

## Heating Curves in the Two-Component Bénard Problem

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### Abstract

In this paper we study experimentally the onset of free convection in a two-component liquid layer heated from below (Rayleigh-Bénard problem) taking into account the Soret effect. Taking the temperature difference, or the rate of heat production in a solid layer below the convection layer as independent parameter, does not cause any differences as long as the relation between heat flux and Rayleigh number is purely monotonic. However in mixtures, when the Soret effect becomes operative, the Rayleigh number and the heat flux are not always monotonically related, and this can lead to the situation where a stable stationary solution does not exist for all values of the heat flux, even when there are stable stationary solutions for all Rayleigh numbers. Thus, the physical situation changes if the heat production is taken as the prescribed parameter, instead of the temperature difference. This is experimentally demonstrated. As a byproduct of the heating curves, we show that accurate values of the ratio of the thermal diffusion coefficient to the isothermal diffusion coefficient are obtained.

### Introduction

It is well known that a layer of a pure liquid heated from below becomes unstable for a critical temperature gradient. In this case, the principle of exchange of stabilities is valid (Chandrasekhar [1]). The numerical value of the critical reduced temperature gradient (or of the critical Rayleigh number) depends on the type of boundary conditions adopted (1707.762 for the so-called “rigid boundaries” or  $27\pi^4/4$  for free boundaries). Also the amplitude of the convective motion is proportionnal to  $(Ra - Ra^{crit})^n$ , where  $n = \frac{1}{2}$ , at least near the threshold of convection. For layers of liquid mixtures, thermal diffusion (also called Soret effect) must be taken into account; this effect induces a molecular separation due to the thermal gradient, and the resulting mass fraction gradient drastically changes the stability of the system. Indeed, we have now two diffusion fields: heat and mass diffuse at two different rates. Thus the present investigation belongs to

what is generally termed "double diffusive convection" taking place in particular circumstances: the concentration gradient is the result of the Soret effect and not at all imposed by some boundary conditions (e. g. prescribed concentrations of the different species at the boundaries). A lot of paper have already been published on the subject, including linear theory, nonlinear theory and some experiments ([2-9]).

One of the features of the two-component problem is the non validity of the principle of exchange of stabilities in a large range of values of the thermal diffusion coefficient, more precisely when the more dense component migrates toward the warm lower plate, and decreases in that way the total density gradient. The present paper only discusses the cases where the temperature gradient is destabilizing the system. In these conditions, convection occurs at values of the Rayleigh number higher than in pure substances, but the amplitude of the convection reaches directly a finite value, even if the temperature gradient exceeds infinitesimally the critical one. This is due to the existence of subcritical instabilities and of an hysteresis loop. Moreover in these cases, the temperature gradient and the heat flux are not monotonically related. Therefore, physically it is not equivalent to impose either the heat flux or the temperature difference as independent variable. Indeed, even if there is always a stationary state for all values of the temperature difference, it is not sure that a stationary state exists for all values of the heat flux.

In order to prove this experimentally, we have designed two different apparatus. In the first one we impose the temperature difference thanks to flows of thermoregulated water and we measure the resulting heat flux; in the second apparatus we impose electrically the heat flux and we measure the temperature difference. For a mixture of water-isopropanol two different physical behaviours are demonstrated experimentally.

## 1. Summary of previous results

An initially homogeneous two-component horizontal fluid layer (in the experiments reported below, a mixture 9.1 wt % isopropanol and 90.9 wt % water) is submitted to an adverse temperature gradient (Fig. 1). The density depends both on temperature and composition, and we use a linear expression

$$\rho = \rho^0 [1 - \alpha(T - T^0) + \gamma(N_1 - N_1^{in})] \quad (1)$$

with

$$\alpha = -\frac{1}{\rho^0} \left( \frac{\partial \rho}{\partial T} \right)_{N_1^{in}},$$

and

$$\gamma = \frac{1}{\rho_0} \left( \frac{\partial \rho}{\partial N_1} \right)_{T^0}.$$

$\rho^0$  is the density at the mean temperature  $T^0$  and at the initial composition  $N_1^{in}$

(the index 1 refers to the more dense component). As usual, we introduce the Rayleigh and the Prandtl numbers.

$$Ra = \frac{g\alpha(T_2 - T_1)d^3}{\kappa\nu},$$

$$Pr = \frac{\nu}{\kappa};$$

$d$  is the thickness of the fluid,  $\kappa$  its thermal diffusivity and  $\nu$  its kinematic viscosity.

