Convective and Free Surface Instabilities Provoked by Heating Below an Interface

G. Gouesbet,* M. E. Weill,† and E. Lefort‡
Institut National Supérieur de Chimie Industrielle de Rouen, Mont-Saint-Aignan, France

This paper discusses a new phenomenon, the so-called optical heartbeat apparently observed for the first time in 1981. The optical heartbeat is formed under certain conditions by the oscillations of a thermal lens produced when a continuous-wave (CW) laser beam propagates below a liquid-free surface. The contents of the paper are divided into two parts: first, a discussion of the mechanisms leading to the observed phenomena is presented; second, the laminar/turbulent transition is examined in some detail to illustrate several universal features of the optical heartbeat. The physical properties connected with the phenomena under discussion include convective heat transfer, which is associated with convective Bénard and Marangoni instabilities possibly coupled to laser irradiation effects.

Nomenclature

A	= spectrum amplitude
C	= concentration
C_p	= heat capacity
d	= depth of immersion of the hot wire
d_m	= depth of immersion of the hot wire at ΔT_m
D	= hot-wire diameter
D_m, D_M	= minimal and maximal diameters, respectively, of the outermost black ring in the HB2
D_r	= ring diameter in the HB2 before dedoubling into D_m and D_M
f	= frequency
f_c	= critical onset frequencies
f_L	= focal length
h	= height of the shallow liquid layer in HB2
H	= cell dimension in the direction of the laser propagation
ℓ	= horizontal cell dimension, perpendicularly to the direction of the laser propagation
L	= hot-wire length, or cell height
P	= laser power
t	= time
T	= hot-wire temperature
T_c	= critical onset temperatures
U	= signal amplitude in the time domain
α	= thermal expansivity
ΔT_c	= relative onset temperatures
ΔT_m	= minimal relative onset temperatures
λ	= laser wavelength or thermal conductivity
ν	= kinematic viscosity
ρ	= density
σ	= surface tension

I. Introduction

IN recent years, the study of the transition to chaos in real dissipative dynamical systems has been receiving increased attention. This field of research is producing a set of strongly linked new concepts that forms a physical and mathematical entity whose beauty can be compared with special and general relativity, or with quantum mechanics. A good review is given by Eckmann[1] and, more recently, by Cvitanovic.[2] A book by Bergé et al.,[3] which presents an appealing and well-documented overview of the topic, also deserves mention. Briefly stated, several routes to chaos have been modeled and discussed by theorists. The most celebrated is probably the Ruelle-Takens scenario, where a strange attractor is likely to appear after three successive bifurcations,[4,5] the transition through an infinite cascade of subharmonic bifurcations,[6-8] and the intermittency model.[9-11]

These routes, and other related phenomena, have been experimentally observed and discussed by many, including Maurer and Libchaber,[12] Rajagopalan and Antonia,[13] Gollub and Benson,[14] Linsay,[15] Snapp et al.,[16] and Croquette and Poitou.[17] A discussion of these experiments enables us to emphasize the relevance of this field of research to various applications. More particularly, a wide range of applications can be mentioned in connection with natural convection, such as problems of crystal growth and solidification or problems of combustion control discussed in Ref. 18. Reference 18 clearly shows that the study of convective transport processes and of the mechanisms leading to instabilities is a domain of much interest, both for the researcher who wants to understand the nature of turbulence and transitional behaviors and for the engineer who has to control mass and heat transfers in various situations.

Our laboratory explicitly entered this field of research after the fortuitous observation of an apparently new phenomenon, the so-called optical heartbeat, which was observed for the first time in 1981. The aim of the present paper is to report on the work carried out during the last four years, to understand, and to describe it.

II. Empirical Observations

From an historical point of view, the original observations of the optical heartbeat were made in Ref. 19. Here an argon-ion laser ($\lambda = 514.5$ nm, TEMoo-mode) was focused on a cell containing ferrofluids (cobalt particles in toluene, with a 120-Å mean diameter). When leaving the cell, the beam exhibited a strong divergence, which produced a very regular and contrasted ring pattern when projected onto a screen. For a short time after switching on the beam (on the order of a fraction of a second) the ring pattern is axisymmetric. It then evolves to a nonsymmetric pattern resembling a half-moon. Visibility and number of rings depend on the

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*Professeur, Laboratoire de Génie Chimique Analytique. Member AIAA.

