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To cite this version:

M.E. Weill, M. Rhazi, G. Gouesbet. Experimental investigation of oscillatory phenomena produced by a hot wire located near and below a free surface. Journal de Physique, 1985, 46 (9), pp.1501-1506. 10.1051/jphys:019850046090150100 . jpa-00210095

HAL Id: jpa-00210095
https://hal.science/jpa-00210095
Submitted on 4 Feb 2008

J. *Physique* **46** (1985) 1501-1506 SEPTEMBRE **1985**, PAGE 1501

Classification
Physics Abstracts
47.25F — 47.20

Experimental investigation of oscillatory phenomena produced by a hot wire located near and below a free surface

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(*Reçu le 31 août 1984, révisé le 26 mars 1985, accepté le 2 mai 1985*)

Résumé. — Un fil chaud, maintenu à température constante, est placé sous une surface libre, à une distance variable comprise approximativement entre 0,5 et 2 mm. Dans certaines conditions, on observe une déformation oscillatoire de la surface libre. Les températures des seuils d'apparition des phénomènes oscillatoires, et les fréquences associées, ont été déterminées en fonction de la distance fil-surface pour une série d'huiles de silicone.

Abstract. — A constant temperature hot wire is located near and below a free surface. In certain conditions, oscillatory deformations of the free surface are observed. The onset temperatures and frequencies have been determined *versus* the distance between the wire and the surface for four different silicon oils.

1. Introduction.

The study of convective transport processes and of the mechanisms leading to instabilities is an area of significant interest, both for the physicist wanting to understand the nature of the transition to turbulence and for the engineer wanting to control mass and heat transfers in various situations. A recent and very comprehensive review of fundamental problems and relevant applications is given in [1].

The authors entered this field of research after the fortuitous observation of a new phenomenon. A cw laser beam had been focused on a cell containing ferrofluids of cobalt in toluene with a 120 Å-diameter. The beam exhibited a strong divergence when leaving the cell, with production on a screen of a regular and contrasted ring pattern. Such phenomena are well known. They have a thermal origin and can be designated using the keywords of thermal lens and thermal blooming [2-5, among others]. Nevertheless, in certain cases when the laser beam crosses the cell near and below the free surface, the ring pattern did not remain steady but started to pulse periodically like a heart [6]. This new phenomenon has been named optical heartbeat. When the laser power is increased, the image of the optical heartbeat becomes more and more complicated, before ultimately reaching a stochastic state which can be thought as being a kind of optical turbulence.

Starting from these original observations, the research can be developed in two different (but complementary) directions.

For the first one, we have to recognize that we are confronted with a kind of laminar/turbulent transition which might exhibit universal features according to recent theories, such as the Feigenbaum theory of transition through a cascade of subharmonic bifurcations [7-8]. From that point of view well established results have been obtained [9], and the current efforts are devoted to this aspect of the question.

The second direction of research consists in trying to describe and understand the specific causality which is activated to produce the phenomena. Using classical optical visualization techniques like shadowgraphy, it has been recognized that the oscillations of the optical heartbeat on the screen were accompanied by oscillations of the free surface. Whatever the precise involved mechanisms, these oscillations are provoked by the local heating of the fluid produced under the surface by the absorption of the laser power. As a matter of fact, optical heartbeats can be obtained by using various (absorbing) liquids. Consequently, the use of ferrofluids is actually not at all necessary, although they produce optical heartbeats which are particularly beautiful and well contrasted. Accounting for these observations, the experimental (and theoretical) problem can be simplified as described below. First, the local heating under the surface can be carried out by means of a well controlled hot wire instead of a laser beam and, as expected, oscilla-

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tions of the free surface appear when the wire temperature is higher than a certain onset value [10]. Second, the use of an absorbing liquid is no longer required and we have chosen to perform the experiments with a series of silicone oils having well known thermophysical properties [11].