In the particular case of mixtures, we also introduce additional parameters: the Schmidt number  $Sc$ , the thermal diffusion Rayleigh number  $R_{th}$ , and the Soret number  $\mathcal{S}$

$$Sc = \frac{\nu}{D},$$

$$R_{th} = \frac{g\gamma N_1^{in} d^3}{\kappa\nu},$$

$$\mathcal{S} = \frac{D'}{D}(T_2 - T_1)(1 - N_1^{in}).$$

$D$  is the isothermal diffusion coefficient and  $D'$  is the thermal diffusion coefficient. Its sign determines the sense of the migration of component 1. Let us observe that the product

$$-\frac{R_{th}\mathcal{S}Sc}{Pr} = \frac{-g\gamma N_1^{in} N_2^{in} \frac{D'}{D}(T_2 - T_1)d^3}{D\nu}$$

may be viewed as the thermosolutal Rayleigh number used generally in double diffusive convection, since

$$-N_1^{in} N_2^{in} \frac{D'}{D}(T_2 - T_1)$$

represents the mass fraction separation  $\Delta N_1$  due to the Soret effect. However  $\Delta N_1$  being not directly imposed, we prefer the use of  $\mathcal{S}$  as independent parameter (itself proportional to  $\Delta T$ ) while the physical properties of the mixture are included in dimensionless numbers such as  $Sc$ ,  $R_{th}$ , ...

The unrealistic case of free and pervious boundaries but theoretically more tractable, has been investigated by Platten [3]. He gives an expression for the critical Rayleigh number as a function of all relevant parameters.

Two cases must be considered separately:

(i) the case where the principle of exchange of stabilities is valid:

$$Ra^{\text{crit}} = \frac{27\pi^4}{4} - R_{th}\mathcal{S} \frac{(Pr + Sc)}{Pr}, \quad (2)$$

(ii) the case of overstability

$$Ra^{\text{crit}} = \frac{27\pi^4 (1 + Sc)(Sc + Pr)}{4 Sc^2} - R_{th}\mathcal{S} \frac{Pr}{Pr + 1}. \quad (3)$$

The pulsation is given by

$$\sigma_I = \left[ -\frac{R_{th}\mathcal{S}}{3Pr(Pr + 1)} - \frac{9\pi^4}{4Sc^2} \right]^{\frac{1}{2}}. \quad (4)$$

Thus, from Eq. (4), overstability occurs only when  $\mathcal{S} < 0$  and  $|\mathcal{S}| > |\mathcal{S}^*|$ , with

$$|\mathcal{S}^*| = \frac{27\pi^4 Pr(Pr + 1)}{4 R_{th}Sc^2}. \quad (5)$$

For the realistic boundary conditions (rigid plates, impervious to the matter, conducting, e.g. two copper plates) numerical solutions (using variational methods such as the local potential technique, see Legros, Platten and Poty [9]) are available and are in qualitative agreement with the results (2–5), i. e. lead to correct predictions of stabilizing or destabilizing effects, of overstability conditions, etc. However the numerical constants, like  $27\pi^4/4$ , are of course completely changed.

In the nonlinear domain, the main result seems the prediction of finite amplitude convection below the critical point, implying the existence of an hysteresis loop (see Platten and Chavepeyer [5]).