†Maître-Assistant, Faculté des Sciences.

‡Boursier.

laser power, the cell (mainly the dimension in the propagating light direction), and the cobalt particle concentration. These phenomena have a thermal origin and can be characterized by thermal lens and (or) thermal blooming. They have been previously observed in Refs. 20 and 22, among others. Livingston[23] showed that the half-moon pattern is the result of free convection. The influence of natural convection is also (qualitatively) illustrated by the rotation of the ring pattern when the laser beam approaches one of the side walls.

When the laser beam traverses the cell a fraction of a millimeter below the free surface (interface liquid/air), the ring pattern does not remain steady but soon starts to pulse periodically, like a heart, for sufficiently high laser power. This new phenomenon (which we have called optical heartbeat) has also been obtained with ludox suspensions or colloidal silver in a solution of rhodamine. In all cases, the incident power and the particle concentration must be adjusted to transition from steady state to an oscillatory behavior. More specifically, consider the thermal lens steady state, which is laminar. As the laser power is increased, the steady state first evolves to a time-dependent periodic state with (apparently) one fundamental frequency. Increasing power further, another periodic state develops, resembling a beating phenomenon in which two fundamental frequencies are present. Continuing to increase the power causes the image of the optical heartbeat to become more and more complicated, ultimately reaching a seemingly nonperiodic state, which can be thought of as a kind of optical turbulence. (We shall refer to it as optical heartbeat turbulence to avoid confusion with an optical turbulence studied in another context.)

III. Approach

Starting from these first observations, research has evolved in two different (but complementary) directions. They are:

1) Attempt to understand the mechanisms leading to the successive instabilities from the laminar thermal lens to the periodic oscillations and then to turbulent optical heartbeats. As a first step, attention will be focused only on the first instability from the thermal lens to the one-fundamental-frequency optical heartbeat.

2) Rather than concentrating on the specific causal mechanisms, recognize that we are faced with a kind of laminar/turbulent transition that might exhibit universal features, independent of the specific physical system under study, using the recent theories mentioned in the Introduction as a guide.

IV. Understanding the Causal Mechanisms

A. Experimental Problem Simplified

Using shadowgraphy and schlieren photography, it was observed that the optical heartbeat oscillations were accompanied by free surface oscillations. Further, it was observed that the presence of particles in the liquid were not necessary. The main role of the particles is to absorb the incoming light. However, optical heartbeats can be produced using liquids with the necessary (but not sufficient) condition that they must absorb the laser power. An example is silicon oils colored with an adequate dye. Whatever the precise mechanism involved, the optical heartbeat and free surface oscillations are provoked by the local heating of the fluid produced under the surface by the laser power absorption.

Accounting for these observations, the experimental (and theoretical) problem can be simplified as follows. First, local heating under the surface can be obtained using a well-controlled hot wire instead of a laser beam. As expected, oscillations of the free surface appear when the wire temperature is higher than a certain onset value, the amplitude of the perturbation increasing continuously with the wire temperature in a fashion that is the signature of a supercritical bifurcation.[24] In preliminary experiments,[25] the wire was heated with a constant power in several different liquids. Table 1 shows that it was not possible to observe any oscillatory phenomena in certain liquids irrespective of the power dissipated in the wire and the free surface/wire distance.

Note that oscillations are observed in water with the addition of about 20% iron perchlorure. However, given a liquid of known thermophysical properties, we are not yet able to predict whether oscillations will be observed.

Other authors have studied the behavior of fluids heated in the neighborhood of a free surface. In Kayser and Berg's experiment,[26] the heated wire was located at the bottom of a thin layer of silicon oil or of a glycerol/water mixture. Reinmann[27] used a hot wire to study the heat transfer near an air/water interface. Incropera and Yaghoubi[28] studied the convection around cylinders near the same interface. Based on their reported results, no free surface oscillations were observed. In Kayser and Berg's experiments,[26] the dissipated power was of an order of magnitude smaller than the present case. Further, convection probably could not develop efficiently because the wire was resting on the bottom of the cell. For the other two experiments, oscillations should not be expected because, as shown in Table 1, they do not appear when the liquid is water.

