\tau = 0$, which clearly is not the case.

Figure 1(c) shows the power spectra of the individual temperatures T_1 to T_8 measured in the fluid at the midheight ($H/2$) plane. The prominent peaks in the power spectra have the same frequency f_0 as in Figs. 1(b) and 1(d). It is seen that no significant oscillations are observed at positions 1 and 5, which are within the circulation plane of the LSC. On the other hand, strong oscillations are present at positions 2, 4, 6, and 8. To understand why oscillation is present at some positions while absent in others at the midheight plane, we plot in Fig. 3 segments of time traces of T_1 to T_8. It can be seen that at positions 1, 2, and 8 positive spikes dominate,

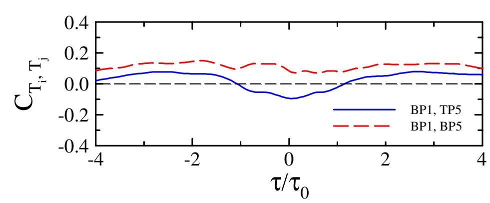

FIG. 2 (color online). Temperature cross-correlation functions measured in-plate at where plumes depart or arrive.

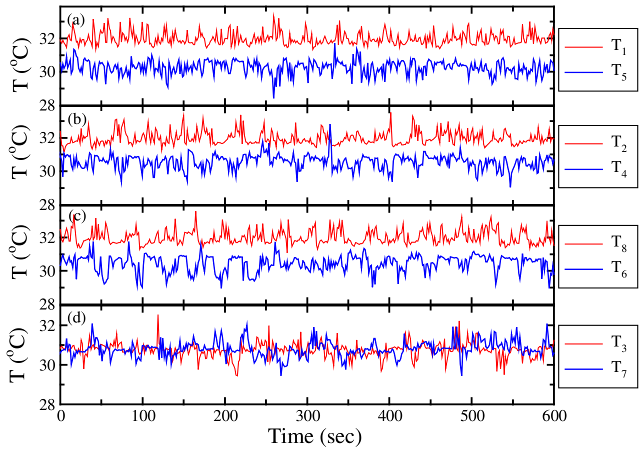

FIG. 3 (color online). Time traces of the temperature measured at the midheight plane by thermistors T_1 to T_8. For clarity, T_1, T_2, and T_8 are shifted up by 1 °C.

suggesting hot plumes are ascending at these positions. At positions 4, 5, and 6 negative spikes dominate, suggesting cold plumes are descending there. At positions 3 and 7, both hot plumes and cold plumes are present. These temperature signals are consistent with a coherent large-scale circulatory flow with a band of about half a diameter wide. Figure 4(a) shows the cross-correlations between the (T_2, T_8) pair and between the (T_4, T_6) pair. The peak of C_{T_2,T_8} (C_{T_4,T_6}) near $\tau = \tau_0/2$ indicates that the hot (cold) fluids pass the positions 2 and 8 (4 and 6) alternately with a time delay of $\tau_0/2$. We calculate $C_{T_i,-T_j}$ for a pair of thermistors when one of them mainly senses the upward spikes and the other mainly downward spikes. Figure 4(b) plots $C_{T_2,-T_4}$ and $C_{T_8,-T_6}$ and the peak near $\tau = 0$ indicates that the hot fluids pass 2 and cold ones pass 4 simultaneously. Similar relationship exists between positions 6 and 8. Simultaneous presence of hot bursts at position 2 (8) and cold bursts at position 4 (6) is another evidence that hot and cold plumes are not emitted alternately. The phase relationships above could also be observed from the temperature time traces shown in Fig. 3. Together, these results suggest a horizontal oscillation of the bulk fluid along the direction perpendicular to the vertical plane containing positions 1 and 5. In this off-center or sloshing mode of the bulk fluid, hot ascending fluid oscillates between positions 2 and 8 and cold descending fluid oscillates between positions 4 and 6, and this explains why the oscillation strength at these positions are approximately the same [Fig. 1(c)]. It should be noted that signatures of this sloshing mode has been observed by Qiu *et al.* [21] in a previous local velocity measurements, who found that the strongest oscillation occurs in the direction perpendicular to the LSC plane.

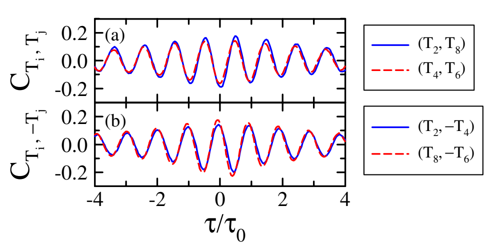

FIG. 4 (color online). Temperature cross-correlation functions measured in-fluid at midheight plane.