The aim of that paper is to present extensive experimental results concerning the oscillations of a free surface heated from below by a hot wire. Although self-contained, the present work is another significant step towards the understanding of the optical heartbeat. Let us also mention that, during the time while the experiments were carried out, a large theoretical effort has been made to predict the onset values of the free surface instability. Actually, this effort has not been successful up to now, and the theoretical problem appears rather challenging. In the absence of satisfactory predictions, we shall consider that the phenomena under study are not fully understood. Consequently, although dimensionless numbers became apparent in our theoretical work, we are not sure whether these numbers are really relevant. For this reason, dimensionless numbers will not be used in that paper to present the results. Nevertheless, care has been taken to provide the reader with thermophysical properties and experimental conditions values enabling us, in the future, to build relevant dimensionless quantities.

2. The experimental set-up.

2.1 THE TANK. — The liquid under study is contained in a copper tank C (17 × 12 × 5 cm^3) equipped with five glass windows on the bottom and on the walls for optical observations. Preliminary experiments having shown the influence of the surrounding air temperature on our measurements, the tank C is encased in a second C′, with temperature control by means of a thermostat (Fig. 1).

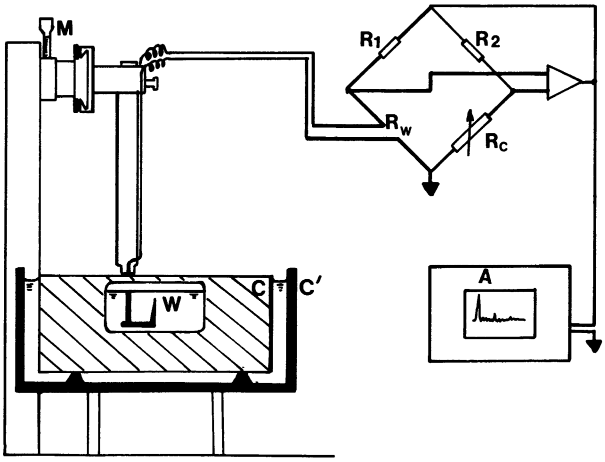

Fig. 1. — Experimental set-up. W : hot-wire ; C : tank ; C′ : thermostatic bath ; M : micrometric pedestal ; A : spectrum analyser ; R_1, R_2, R_c, R_w : Wheastone bridge, constant temperature anemometer.

2.2 THE HOT-WIRE. — The hot-wire (W) is immersed under the free liquid/air surface. It is a platinum wire with the following characteristics :

— length L : 3 cm ;
— diameter D : 20 μm ;
— temperature coefficient : $3.92 \times 10^{-3}\ K^{-1}$.

The L/D ratio is equal to 1500. It can be theoretically shown that this ratio is large enough to avoid significant disturbances due to edge effects in such a way that the temperature profile along the wire can be considered as a constant. Other measurements with smaller L/D have not shown noticeable differences and confirm the theoretical statement.

In order to stretch the wire, it is soldered under a microscope on the tip of flexible prongs. The depth d of immersion of the wire can be adjusted by means of a micrometric pedestal (Fig. 2). Screws are used to position the wire and keep it horizontal, the adjustements being done by observing the wire and its image produced by the surface.

2.3 TEMPERATURE CONTROL OF THE WIRE. — In order to study quantitatively the conditions in which oscillations appear, the wire was temperature regulated by means of a Constant Temperature Anemometer