B. Experimental Setup

For the more recent hot-wire experiments, we chose to perform measurements with a series of silicon oils having well known thermophysical properties. Furthermore, the hot wire was maintained at constant temperature instead of working at constant power as discussed in the previous section.

The liquid under study was contained in a copper tank ($17\times 12\times 5$ cm^3) with five glass windows on the bottom and on the walls for optical observations. This tank was encased in a second tank, with the temperature thermostatically controlled. The hot wire, immersed under the free liquid/air surface, was a platinium wire of length $L=3$ cm, diameter $D=2$ μm, and a temperature coefficient of 3.92×10^{-3} K^{-1}. The L/D ratio was large enough to assume a constant wire temperature. Mechanical and optical devices enable us to stretch the wire, to adjust the depth of immersion of the wire, and to keep it horizontal.

The wire temperature was regulated by means of a constant temperature anemometer (CTA), usually used for velocity measurements in gases. Preliminary experiments

Table 1 Observations of free-surface oscillations in different liquids

Liquid	Oscillations	Liquid	Oscillations
Acetone	Not observed	Ethanol	Not observed
Benzene	Observed	Ether	Not observed
Cyclohexane	Not observed	Silicon oil[a]	Observed
Water	Observed	Tolune	Observed

[a]Rhodorsil 47V20.

Table 2 Physical properties of oils used (CGS at 25°C)

	47V5	47V10	47V50	47V100
ν	5.10^{-2}	10.10^{-2}	50.10^{-2}	100.10^{-2}
ρ	0.91	0.93	0.959	0.965
K_T	6.7×10^{-4}	7.6×10^{-4}	1.13×10^{-3}	1.12×10^{-3}
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

NB: ν, kinematic viscosity; ρ, density; K_T, thermal diffusivity; σ, surface tension; α, thermal expansivity.

established a calibration curve correlating the wire temperature T and an external adjustable control resistance R_c.

For the liquid, volatile products were excluded because of interfacial evaporation, which modifies the surface properties. Rhodorsil silicon oils 47V5, 47V10, 47V50, and 47V100 were chosen because they have low evaporation and aging rates. Their physical properties, as provided by the manufacturer, are given in Table 2.

C. Oscillation Detection and Threshold Measurements

Steady velocity and temperature fields are associated with steady behavior of the CTA. Conversely, oscillatory convection in the liquid produces an oscillatory behavior of the regulated wire voltage output. To detect this change of behavior, the voltage output is analyzed by means of an FFT HP 3582A spectrum analyzer connected to an XY plotter.

Detection of free surface deformations was best achieved using a standard reflecting schlieren system. The light source was an He-Ne enlarged laser beam directed onto the surface of the liquid above the wire. The reflected light was focused by a lens ($f_L = 15$ cm) and half-cut by a knife. The light was then received on a viewing screen located at ~ 1 m from the focusing lens. Sensitivity of the technique was tested by simulating the deformations of the free surface with a straight (cold) wire, which is allowed to cling to the surface to stress it, producing ad libitum a crest or a trough.

Measurements of the instability threshold were performed using the spectrum analyzer output. For a given immersion depth d of the wire, the object is to determine the critical wire temperature below which no oscillations will be generated independently of time. That critical temperature is experimentally defined through an iterative procedure as the one at which the amplitude of the fundamental peak of the power spectrum of the voltage output vanishes. The frequency of the fundamental is also measured. Critical temperatures T_c can be reproduced within 1°C and associated frequencies f_c within $\pm 1/100$ Hz.

Strictly speaking, the above measurement procedure quantifies the onset values for an oscillatory behavior of the convection in the liquid surrounding the wire. By comparison with simultaneous optical detection, it has been observed that the onset values for time-dependent convection correspond to the onset values for time-dependent motion of the free surface.

D. Results

Onset temperatures T_c are obtained from the control resistor R_c when the amplitude of the fundamental peak is zero, using the $R_c(T)$ calibration curve. Figure 1 shows the relative onset temperatures $\Delta T_c = T_c - T_\infty$ ($T_\infty = 25$°C) vs the depth of immersion d. The curves are fairly parabolic. The minimal temperature ΔT_m, associated with the depth d_m, decreases as the fluid viscosity decreases. Figure 2 shows the onset frequencies f_c vs d. As d increases, f_c first decreases rapidly, approximately as $1/d^2$, and then remains fairly constant for d above $\sim d_m$. Frequencies increase as the viscosity decreases. These results indicate that there are two different behaviors, depending on whether $d > d_m$ or $d < d_m$. The existence of these two different behaviors is strikingly exhibited in Fig. 3, which shows f_c vs ΔT_c.