To study the sloshing oscillation of the bulk fluid quantitatively, we determine the hottest and coldest azimuthal positions of the bulk fluid along the sidewall from the instantaneous azimuthal temperature profile measured by the 8 thermistors at the midheight plane. These positions are determined by making a quadratic fit around the hottest and coldest temperature readings respectively [22]. The line connecting these two positions is the central line of the LSC band. The orientation of this line is the orientation of the LSC's vertical circulating plane, which is found to be very similar to that obtained by fitting a cosine function to the instantaneous azimuthal temperature profile [22]. We define the distance between this line and the cell's central vertical axis as the off-center distance d_{oc}, which exhibits a periodic oscillation with an amplitude about 1/3 of the cell diameter [Fig. 5(a)]. Figure 5(b) shows the power spectrum of d_{oc}, which has a peak at f_0 (0.028 Hz). It also shows that the sloshing mode exists in both tilted and leveled cases and that it is not a result of the LSC being locked in a fixed azimuthal orientation. The schematic picture [Fig. 5(c)] drawn based on the measured properties of d_{oc} confirms some of the above conclusions inferred from the properties of cross-correlation functions between the local temperature probes. For example, it is seen that due to this peri-

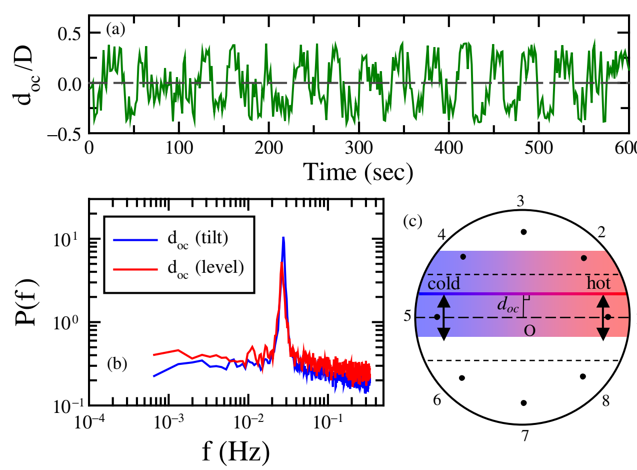

FIG. 5 (color online). (a) A time trace of off-center distance d_{oc}. (b) Power spectra of d_{oc} for both leveled and tilted cells. (c) A schematic drawing of the off-center motion of the LSC at midheight plane. The shaded band represents an instantaneous position of the horizontal cross-section of the LSC with its center at a distance d_{oc} away from its average position (long-dashed line), and the two short-dashed lines represent the average position of the LSC band. The black dots represent the actual positions of the 8 thermistors.

odical sloshing motion of the LSC, the thermistors at positions 2 and 8 (positions 4 and 6) will alternately experience the hot ascending (cold descending) flow. For the positions 1 and 5, as the LSC has a width of roughly half cell diameter, they will always experience the hot ascending and cold descending flow but the degree of "hot" and "cold" varies due to the off-center oscillation. This explains the very weak peak at f_0 in the power spectra of T_1 and T_5 [Fig. 1(c)]. The peak at $2f_0$ of these spectra is due to the fact that within one period of the off-center motion the central line of the LSC crosses the (1, 5) plane twice. From Fig. 5(c) it is seen that the positions 3 and 7 are farthest from the band of LSC and so they can barely sense the bulk off-center oscillation. This is evidenced by the barely visible peaks at f_0 in the power spectra of T_3 and T_7.

Some of the features observed by the thermistors embedded in plates can also be understood now. The oscillation with frequency f_0 at positions TP2, TP3, TP7, TP8, BP3, BP4, BP6, and BP7, and the oscillation with frequency $2f_0$ at positions TP1 and BP5 are due to the sloshing plus twisting motion of LSC. On the other hand, no significant oscillation is seen at positions BP1, BP2, BP8, TP4, TP5, and TP6. But when we placed the 8 small thermistors 3 mm above the bottom plates, positions 2 and 8 have strong oscillations. This is because the horizontal positions of the plumes are modulated by the flow field only *after* they leave the respective plates and are thus not sensed by the embedded probes. This is a further evidence that the temperature oscillation does not originate from the boundary layers. It may be noted that some recent models of the LSC dynamics [18,23] have ignored the thermal boundary layer and the plumes. Thus, these models could in principle be modified to explain the results reported here.

With the above picture, we can understand why some earlier measurements made in a 2D plane appear to observe that thermal plumes are emitted periodically. In the present experiment the orientation of the LSC is locked steadily in the (1, 5) plane by tilting the cell with a 2° angle so that it has a very small range of azimuthal angular fluctuation ($\phi_{\rm rms} = 8.5°$). In some of the previous studies that observed temperature oscillations within the plane of the LSC, the convection cell was titled by less than 1° [13,15,21]. When we tilted our cell by 0.5° it is found that the LSC is able to explore much broader azimuthal range ($\phi_{\rm rms} = 22.6°$), which is similar to a previous finding [24]. When this azimuthal meandering is combined with the sloshing motion the LSC band could leave and return to the (1, 5) plane so that the alternate occurrence of the hot and cold bursts in T_1 and T_5 can be observed. In fact, in this case temperature oscillations at all 8 positions can be observed [22]. Therefore, the alternate appearance of hot and cold bursts at positions 1 and 5 when the azimuthal orientation of the LSC is not steadily locked can be understood as a result of the horizontal motion of hot ascending and cold descending fluids being modulated by the sloshing mode. To conclude, our simultaneous multipoint temperature measurements show directly and convincingly that thermal plumes are emitted neither periodically nor alternately from the top and bottom plates and that temperature oscillations are caused by the sloshing mode and the torsional mode of the velocity field in the central and boundary layer regions of the system, respectively.

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