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Measurement of Temperature Distribution in Thermocapillary Instability.

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Summary. — We report the measurement of the temperature field inside a fluid layer with a free surface, heated from below, in the unstable regime (thermocapillary instability or Marangoni effect). The measurements have been done when the convective flow was time dependent. We show the evolution of the temperature spatial distribution in the periodic and biperiodic regimes. We also discuss the main differences of the temperature field between Rayleigh-Benard and Marangoni instabilities.

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Convective instabilities driven by surface tension gradients (Marangoni convection) ([1]) play a very important role in many technological applications such as crystal growth in the absence of gravity, laser annealing, metal fusion and more generally in all those phenomena in which a convective flow occurs in a thin layer of fluid with a free surface. These instabilities are experimentally studied in liquid bridges (that is a small fluid drop confined between two horizontal solid plates at a different temperature) ([2]) and in thin fluid layers with a free surface heated from below ([3]).

In spite of its technological importance, Marangoni convection has not

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([2]) CH. CHUN and W. WEST: *Acta Astronautica*, **6**, 1073 (1979).

([3]) P. CERISIER, C. JAMOND, J. PANTALONI and J. C. CHARMONT: *J. Phys.* (*Paris*), **45**, 405 (1984).

received much attention in comparison to the large amount of data available for buoyancy-driven instabilities (Rayleigh-Bernard convection) [4]. In particular, there are only few experiments in which the time-dependent regimes of Marangoni convection have been studied in liquid bridges [2] and in horizontal fluid layers heated from below [5]. In these experiments it has been shown that an oscillatory regime either periodic or chaotic can be present in the convection, but only in ref. [5] there is some information on the spatial distribution of the time-dependent flow. On the contrary, knowledge of the spatial distribution of a variable is very useful to investigate how Marangoni convection is influenced by different parameters such as the dimensions of the cell, the conductivity of the walls, the Prandtl number and the ratio between buoyancy and surface forces. Furthermore, a detailed analysis of the spatial patterns produced by the convective motion can explain, in certain cases, the mechanism that produces a time-dependent behaviour in a fluid. For example, this analysis has been successfully used to study surface wave instabilities in which the chaotic behaviour clearly arises from the competition between spatial modes or patterns [6].

In this paper we report the measurement of the temperature field, produced by a time-dependent convective motion inside a horizontal fluid layer with a free surface heated from below.

1. – Experimental set-up.

The fluid layer has horizontal sizes $l_x = 4$ cm, $l_y = 1$ cm and height $d = 0.6$ cm. The cell containing the fluid has plexiglass lateral walls and the bottom and top plates are made of aluminium. The temperature stability of the two plates is of the order of 1 °mC. The fluid is silicon oil with a Prandtl number about 30. Between the free surface of the oil and the top plate there is a layer of air 0.4 cm thick. At 20 °C the other important parameters of the oil are $\alpha = 8.9 \cdot 10^{-4}$ °C^{-1}, $\varrho = 0.88$ g cm^{-1}, $k = 1.05 \cdot 10^{-3}$ cm^2 s^{-1}, $d\sigma/dT = -0.2$ dyn cm^{-1} °C. Here α, ϱ, k, σ, T are, respectively, volumetric expansion coefficient, density, thermal-diffusion coefficient, surface tension and temperature.

We point out that the oil surface is almost a black body at 300 K. Therefore, to perform a good evaluation of the radiative heat exchange between the oil and top plate we made this plate black. Considering also the conducivity across the air layer, we find that the Biot number [7], that defines the heat

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losses at the surface of the fluid, is about 1. Using the above values in eqs. (1) and (2) of ref. (5) and in table I of ref. (7), we evaluate the critical numbers, thus obtaining that the critical value of the temperature difference ΔT between the two plates is $\Delta T_c = 20$ °mC and that convection at threshold is ruled for 85 % by surface tension (Marangoni effect) with a residual 15 % due to buoyancy (Rayleigh-Benard effect).