Accuracy is estimated to be within 3 K for the temperature measurements and within a few hundredth of a hertz for the

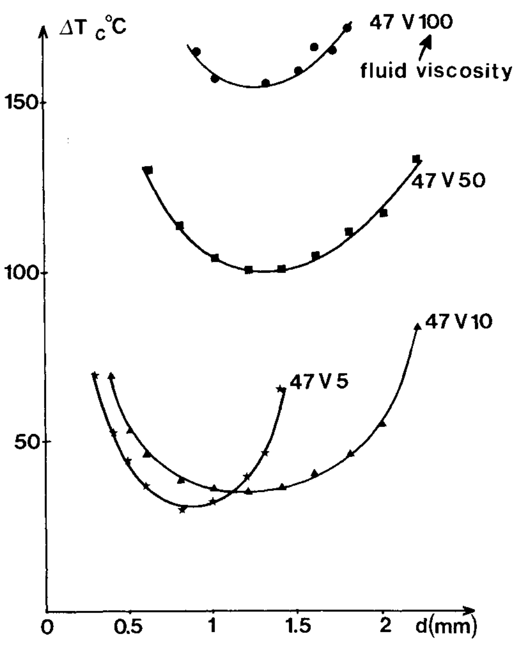

Fig. 1 Onset temperatures for the hot-wire experiments.

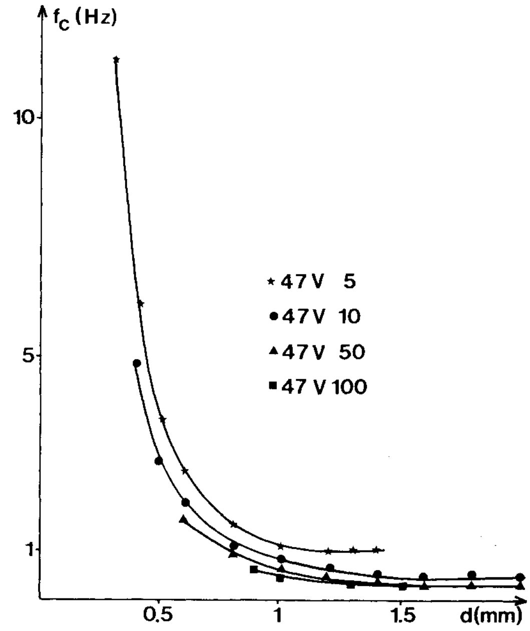

Fig. 2 Onset frequencies for the hot-wire experiments.

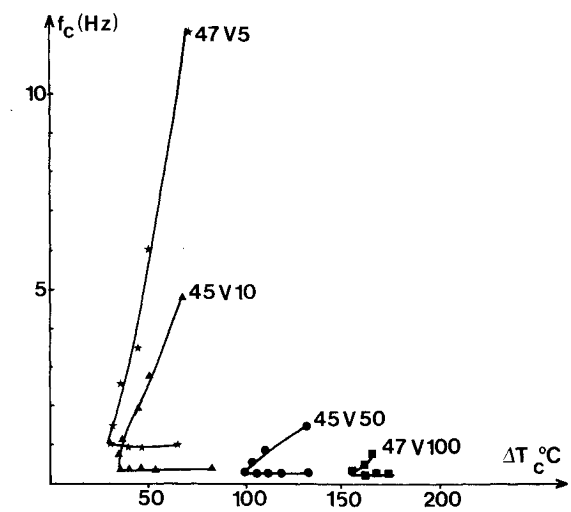

Fig. 3 Onset frequencies vs relative onset temperatures for the hot-wire experiments.

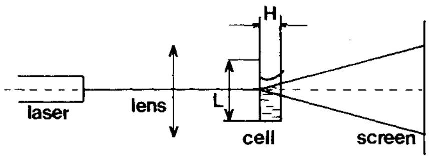

Fig. 4 Experimental setup for the HB1.