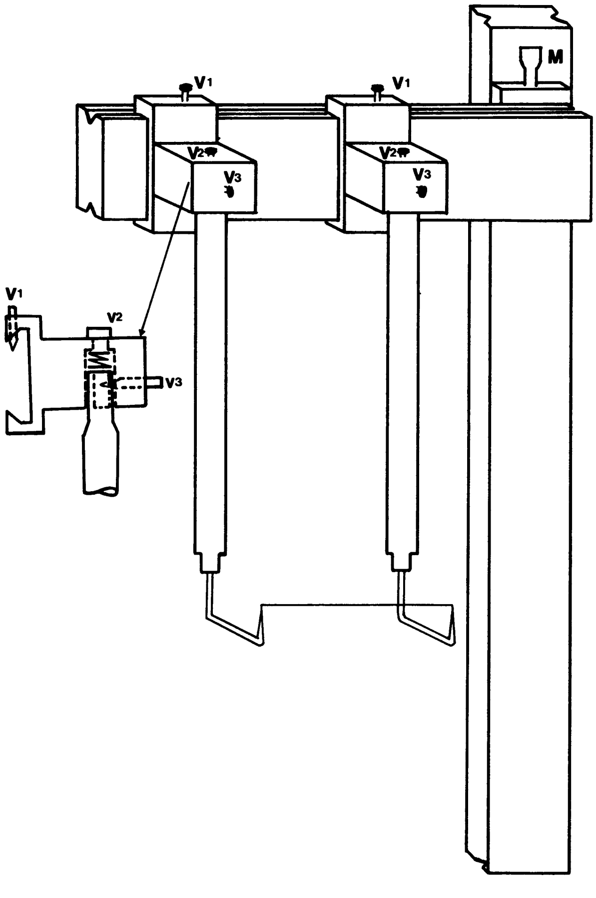

Fig. 2. — The hot-wire. M : micrometric table ; V_1 : locking screw ; V_2 : horizontality screw ; V_3 : antirotating screw ; P : prongs.

(CTA), usually used for velocity measurements in gases. The principle of the CTA relies on the balance of a Wheastone bridge formed with two constant resistors R_1 and R_2, a variable control resistor R_c and the wire, which is the sensitive probe (Fig. 1). When R_c is fixed, the bridge is in equilibrium for a value of the resistance R_w of the wire corresponding to the temperature T. If the wire temperature T' is not equal to T, there is a feed back mechanism through the bridge which reestablishes the equilibrium resistance $R_w(T)$. The CTA used can follow frequencies up to 25 kHz, a range which is sufficient for our purpose.

Preliminary experiments where the wire was immersed in a thermostat of oil at constant temperature T enabled us to determine the curve of calibration $R_c(T)$ of the CTA. Orders of magnitude are $R_c \sim 50\,\Omega$ for $T \sim 75\,^{\circ}\mathrm{C}$.

3. Detection of oscillations and threshold measurements.

3.1 Electrical detection. — When the field (velocity, temperature) is steady around the wire, the behaviour of the CTA is also steady. The appearance of oscillations in the liquid is conversely linked to oscillations in the regulated wire voltage output. To detect them, this output is analysed by a FFT HP 3582 A spectrum analyser, and the spectrum is fed to a XY plotter.

3.2 Optical detection. — Optical detection is achieved using either shadowgraphy or Schlieren by reflection. The shadowgraphy appeared to be a very sensitive technique to detect oscillation phenomena, but its integrative character excludes the possibility of a quantitative analysis. We rather discuss a reflecting Schlieren system, identical with the Kayser and Berg one [12], enabling us to observe the free surface deformations. The light source is a He-Ne enlarged laser beam directed on to the surface of the liquid above the wire. The reflected light is focused by a lens ($f = 15$ cm) and half cut by a knife. The light is then received on a viewing screen located at 0.8 m from the focusing lens.

The sensitivity of the technique has been tested by simulating the deformations of the free surface. This is done by means of a straight (cold) wire which is allowed to cling to the surface to stress it, producing at will a crest or a trough. The corresponding distributions of illumination on the screen are shown in figure 3.

3.3 Determination of the oscillation thresholds. — For a given depth, the aim is to determine the critical wire temperature below which no oscillations are generated. In fact, before deciding there is no oscillations at a given temperature it is necessary to wait for several minutes. Indeed, in certain cases the oscillations do not appear immediately even if the wire temperature is above the critical temperature. After various attempts, the following procedure has been chosen.