The detection system consists of a laser beam that crosses the silicon oil perpendicular to the (x,z)-plane and is deflected by the thermal gradients inside the fluid. The x, y, z axes are oriented as shown in ref. (5). The laser beam sweeps the (x, z)-plane and we can measure the temperature gradient averaged along y in 1024 points of the (x, z)-plane by a method described elsewhere (8). Precisely, for each position of the impinging beam, the unperturbed zero gradient is measured by a position-sensitive detector and recorded in a computer. Later upon application of temperature gradients we can measure the horizontal- and vertical-shift components, respectively proportional to the horizontal and vertical refractive index gradients $\partial n/\partial x$ and $\partial n/\partial z$ averaged along the y-axis, that is along the optical path of the laser beam. From these gradients one infers the temperature through the relation $\partial n/\partial x = (\partial n/\partial T)(\partial T/\partial x)$ and similar for z. The temperature field is then easily recovered by numerical integration of the two recorded gradients. The sweeping time is fast as compared to the time scales of the phenomena under study. Therefore, by this method we can study the time evolution of the temperature field.

2. – Experimental results.

Analysing the fluid behaviour we find that the convective motion is stationary for $\Delta T/\Delta T_c < 500$, whereas above this threshold it becomes time dependent.

In fig. 1 we report the Fourier spectra of the horizontal temperature gradient measured in the point of maximum fluctuation.

At $\Delta T/\Delta T_c = 500$ (fig. 1*a*)) the oscillation is periodic with a frequency $f_1 = 21$ mHz, whereas at $\Delta T/\Delta T_c = 1100$ (fig. 1*c*)) the oscillation is biperiodic with frequencies $f_1 = 33.2$ mHz and $f_2 = 42.04$ mHz. All other frequencies in the spectrum of fig. 1*b*) are linear combinations of f_1 and f_2.

The frequency f_1 depends on ΔT. This is shown in fig. 2, in which the period of oscillation $\tau = 1/f_1$ is plotted *vs.* $\Delta T/\Delta T_c$ in a log-log scale. The straight line drawn in the picture is obtained by a least-square fit of the experimental data and it corresponds to a power law $\tau \propto (\Delta T/\Delta T_c)^{-0.66}$. The exponent is exactly the same as that found in a Rayleigh-Benard experiment in a small aspect ratio cell (9).

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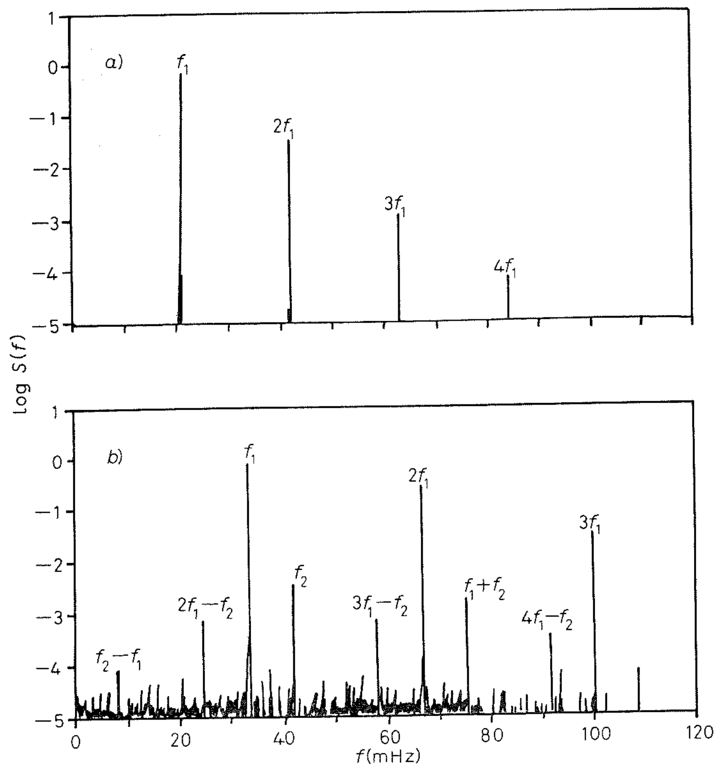

Fig. 1. – Spectra of the horizontal temperature gradient measured at the point of the cell in which the fluctuations are largest. In *a*) is shown the spectrum at $\Delta T/\Delta T_c = 500$ (periodic regime) and in *b*) that at $\Delta T/\Delta T_c = 1100$ (biperiodic regime).

At $\Delta T/\Delta T_c > 1550$ the temperature oscillations are chaotic. We do not investigate this regime here because the purpose of this paper is to analyse the spatial distribution of the fluctuating temperature. Therefore, we focus our attention on the periodic and biperiodic regime in which this analysis is more significant.