The experimental verification is generally realized with the help of heating curves also called Schmidt-Milverton plots [10]. A heat flux is imposed electrically to the fluid layer and the resulting temperature difference is measured. For the lowest values of the heat flux (close to the equilibrium state), we observe a linear relation between heat flux and temperature difference, according to Fourier's law. At higher values of the heat flux, convection occurs and heat is now transported by the two mechanisms. The temperature difference measured is thus lower than the one that would be observed at the same heat flux in a pure conducting case.

For liquid mixtures (in conditions of overstability) the existence of the hysteresis loop was already observed in laboratory experiments by Caldwell [6] and by Platten and Chavepeyer [8]. Both experiments were realized in similar apparatus

where the heat flux was imposed. They produce “anomalous” heating curves showing a negative slope for some values of the heat flux; also very regular oscillations in the temperature field were observed, demonstrating the existence of stable periodic states. These periodic states were observed above the critical heat flux corresponding to the onset of convection, but due to the negative slope in that part of the heating curve, the onset of convection was accompanied by a drop of the temperature gradient, which becomes now subcritical. It seems thus interesting, first of all to confirm these previous experimental findings, but also to perform new experiments in which the Rayleigh number is prevented to drop. This is the main subject of this paper.

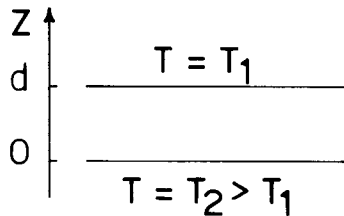


Fig. 1: Horizontal fluid layer submitted to an adverse temperature gradient.

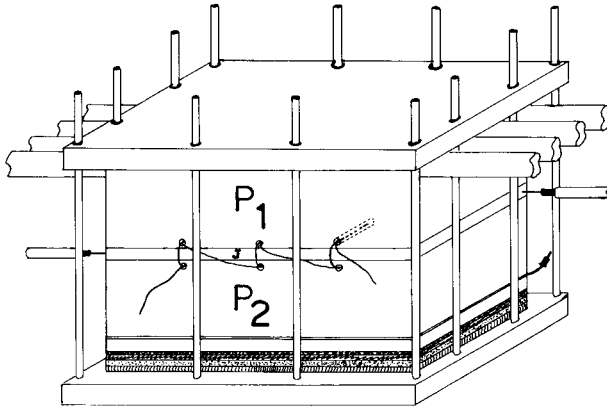


Fig. 2: Constant heat flux apparatus.

## 2. Experimental results

We shall show here that experimental procedure is important, by reporting the results of two different experiments. The first is conducted in an apparatus where the heat flux is imposed and the second in an apparatus where the temperature difference is imposed.

*Imposed heat flux (Fig. 2)*

The horizontal liquid layer is confined between two copper plates P1 and P2, and is bounded laterally by a plexiglas joint  $J$  (thickness of the liquid layer  $d = 3.07$  mm). The temperature  $T_1$  of the upper copper plate is imposed by means of thermoregulated water. An electrical resistance is inserted between an insulating material and the lower plate. The heat flux is imposed by changing the current intensity  $I$ . More precisely, we do not really impose the heat flux across the liquid layer but rather the rate of heat production in a conductive layer below the convective liquid layer. The temperature  $T_2$  adjusts itself to a certain value. Let us note that the thermal conductivity of the copper is much higher than the thermal conductivity of the liquid. Thus, the correct boundary condition is that the temperature fluctuations are zero, even if we impose the mean heat flux to the horizontal lower copper plate. The temperature difference  $(T_2 - T_1)$  is measured by means of three pairs of thermocouple junctions, as a function of the imposed heat flux. We have performed this first experiment on a water-isopropanol system (0.09 wt% alcohol). We show in Fig. 3 the Schmidt-Milverton plot [10] obtained in this apparatus. An equivalent experiment was already performed by Platten and Chavepeyer [8]. We confirm here their results. Let us observe that:

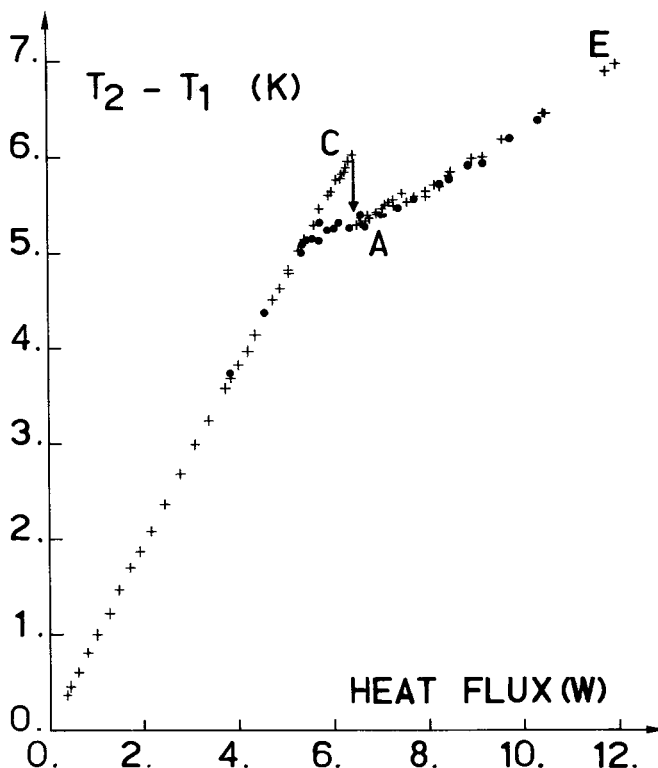


Fig. 3: Schmidt-Milverton plot for the water-isopropanol mixture in the constant heat flux apparatus.

+: results with heat flux increasing.

∴: results with heat flux decreasing.

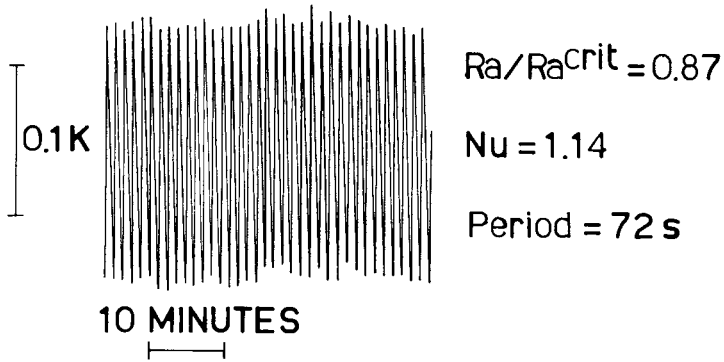


Fig. 4: Sustained oscillations in the constant heat flux apparatus.

- (i) the critical temperature difference is equal to 6.02 K, and gives  $Ra^{crit} = 2591$  (see appendix) ( $\geq 1708$ , the value for a pure liquid). Thermal diffusion has thus a stabilizing effect ( $D'/D < 0$ ).
- (ii) At the critical point  $C$ , if the heat flux is slightly increased, there is an instability and a drop in the temperature difference (see arrow), and the “final” state lies in the neighbourhood of point  $A$ . If the heat flux is still increased, the line  $A-E$  is obtained. By decreasing the heat flux, the curve is not retraced: at  $A$ , there is no jump back to  $C$ , but there is an hysteresis loop.
- (iii) After instability, in the convective regime, in the neighbourhood of  $A$ , the states of the system are not steady. Temperature measurements by negative temperature coefficients resistances, inside the liquid layer, show very regular oscillations (period = 72 s, amplitude  $\simeq 0.2$  K) recorded during more than 80 hours (Fig. 4.). These oscillations are similar to those obtained by Platten and Chavepeyer [8].

#### *Imposed temperature difference*

Figure 5 shows a new apparatus, quite similar to the first one, except two specific characteristics. First, the temperature  $T_2$  of the lower plate  $P_2$  is also controlled by thermoregulated water and adjusted to a desired value:  $(T_2 - T_1)$  becomes now the independent variable.