The onset temperature T_c is associated with a regulated wire voltage output signal which produces a spectrum having a fundamental peak of frequency f_c and of amplitude a_c approximately equal to zero.

a) The wire is heated to reach a temperature

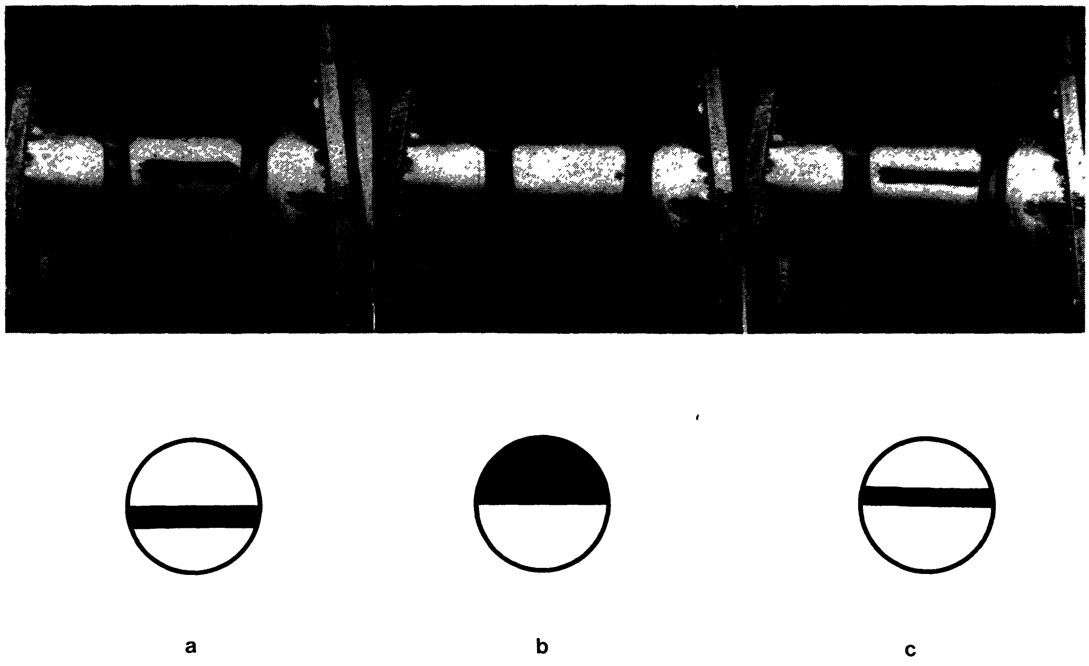

Fig. 3. — 3 shapes of the free surface (photos) and the corresponding Schlieren pattern (drawings) : a) crest; b) flat; c) through.

$T_1 > T_c$. The stability of the oscillations and the corresponding spectrum are checked on the spectrum analyser.

b) The power supply of the wire is cut off and the temperature of the liquid is decreased to 25° (the reference temperature here) by gentle agitation.

c) The wire is then heated again to reach a temperature $T_2 < T_1$; we observe that the frequency and the amplitude of the fundamental peak have decreased. The operations b) and c) are repeated until the amplitude a_c vanishes. Note that f_c does not vanish.

For a given d, the temperatures T_c are reproduced within 1° and the frequencies within ± 1/100 Hz. One example of a signal and of its spectrum is shown in figure 4.

Strictly speaking, that procedure measures onset values for an oscillatory behaviour of the convection field around the wire. We have checked, by comparison with optical detection, that these onset values also correspond to the onset of free surface oscillations.

3.4 TESTED LIQUIDS. — A large variety of liquids have been tested. We observe that no oscillations have been produced with water, ethanol or cyclohexane, for instance. On the other hand, oscillations are produced by toluene, benzene, heptane, mineral oils and silicone oils. At the present time, we are not able to explain this difference of behaviour.