To reconstruct the time-dependent component of the temperature field we proceed as follows. We first record the stationary-temperature field $\tilde{T}(x, z)$ that is obtained by time averaging the istantaneous temperature field $T(x, z, t)$. An example of $\tilde{T}(x, z)$ at $\Delta T/\Delta T_c = 950$ is reported in fig. 3. On the vertical axis of the figure is reported the temperature, whereas L_x and L_z are the lengths of the laser sweep in the x and z directions, respectively. They are slightly smaller than the corresponding dimensions of the fluid layer to avoid deflections of the light from the lateral surfaces. In this figure we distinguish the linear component of the temperature field from the temperature distribution produced by the convective motion. Nevertheless this record yields only qualitative information because it is the sum of the temperature field inside

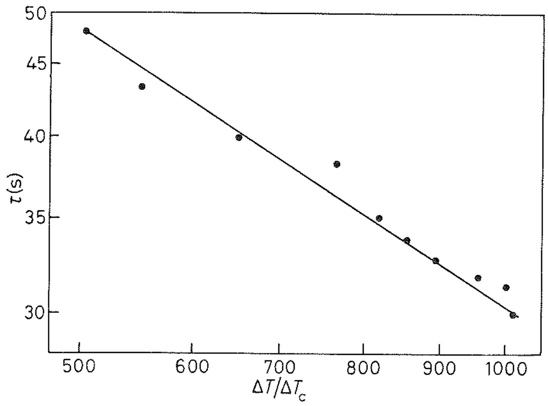

Fig. 2. – Dependence of the first oscillation period $\tau = 1/f_1$ on ΔT. Slope = – 0.66.

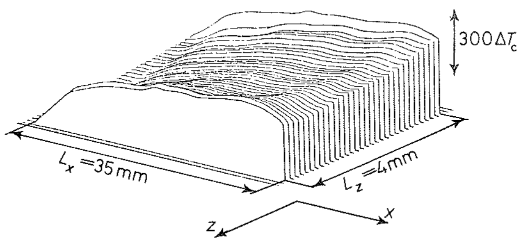

Fig. 3. – Temperature field in the (x, z)-plane averaged along the y-axis. The field here reported is time averaged at $\Delta T/\Delta T_c = 950$ where an oscillatory regime is present. The vertical axis of the figure is the temperature amplitude, whereas L_x and L_z indicate the length of the laser sweep in the x and z directions, respectively. The z-axis corresponds to heights increasing from right to left, so that the front section corresponds to the top fluid layer explored (just below the free surface).

the fluid plus that inside the plexiglass walls. With our apparatus we can take into account the plexiglass disuniformity field. This is done by recording this field at $\Delta T/\Delta T_c = 0$ and subtracting it from that grabbed at $\Delta T/\Delta T_c \neq 0$. However, the plexiglass disuniformities are functions of temperature, thus providing a residual error which can be nonnegligible.

On the contrary the measurement of the fluctuating component temperature field $T_c(x, z, t) = T(x, z, t) - \tilde{T}(x, z)$ is very accurate. Indeed taking the difference between T and $\tilde{T}$ recorded at the same temperature, all stationary disuniformities are eliminated from the final result. This way the only error is that due to the nonuniform detection efficiency across the detector area that is 5 % [8].

Two sequences of the time evolution of $T_d(x, z, t)$ are reported in fig. 4 and 5. They are taken, respectively, at $\Delta T/\Delta T_c = 950$ (periodic regime) and at $\Delta T/\Delta T_c = 1100$ (biperiodic regime). The data are recorded every 6 s and the recording time for each one is about 1 s.

