TRANSIENT TEMPERATURE FLUCTUATIONS IN AN ASPECT RATIO ONE TURBULENT CONVECTION CELL

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Abstract

Temperature fluctuations are measured from the moment a constant heat flux is applied to the bottom plate of a cell of aspect ratio one using cryogenic helium gas as the working fluid. This has enabled us to reach values of the principal control parameter for thermal convection, or Rayleigh number Ra. Temperature fluctuation data obtained in the cell interior are analyzed through autocorrelation and power spectral density (PSD) functions to investigate the transient formation of the large scale circulation. It is found that at Ra $=1\text{x}10^{13}$ the time required for a coherent mean wind to be established in the Rayleigh-Bénard apparatus corresponds closely to the time required for the mean temperature within the cell to reach its steady state value after a constant heat flux has been applied to the lower (hotter) boundary.

Përmbledhje

Në një enë me raport përmasash njësi që përdor si fluid punues gazin helium kriogjenik janë matur luhatjet e temperaturës duke filluar nga momenti në të cilin bazës së poshtme të enës i jepet një sasi nxehtësie. Matjet janë analizuar me anën e korrelacionit vetjak dhe probabilitetit spektral te fuqisë (PSD). Është gjetur se për Ra = $1\text{x}10^{13}$ koha që i duhet erës koherente të vendoset në aparatin Rayleigh-Bénard i korrespondon kohës që i duhet temperatures mesatare të enës të arrijë nje vlerë të qëndrueshme pasi një fluks konstant nxehtësie i është dhënë bazës (së ngrohtë) së poshtme

Introduction

Turbulent Rayleigh–Bénard convection is the paradigm for several natural phenomena and industrial applications like heat transport in oceans, atmosphere, stars, solar heaters etc.

It occurs when a layer of fluid is sufficiently heated from below and cooled from above that a macroscopic flow is generated augmenting the transport of heat above that which would occur in the absence of fluid motion, i.e., due to molecular conduction alone. One of the peculiarities of turbulent convection is the formation of an organized motion referred to as the mean wind [1, 5, and 6].

The canonical boundary condition of Rayleigh-Bénard convection is a constant temperature at the top and bottom boundaries where the bottom boundary is warmer than the top one [10]. In experiments, it is more common to control the top plate temperature but to apply a constant heat flux to the bottom plate. When steady-state conditions have been obtained and the plates are sufficiently conductive (low Biot number) the two boundary condition are equivalent. During the transient stage, the thermal boundary layers are established in the fluid and their instability leads to plumes and thermals of either "hot" fluid rising from the bottom plate or cold fluid falling from the top one. These plumes, which are a common feature in all turbulent convective flows, can organize into a mean wind so that there is a preferred direction separating those which rise from those which fall (i.e. they do not randomly mix throughout the fluid layer). It is very interesting to investigate the time required for this *self-organizing* process to effectively initiate a wind and specifically whether the wind is formed during this transient phase or requires steady state conditions to prevail.

Natural phenomena usually occur at very high values of the principle control parameter for convection, or Rayleigh number [8]. The Rayleigh number is a measure of the rate at which gravitational potential energy is liberated in a buoyant mass of fluid to the rate at which it is dissipated due to the diffusion momentum and heat. It is defined as Ra = $g\alpha\Delta TH^3/\upsilon\kappa$, where α is the isobaric thermal expansion coefficient of the fluid in the container, ΔT is the temperature difference between the bottom and top boundaries, g is the acceleration due to gravity, H is the vertical dimension of the convection cell, υ is the kinematic viscosity of the fluid and κ its thermal diffusivity.

We have analyzed transient data for $Ra = 10^{13}$. This can be regarded as the highest Ra for which the wind remains well-defined [5].

The apparatus and some experimental conditions

The apparatus was the same as the one used by authors of [4] except that the height of cylindrical convection cell was halved from 100 cm to 50 cm (diameter to height aspect ratio $\Gamma = 1$).