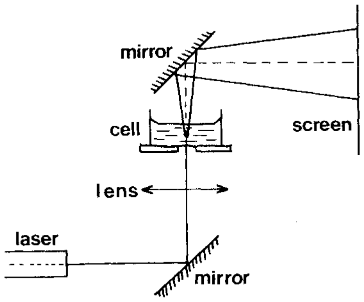

Fig. 5 Experimental setup for the HB2.

frequency measurements, except for the 47V100 case where measurements were rather difficult. As a matter of fact, that very viscous oil must be heated for more than 20 min before appearance of the oscillatory behavior.

It could be argued that the above results should be presented in terms of dimensionless numbers. To do this requires the correct identification of the dimensionless groups relevant to the phenomena. As stated in Sec. E, a linear analysis is currently being pursued to predict the onset temperatures and frequencies. Due to the lack of symmetry in the problem, the linear analysis appears to be a very difficult task to perform and is not yet completed. A very large number of dimensionless quantities have appeared in the theoretical procedure including the Rayleigh, Marangoni, Prandtl, crispation, and viscosity numbers. Since the linear analysis is not completed, adequate identification of the appropriate dimensionless numbers is uncertain.

E. Discussion of Results

Similarity between the results of these experiments and the Bénard-Marangoni (BM) and Rayleigh-Bénard (RB) effects must be stressed. It is now well established[26,29,30] that, for tension-driven convection (BM), the free surface is depressed above a hot stream, while for buoyancy-driven convection (RB), it is elevated. The transition between depression and elevation has been classically observed for a pool depth of ~3-4 mm. In the present case, schlieren observations of the free surface before oscillations have shown that the surface is depressed for $d<d_m$ (suggesting that a tension-driven mechanism is dominating) while it is elevated for $d>d_m$ (suggesting that a buoyancy-driven mechanism is dominating). It is also well known[31,32] that for a liquid pool supported by a heated surface, the onset of instability depends mainly on the Marangoni number for a shallow pool and on the Rayleigh number for a deep pool, with both surface tension and buoyancy acting together in between. This is similar to the results shown in Figs. 1-3. We are thus inclined to think that our instability is mainly surface-driven for $d<d_m$ and mainly buoyancy-driven for $d>d_m$, with both mechanisms acting in between to produce a minimum in the $\Delta T_c=f(d)$ profile. The main difference with BM and RB effects, on the other hand, is as follows. In BM and RB, the basic state is a pure conduction state, the first instability leading to a steady convection state. In our case, gravity is not parallel to the temperature gradient. Consequently the basic state is a convective one, at least if the fluid is reasonably governed by the Oberbeck-Boussinesq equation.[24] For the first instability, the system evolves from a steady convective state to a periodic convective one. This is the present picture we have in mind to explain the phenomenon. To confirm this interpretation, we are attempting to predict the onset values of instability in the framework of a linear analysis which should be, in principle, successful, as far as the observed bifurcations appear to be supercritical. In practice, the theoretical problem is formidable and we failed up to now, although some progress has been made.[33-35] More details on the hot-wire experiments are available in Refs. 35 and 36.

The picture is just a bit more complicated for the optical heartbeats. The incoming laser beam heats the liquid and produces a temperature gradient field initially having the same axial symmetry as the beam. Due to the dependence of refractive index on temperature, however, this temperature gradient acts as a diverging thermal lens and scatters the beam. When projected on a screen, an axisymmetric ring pattern is observed.

In terms of geometrical optics, we could say that the beam path is altered by absorption and refraction. We actually prefer to use the word scattering, which refers to a more fundamental phenomenon, in which the light is considered as being an electromagnetic wave rather than a bundle of rays. To clarify this point, consider the classical Mie theory, which describes the scattering of a plane wave by an ideal spherical particle. It is only when the ratio of the particle diameter to the light wavelength becomes very large that the description of the light/particle interaction in terms of refraction, absorption, and diffraction makes sense.