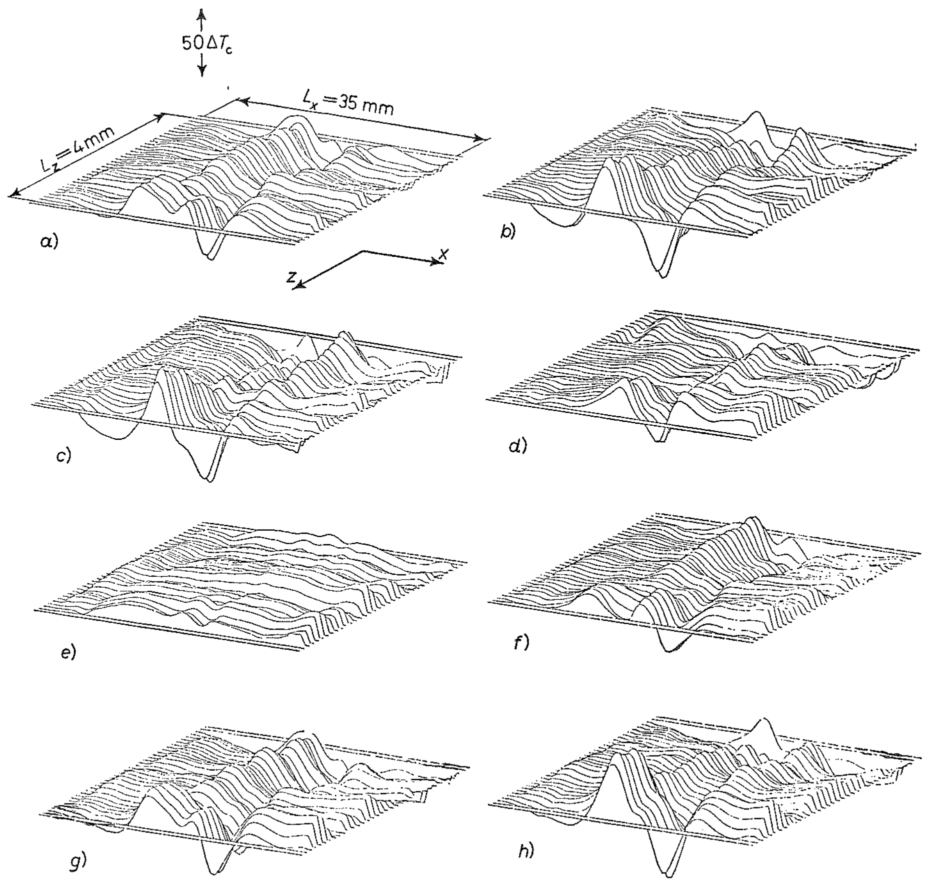

Fig. 4. – Evolution of the time-dependent component of the temperature field T_d in the (x, z)-plane averaged along the optical path at $\Delta T/\Delta T_c = 950$ in the periodic regime. The records are taken 6 s apart and the time to construct one of them is about 1 s. That is from *a*) to *h*) the corresponding times are, respectively, 6, 12, 18, 24, 30, 36, 42 and 48 s. The scales reported in *a*) are the same for all other records and the front section of the drawings corresponds to the top fluid layer just below the free surface. This sequence shows that the period of the temperature oscillation is about 30 s.

Looking at fig. 4 we see that the peak amplitude of the fluctuating temperature field is about 1/10 of the stationary temperature difference between the two plates. Besides, it is important to note that there is a good correspondence between the picture taken at 6 s and 36 s after almost a period of oscillation, indicating the reproducibility of our detection system. Of course the coincidence of the two images is not perfect because the sampling time is not an exact submultiple of the oscillation period.

From this sequence we clearly see that the region of maximum fluctuation is localized near the free surface. We have observed that this feature does not depend on the aspect ratio of the cell, as should be expected, since the