The cell was bounded at the top and bottom by two copper plates of thickness 3,8 cm, and at the side by a type 304 stainless steel wall of thickness 0.267 cm. The working fluid filling the cell was cryogenic helium gas [7]. To satisfy the Rayleigh-Bénard boundary condition of uniform temperature distribution at the top and bottom boundaries, the copper was annealed under oxygen-free conditions, resulting in a thermal conductivity of the order of 2 kW/mK at the operating temperature of 5 K. The sidewalls, on the contrary, were required to have thermal conductivity as low as possible to limit heat conduction up the walls in favor of convection through the gas. Stainless steel was used for its structural rigidity, and even though it is not really an insulating material, it was made thin so that the conductance was low, even if the conductivity was not. The thickness was set according to the requirements of withstanding the pressure differential between the contained fluid and the surrounding vacuum. In our experiment the conductivity of stainless steel at the operating temperature was approximately 0.25 W/mK. Special efforts were made to heat the plates uniformly. A constant heat flux occurred at the bottom plate whenever experimental conditions were altered. The top wall was connected to a helium reservoir through a distributed and adjustable thermal link, and its temperature was maintained constant by means of a resistance bridge and servo.

The temperature difference between two plates was kept typically of the order of 100 mK.

The convection cell was insulated from radiative heating by metallic shields residing in a common vacuum space, principally at 77K and at 4.2K.

Temperature fluctuations of the fluid inside the convection cell were measured by sensors made of doped germanium semiconductor resistance thermometers, starting from the moment the heat was applied to the bottom plate. Each time series typically contained 2^{19} data points, taken at 100 Hz and corresponding to about 1.5 hours total time (limited only by the software). The sensors were located on a plane at the cell half-height, parallel to the two horizontal plates, and about 4 cm radially in from sidewall.

Results

Figure 1 shows one transient time series of about 1.5 hours, measured starting from the moment heat flux is applied to the bottom plate, at Ra = 1×10^{13}. It can be seen that the average temperature is increasing more or less exponentially as a

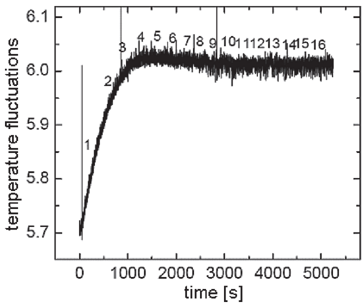

Figure 1. One transient time series measured from one of the sensors near sidewall for Ra = 1x10^{13}. Numbers 1, 2, 3, …, 16 correspond to 16 segments in which our temperature signal was divided

result of the sudden application of heat. In order to analyze the signal step by step we have divided it in 16 segments of 2^{15} data points (327.68 s) each (fast Fourier transform schemes rely on powers of two of the input data). To focus attention on the fluctuations we have removed to slow trend from the data and then we have computed the autocorrelation to various segments of the time series. The autocorrelation is a useful tool for finding periodicity masked by random noise (which could also be a strong turbulent background). Since the experimental conditions are of a closed cell, coherent flows can lead to a periodicity in the autocorrelation function, albeit with exponentially decaying amplitude due to the turbulent background. Such a periodic correlation of the signal on itself has been used to measure the properties of the large scale circulation [3]. In figure 2 we plot various autocorrelations corresponding to sequential segments of the time series. It can be seen that there is no periodicity in the autocorrelation shown in the first eight plots, which belong to first eight segments (a total of around 44 minutes from the moment we started to record the data). Periodicity would indicate the presence of a time-coherent flow (the wind) embedded within the turbulent background.

In the autocorrelation of the 9th segment of the temperature signal can be seen a periodicity of about 40 s (see [2] and [6]), which corresponds to the known period of circulation of the wind when measured under statistically steady conditions (see Figure 3).

The autocorrelation results give us an indication of the establishment of the mean wind, and it is interesting to compare this to the temperature stabilization. We see that the mean temperature increases up to the fourth segment and after that it overshoots up to the 8th one, and only after that it relaxes to its stable value (see Figure 1). Thus the mean wind, which we observe after about 50 minutes, requires steady conditions even though the plumes and thermals which drive it presumably begin shortly after the initial jump in heat flux at the bottom plate. This is not so surprising when we consider that the mean wind is prone to irregular reversals of its direction [5, 9] and hence presumably sensitive to fluctuations in the thermal background. The present results are consistent with this picture.