Volatile products have been excluded due to interfacial evaporation which modifies the surface properties. For the measurements, we have used Rhodorsil silicon oils 47 V 5, 47 V 10, 47 V 50, 47 V 100 which are very suitable : low evaporation, slow ageing. Their physical properties are listed in table I, according to reference [13].

4. Results and discussion.

4.1 RELATIVE ONSET TEMPERATURE T_c. — They are obtained from the control resistors R_c, using the calibration curve. Figure 5 shows the relative onset temperatures $\Delta T_c = T_c - T_\infty$ ($T_\infty = 25$ °C) *versus* the depth of immersion d. In all cases, the curves are fairly parabolic with a minimum characterized by the depth d_m for which the oscillations start with the lower onset temperature : ΔT_m.

For reasons indicated in the introduction, these results are not given under non-dimensional forms. Nevertheless, in the present case table I shows that the thermophysical properties are approximately constant except for the viscosity, which ranges from 5 to 100 centistokes. Furthermore, the results show that the ratio $\Delta T_m/\sqrt{\nu}$ is fairly constant. It is equal to

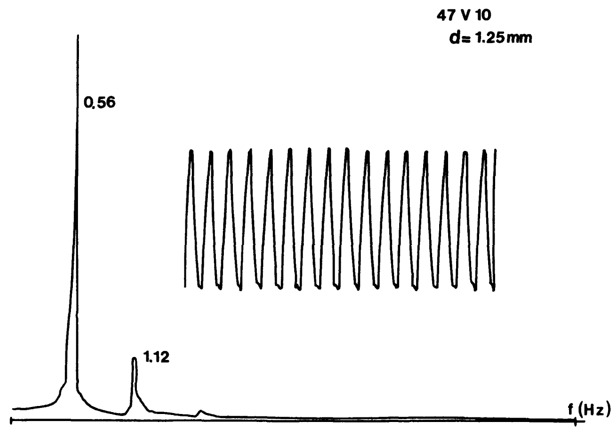

Fig. 4. — An example of a signal and of its spectrum.

Table I. — *Physical properties of oils used* (*CGS at* 25 °C).

	47 V 5	47 V 10	47 V 50	47 V 100
ν	5×10^{-2}	10×10^{-2}	50×10^{-2}	100×10^{-2}
ρ	0.91	0.93	0.959	0.965
λ	2.8×10^{-4}	3.4×10^{-4}	3.8×10^{-4}	3.8×10^{-4}
C_p	0.46	0.45	0.35	0.35
σ	19.7	20.1	20.7	20.9
α	1.05×10^{-3}	1.08×10^{-3}	1.05×10^{-3}	9.45×10^{-4}
$\frac{\partial \sigma}{\partial T}$	-0.07	-0.07	-0.07	-0.07

with :

ν : kinematic viscosity; ρ : density; λ : thermal conductivity; C_p : heat capacity; σ : surface tension; α : thermal expansivity.

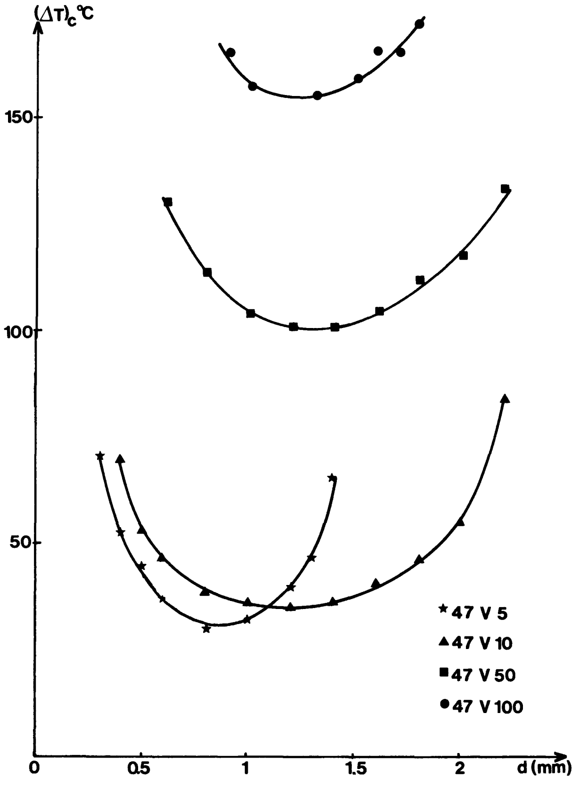

Fig. 5. — The onset temperatures *versus* the wire-surface distance.