In the absence of convection, the observed ring pattern would remain axisymmetric and come to a steady state. Since the temperature gradient is not parallel to gravity, convection is present. This distorts the axisymmetry of the thermal lens, leading to the steady half-moon pattern. When the thermal lens approaches the free surface, heat is transported to the free surface by both diffusion and convection, producing a temperature gradient field in the surface, and consequently a surface-tension gradient. Under certain circumstances, which remain to be fully specified, a Marangoni instability develops, leading to an oscillatory behavior of the free surface. This Marangoni instability generally seems to be coupled to a buoyancy instability as previously discussed. As a result of the free surface time-dependent behavior, heat transport becomes time-dependent and modulates the scattering object (thermal lens), which also becomes time-dependent, thus producing the optical heartbeat. After several instabilities, the optical heartbeat behavior apparently becomes turbulent, leading to the question of how to characterize the corresponding laminar/turbulent transition and to the problem of how to demonstrate the expected universal features of this process.

V. Transition to Turbulence

A. Two Kinds of Optical Heartbeat

The optical heartbeat discussed up to now will be called HB1 (heartbeat 1). The experimental setup used to produce it is sketched in Fig. 4. Da Costa and Calatroni[37] reported on phenomena observed when intense light beams interact with certain liquid media. More precisely, in their experiments, thin liquid slabs of heavy hydrocarbons with a top free surface were irradiated vertically from above by a Gaussian laser beam. Nonuniform heating of the surface produced a surface-tension gradient, depressing the free surface due to laser-induced thermocapillarity. Backward reflection of the beam also produces an axisymmetric ring pattern quite similar to that of a thermal lens but without any oscillatory behavior (up to now). Such a feature is not surprising. First, since the laser propagates downward, the fluid is heated more above than below, a buoyancy-stable situation. Second, the surface is probably constrained by the laser, which hits it directly to a tension-stable situation. This

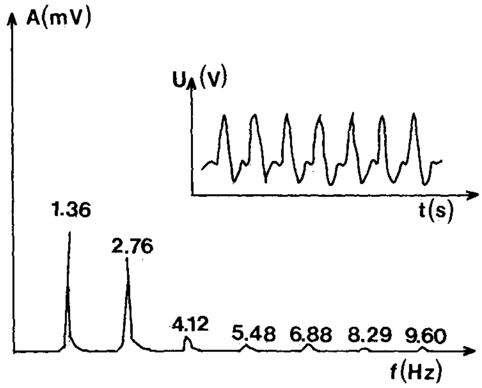

Fig. 6 HB1 in the frequency and time domains ($P=0.42$ W). The signal is periodic.

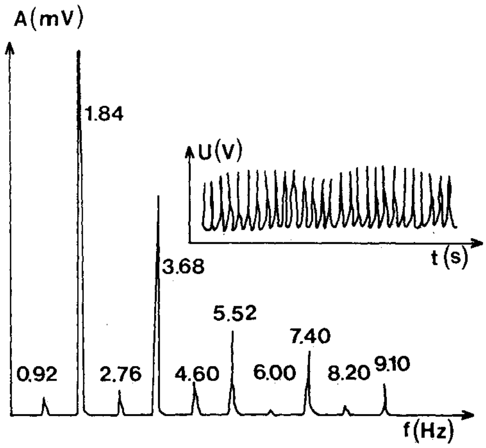

Fig. 7 HB1 in the frequency and time domains ($P=0.56$ W). The signal is periodic, but a period doubling bifurcation has occurred.

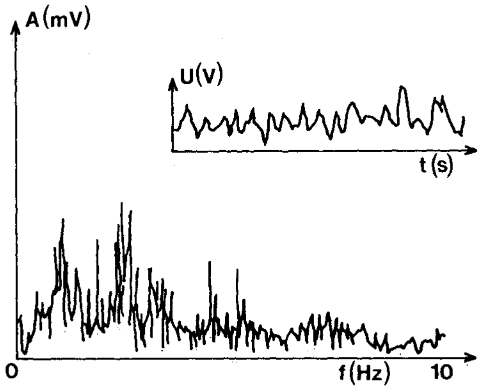

Fig. 8 HB1 in the frequency and time domains ($P=0.66$ W). The signal is aperiodic (and turbulent). Note the background noise in the spectrum.