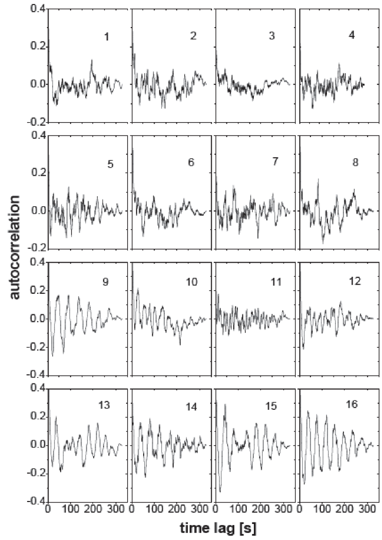

Figure 2. Autocorrelation of 16 segments in which the temperature signal shown in figure 1 is divided

Even after being established, the mean wind at this high Ra is not stable except in long-time averages. This is a consequence of the highly turbulent environment that exists at *Ra* = 1x10^{13}. In fact we see that the periodicity is lost in the 11th segment and gained again in the 12th segment up to the end of run. In fact, time series measured 17 hours after the establishment of steady-state conditions at this Ra and treated in the same way (analyzing them in short, sequential segments) revealed also this sometimes-on sometimes-off behavior.

We also performed power spectral density

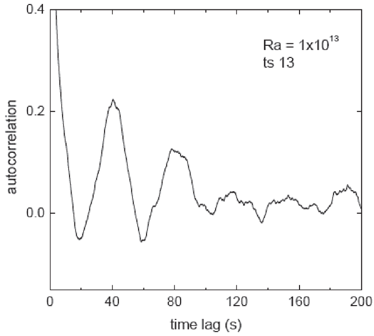

Figure 3. Autocorrelation of another time series (as a whole), measured at the same experimental conditions of the transient time series shown in figure 1, but about 17 hours later.

(PSD) analysis to each of the segments in which the transient time series was divided. Although there is no fundamental difference between the PSD and the autocorrelation, which are related to each other through a transform, the PSD provides a quantitative measure for all frequency components which can be read off of a single graph. From the broad peaks of PSD it was found that in the flow persists more than one frequency. We considered only the peaks in the frequency range [0.02Hz; 0.03Hz] within which lie the physically reasonable values for the large scale wind (see

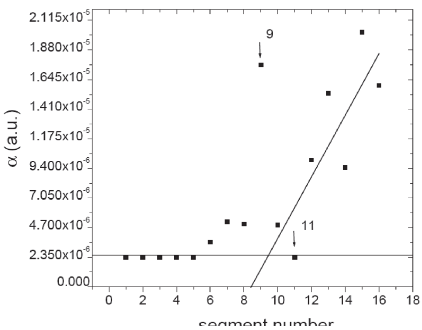

Figure 4. A plot of the sum of power of all frequency components inside the range (0.020Hz; 0.030 Hz) (named as α) as a function of the segment numbers

[2]), and with amplitude higher than the noise floor. Figure 4 shows the result of summing up the value of power of all such frequency components, for each segment of the time series, plotted against the segment number. For low segment numbers the sum does not significantly differ from a line of zero slope at the value that corresponds to the noise level (i.e., in the absence of a strong periodicity). For higher number segments the amplitude is substantially larger. By fitting two lines, one of zero slope and the other to the region of increasing amplitude, we can find the intersection which gives us a semi-quantitative evaluation of the transition to a state in which the large scale circulation survives. While such a linear fit for the latter data is by no means predicted, a linear approximation is always applicable to any curve over a suitably narrow range and it is in this spirit that we have applied the procedure. It is not surprising that the intersection of these two lines is around the ninth segment. For a non-turbulent system this procedure might have also provided information on the sharpness of the bifurcation; here it merely provides a more objective method for determining the transition.

As for the autocorrelation function, the amplitude falls for the 11th segment where evidently the wind has temporarily lost its coherence. After that the power has an increasing trend up to the last segment of the transient time series and we must expect that it saturates at some point consistent with the amount of available buoyant energy that can be given to the mean flow (see, e.g., ref [11]).

Conclusions

In this experiment we have studied the transient formation of the large scale circulation at the highest value of Ra for which it is known to remain coherent. Previously our investigations of the wind have started from a statistically steady state, which could be up to 100,000 turn-over times of the large scale circulation [12]. The advantage for transient studies here is that the low temperature properties of the copper plates ensure that its thermal inertia is large and orders of magnitude smaller than that of the fluid [12].

The time required for the mean wind to be established in a cell of aspect ratio one at Ra = $1x10^{13}$ is found to correspond to the time required for the mean temperature in the cell to reach its equilibrium value. From previous work we know that the mean wind under steady state conditions is robust, yet subject to sudden reversals of its direction at any given point [5, 9]. This indicates a sensitive dependence on thermal fluctuations of the turbulent background in which it exists. It is perhaps not surprising therefore that the wind cannot maintain itself during the transient phase following a change in cell conditions when the temperature background is continually changing.

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