140, 110, 140 and 150 CGS units for the oils 47 V 5-47 V 100 respectively. Thus might be a clue for saying that the ratio $\Delta T_m/\sqrt{\nu}$ could enter in a relevant dimensionless number. The possible confirmation from a future theory of such a number must take into account the fact that no oscillations appear with 47 V 2 and 47 V 1 oils.

4.2 ONSET FREQUENCIES f_c (FUNDAMENTAL OF THE ONSET SPECTRA). — The onset frequencies f are given *versus* d for the different oils in figure 6. When d increases they first decrease rapidly as $1/d^2$ to finally reach a fairly constant value for d above $\sim d_m$. For a given d they increase when the viscosity decreases.

The existence of two different behaviours, depending on whether d is larger of smaller than d_m, can clearly be seen in figure 7 showing f_c *versus* ΔT_c.

4.3 ACCURACY. — Inaccuracies are due to temperature and frequency measurements and from the evaluation of the depth of immersion of the wire. According to figure 5, an error on the depth equal to the wire radius (0.01 mm) can produce variations of the onset temperatures of about 1 K. Repeated experiments lead us to the conclusion that our data are accurate within ± 3 K for the temperatures and ± a few hundreth of a hertz for the onset frequencies, except for the V 100 case where measurements are more difficult. As a matter of fact, that viscous oil must be heated for more than 20 min before the appearance of the oscillations can be observed.

4.4 DISCUSSION. — The present experiments are reminiscent of the Bénard-Marangoni and Rayleigh-Bénard effects. An example of similarity concerns the shape of the free surface.

Ending a long controversy, Scriven and Sternling [14] have shown that, for tension driven convection, the free surface is depressed above the hot stream while it is elevated for buoyancy driven convection. This has been experimentally confirmed by Kayser and Berg [12] who stretched a hot wire at the bottom of a Petri dish filled with silicon oil using various pool depths. The transition between depression and elevation is observed for a pool depth of about 3.5 mm. Similar conclusions have been stated by Loulergue [15] in a different context.

Similarly, in our case, observations of the free surface before oscillations, using the Schlieren technique, have shown that the surface is depressed for $d < d_m$ and elevated for $d > d_m$.

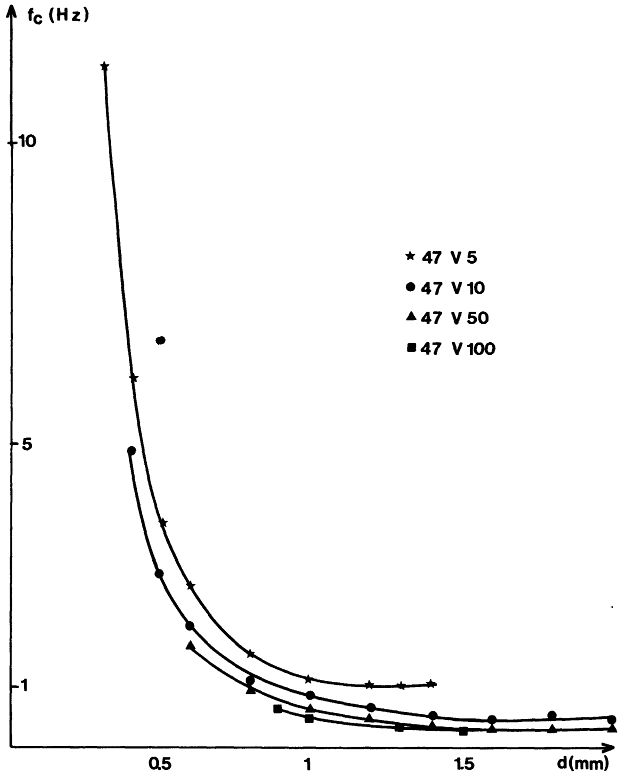

Fig. 6. — The onset frequencies against the wire-surface distance.