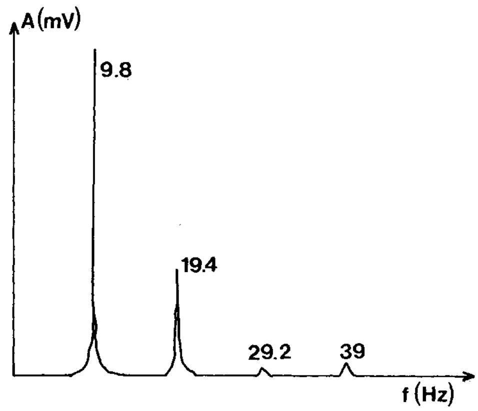

Fig. 9 Example of spectrum for the periodic HB2.

suggests carrying out similar observations with the laser beam propagating upward. The standard experimental setup is sketched in Fig. 5. It leads to another optical heartbeat that we shall call HB2.

B. Transition to Turbulence in HB1

In HB1, the focusing lens (focal length = 16 cm) is located 9 cm from the median plane of the cell. The horizontal cross section of the cell is a 1×1 cm^2 square, and the depth of the liquid is ~ 4 cm. The laser beam (Ar-ion spectra physics, TEMoo mode) horizontally crosses the cell at ~ 1.5 mm below the free surface. The liquid is toluene containing particles of cobalt, i.e., a ferrofluid solution. The final solution is obtained by diluting in toluene a manufactured solution (Ferrofluids Corp. EM4. 600 G) down to a concentration of $C=0.05\%$. The outgoing diverging beam is directed onto a beam scatterer with a photodiode behind it. The photodiode output is fed to an FFT spectrum analyzer. Examples of results are given below. For a laser power $P=0.42$ W, the thermal lens starts to beat. Figure 6 shows the signal as a function of time and frequency (fundamental at 1.36 Hz). From $P=0.42$ W to $P\sim 0.52$ W, the frequencies increase steadily. At $P\sim 0.54$ W, a doubling period bifurcation is observed, suggesting that we are at the beginning of a Feigenbaum cascade of subharmonic bifurcations. Figure 7 shows the corresponding signal. Note the peak at half the fundamental frequency and harmonics. Increasing the laser power, we will utltimately reach a seemingly turbulent behavior characterized by background noise in the spectrum (Fig. 8). More details are available in Ref. 38.

C. Return to the Steady State in HB2

For HB2, the beam is focused by a lens (focal length = 16 cm). The horizontal cross section of the (glass) cell is a 5×5 cm^2 square, and the laser beam passes through the intersection of its diagonals. The liquid is the same as that for HB1, but with $C=0.1\%$. The pool is a shallow layer of height h. In the absence of the layer, the beam waist is located at ~ 5 cm above the bottom of the cell. A photodiode output is produced as in HB1 and fed into the spectrum analyzer. When projected onto a screen, we observe a ring pattern (thermal lens), which remains axisymmetric and which is steady in most situations. But, for particular values of h and laser power P, a periodic oscillatory state is reached which is HB2. Figure 9 shows an example of spectrum. The shape of the ring pattern remains circular above the critical values of the control parameters so that HB2 then can be characterized by simple quantities such as the minimal D_m and maximal D_M, diameters of the outermost black ring. The diameters tend to increase when h increases because the divergence of the beam in the pool occurs over a longer distance. For $P\sim 0$, the heart is just a spot whose diameter is equal to the laser beam diameter and is not measured unless the outermost black ring appears. Then, the diameter D_r of that ring increases with P, up to the onset of instability and the diameter dedoubling into D_m and D_M. Nevertheless, an important (and at first unexpected) result is that by increasing P further, the phenomenon does not become more complicated but returns to its steady diverging beam state. This return to the steady state is attributed to the constraining of the surface by the high power beam, which prevents the development of further instabilities. Again, more details are available in Ref. 38.

D. Low-Power Optical Heartbeats

It could have been possible to pursue this direction further by systematic parameter variation. Nevertheless, we decided

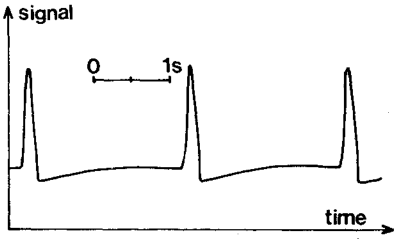

Fig. 10 Time signal for a low-power optical heartbeat (CCl_4 with 1 g/ℓ of "vert organol").