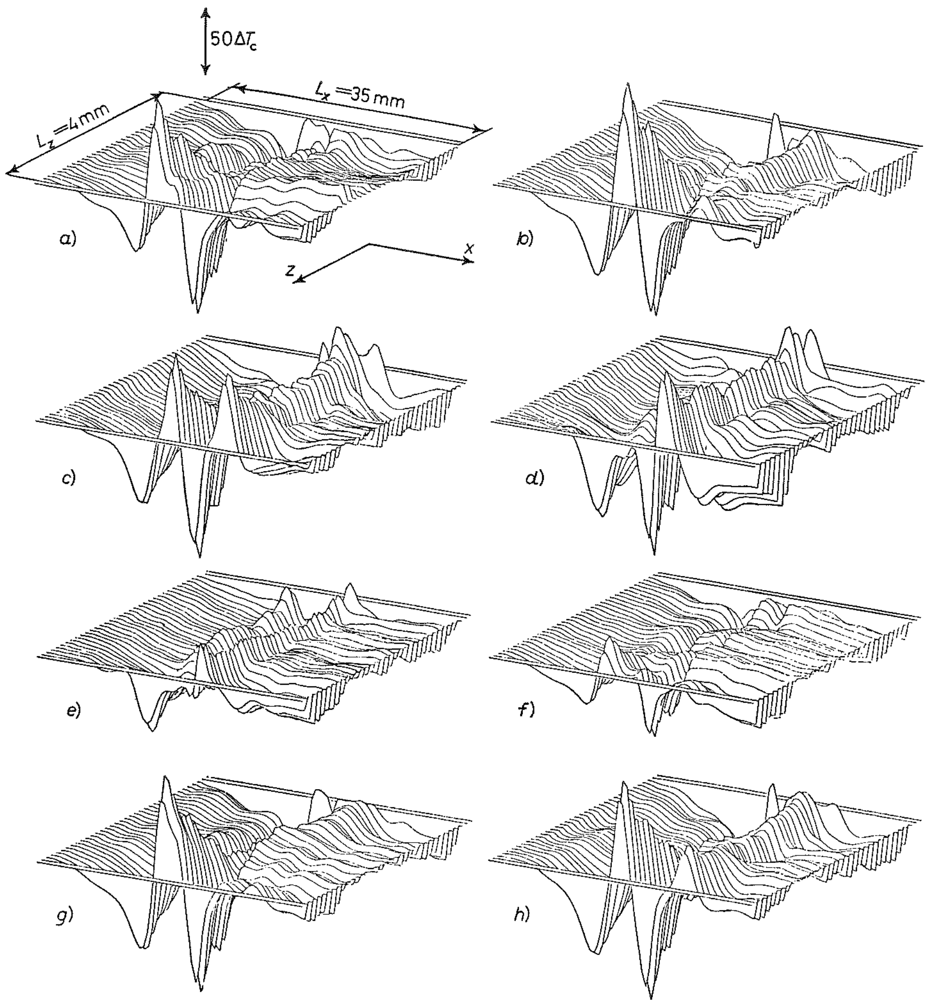

Fig. 5. – The same as in fig. 4 but with $\Delta T/\Delta T_c = 1100$, where a biperiodic regime is present.

destabilizing force is just the surface tension gradient. On the contrary in Rayleigh-Benard experiments done with the same fluid in a cell with aspect ratio similar to that of the experiment here described ([10]) the maximum fluctuations are normally found inside the fluid close to the boundary layers ([11]). Looking at the sequences in fig. 4 and 5 we clearly see that the spatial dependence of the fluctuating temperature field depends more on the x than on the z coordinate. This is another important difference between buoyancy-driven and surface-tension–driven convection. In fact, in Rayleigh-Benard instability it

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has been found that the temperature field is a sensitive function of both co-ordinates [10].

The same comments done for fig. 4 hold also for fig. 5, except for differences on the space distribution due to the presence of the frequency f_2.

3. – Conclusion.

We have measured the time-resolved temperature field inside a fluid layer with a free surface heated from below.

Our experimental results depend on the chosen experimental configuration, that is on the Prandtl number of the fluid, on the aspect ratio of the cell and on the nature of the lateral walls. Due to these reasons and to the mathematical difficulties of a realistic model, a direct comparison of our results with a sensible theory is almost impossible.

Nevertheless our measurements have quantitatively shown the main differences between Rayleigh-Benard and Marangoni convection in highly non-linear regime in cells of similar aspect ratio. These differences are related to the space distribution of the oscillating flow and they would not be observed if just local investigations were performed.

We stress that the technique of ref. [8], here applied to a specific configuration, is of much wide applicability in exploring the general mechanism of onset of chaos in a fluid, resolving in time the spatial patterns formed by convection.

Furthermore, the study of the spatial Fourier transform of the temperature field can give useful information on the number of modes necessary to construct a suitable model of the observed dynamical regime.

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● RIASSUNTO

Si riporta la misura del campo di temperatura in uno strato di fluido scaldato dal di sotto e con una superficie libera nel regime instabile (instabilità termocapillare o effetto Marangoni). Le misure sono state effettuate quando il moto convettivo non era stazionario. L'evoluzione della distribuzione spaziale della temperatura è stata seguita nel regime periodico e biperiodico. Si discutono inoltre le principali differenze del campo di temperatura fra l'instabilità di Rayleigh-Benard e quella di Marangoni.

Резюме не получено.