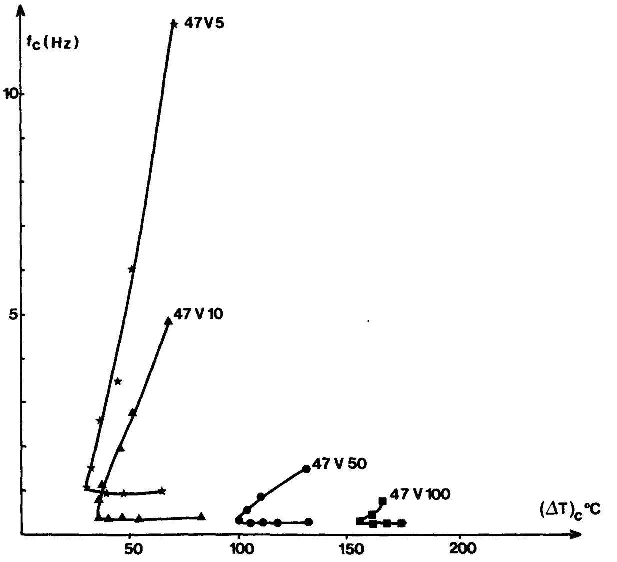

Fig. 7. — The onset frequencies against the onset temperatures.

On the other hand, Nield has shown in a basic paper [16] that for a liquid pool supported by a heated surface, the onset of instability mainly depends on the Marangoni number for a shallow pool and on the Rayleigh number for a deep pool. Both agencies, namely surface tension and buoyancy forces, reinforce each other in the intermediary situation. This has been experimentally confirmed by Palmer and Berg [17] and Pantaloni *et al.* [18]. Similarly, the examination of the experimental curves 5, 6, 7 clearly shows the appearance of two areas, depending on the depth of immersion. We actually think that, in our case, the instability is mainly surface tension driven in the $d < d_m$ area and mainly buoyancy driven in the $d > d_m$ area. In between, the two agencies of instability would reinforce mutually, leading to minimal values for the critical temperature.

There is, nevertheless, a drastic difference between our case and classical Rayleigh-Bénard (RB) or Bénard-Marangoni (BM) situations. Usually, in RB or BM, the basic state is a zero velocity conduction state and the first instability leads to steady convection at a critical Rayleigh number Ra_c or Marangoni number Ma_c, respectively. Later on, for much higher values of the driving dimensionless numbers, a time-dependent convection will appear. In our case, heating of the liquid is not achieved by a heated bottom plate supporting the liquid but by an immersed hot wire. Consequently, **grad T** is not parallel to **g**, with the consequence that the convection develops from the beginning [19], the basic state being then a steady convective state, and we expect that the phenomena we observed would correspond to a first instability leading from that steady convective state to a time-dependent convective state. A theoretical attempt to predict our measurements is currently being developed in this spirit, by perturbing the basic convective state and performing a linear analysis to determine the onset values of oscillatory convection.

5. Conclusion.

We have reported quantitative results on a presumably new effect, namely the appearance of oscillatory phenomena in liquids heated by a linear hot-wire source located under the free surface. Onset temperatures and onset frequencies have been measured for a series of silicone oils, in well controlled situations. A discussion is also provided to discuss the similarities and differences with classical Rayleigh-Bénard or Bénard-Marangoni kind of experiments.

Acknowledgments.

We are indebted to the referees, whose remarks have greatly helped us to improve our manuscript and to ensure a better transmission of information.

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