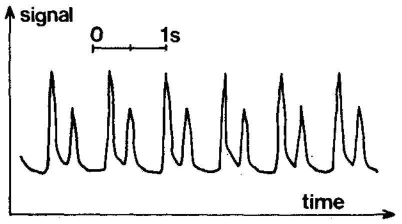

Fig. 11 Another time signal for a low-power optical heartbeat.

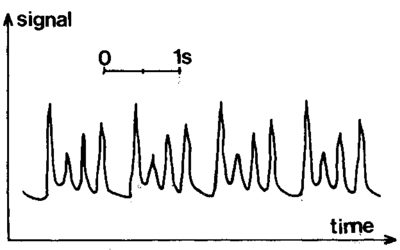

Fig. 12 Another time signal for a low-power optical heartbeat.

to attack another problem first. Remember that in HB1 the first bifurcation of the steady thermal lens to the periodic optical heartbeat occurred for a laser power of order ~500 mW. It was decided to search for a more sensitive system with the aim of making the first critical power smaller than about 10 mW. We hoped that if we were successful, it would be possible to 1) replace the use of a powerful costly laser (Ar-ion) by a low power much cheaper laser (He-Ne) 2) avoid interruptions of observations by boiling, which has occurred in some circumstances, 3) learn more about the conditions necessary to obtain optical heartbeat phenomena, and 4) obtain in fact a more sensitive system, which can be expected to provide us with a wider range of observations.

That quest was not easy because we lacked a complete theory of optical heartbeat instabilities to guide our efforts. Nevertheless, using intuition, some positive results, which are given below, have been obtained. Again using ferrofluids, adjusting the concentration and decreasing the width of the cell to ~1 mm, well contrasted optical heartbeats have been produced with powers of about 20-30 mW. Unfortunately, this value is still too high, and it was found difficult to go below that value. Other liquids have been successfully tested to produce optical heatbeats (styrene, benzene, acetone colored with ferrofluids, ferrofluids, and "rouge organol BX1750," respectively). A special effort was made using silicon oils colored with a "rouge organol BX1750" dye from ICI-Francolor. The critical powers were of about 28 mW, 13 mW, and 12 mW for oils having respective kinematic viscosities of 5.10^{-2}, 4.10^{-2}, and 3.10^{-2}, stoke for a ($H=5$, $\ell=10$, and $L=45$ mm) cell. No optical heartbeat was obtained with an oil having a viscosity of 2.10^{-2} stoke. By heating a 47V5 oil (5.10^{-2} stoke at 20°C) at a temperature of about 70°C in a cylindrical thermostated cell, we obtained an optical heartbeat at about 5 mW. Since the critical P value finally obtained was smaller than 10 mW, we decided to pursue the experiments with a low-power He-Ne laser.

With a 10-mW He-Ne laser, no optical heartbeats have been obtained with silicon oils, probably because we have failed (up to now) to find an adequate dye to absorb the 632.8-nm light of the beam. Further efforts should be devoted to this kind of liquid. A successful result has been obtained with (among other cases) CCl_4 colored by "vert organol 2J" dye from ICI-Francolor, at a power of about 4-mW. The optical heartbeat is particularly well contrasted. More details are available in Ref. 39. Another good liquid is n-decane, which easily produces optical heartbeats at low powers.

Finally, spectrum analyzer outputs can be obtained in a way similar to the ones described in the preceding sections. Examples of XY recordings giving photodiode output voltages vs time are shown in Figs. 10-12. The three different cases corresponding to various distances between the laser beam and the free surface.

The full time scale corresponds very roughly to about 1 s. Figure 10 shows the signal after the first bifurcation from the steady thermal lens to the optical heartbeat and Figs. 11 and 12 after a second bifurcation and third bifurcation, respectively.

VI. Conclusion

This paper reports on the oscillations of the thermal lens, namely, the optical heartbeat phenomenon, produced when a laser beam travels near and below the free surface of an absorbing liquid. A simpler experiment, where the laser beam is replaced by a hot wire, allows the identification of causal mechanisms that are similar to the phenomenon associated with Bénard-Marangoni and Rayleigh-Bénard convection. Further, it allows one to stress significant differences and to suggest a mechanism to understand the appearance of the instabilities. The optical heartbeat also exhibits a very beautiful and fascinating example of laminar/turbulent transition, which should posses universal features, irrespective of the precise details of the system. Finally, a way to produce optical heartbeats using a low-power laser has been discussed.

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