Secondly, the heat flux (which is now the dependent variable) is measured by means of 24 pairs of thermocouples inserted in holes in the upper plate  $P_1$ . This heat flux meter has been calibrated by putting the “top” of this apparatus onto the “bottom” of the first one. The response of this heat flux meter is linear (Fig. 6). Let us also note that the thickness of the plexiglas joint in this second apparatus is slightly different ( $d = 3.32$  mm).

The heating curves obtained with both apparatus are absolutely identical for the pure liquids (verified both on water and on isopropanol) and provides a mean

value of the critical Rayleigh number  $Ra^{\text{crit}} = 1790$  instead of the theoretical value  $Ra^{\text{crit}} = 1708$  (the error is smaller than 5%).

However, for the mixture considered in this paper, the heating curve with the new apparatus (Fig. 7) is quite different than the one obtained in the constant heat flux experiment (Fig. 3). Let us observe its characteristics:

- (i) the critical temperature difference is equal to 5.05 K. We compute a value of  $Ra^{\text{crit}}$  equal to 2688 (we obtain  $(T_2 - T_1) = 6.02$  K and  $Ra^{\text{crit}} = 2591$  with the other apparatus). Once more, a stabilizing effect due to thermal diffusion is evident.
- (ii) At point *C*, where the temperature difference  $\Delta T = (T_2 - T_1)$  is slightly increased (e. g. of 0.03 K), there is an important jump in the heat flux (of 47%) up to *D*. By further increasing  $\Delta T$  the line *D-E* is obtained. Once more, by decreasing  $\Delta T$ , the curve is not retraced: at point *D*, there is no jump back to the motionless state *C*; the system still remains in convection even if  $\Delta T < \Delta T^{\text{crit}}$ : line *D-F* is obtained. At *F*, a small decrease of  $\Delta T$  (e. g. 0.01 K) results in an important decrease of the heat flux (of about 10%) and the system goes back to a motionless state *G*. We have thus described an hysteresis loop, more easily related to the nonlinear theory than the hysteresis loop obtained in the constant heat flux experiment.
- (iii) During the transition from *C* to *D*, there are *transient* oscillations. Initially, instability sets in as oscillations of increasing amplitude (if  $t \leq 15$  min). The observed period is 37 s (Fig. 8a). During this first stage, there is no increase of the heat flux (the Nusselt number  $Nu$ , which is the value of the total heat flux relatively to the conduction heat flux, remains equal to 1). Later on, oscillations become irregular and of greater period; finally after 3–4 hours, oscillations become irregular and of greater period; finally after 3–4 hours,

Tab. 1: Data characterizing the thermo- and fluid mechanical behaviour of the water – isopropanol fluid layer.

Time interval (in min)	Mean value of the period (in s)	Flux meter output (in $\mu\text{V}$ )	Nusselt number	Amplitude of the oscillations (in K)
$0 \leq t \leq 12$	37	36	1	0.06
$12 \leq t \leq 15$	38	36	1	0.11
$15 \leq t \leq 19$	39	37	1.03	0.17
$19 \leq t \leq 24$	45	38	1.06	0.25
$24 \leq t \leq 30$	51	39	1.08	0.26
$30 \leq t \leq 35$	66	40.5	1.13	0.30
$35 \leq t \leq 52$	81	44	1.22	0.45
$52 \leq t \leq 69$	74	46	1.28	0.75
$69 \leq t \leq 84$	79	47.5	1.32	0.55
$t \approx 94$	104	48.5	1.35	0.55
$t \approx 104$	170	49	1.36	0.55
$t \approx 117$	600	49.5	1.38	0.41
$t \approx 144$	750	49.5	1.38	0.2
$t \approx 200$	1000	50	1.39	0.25
$t = \infty$	$\infty$	52.8	1.47	–



they disappear (Fig. 8b, c, d) and the final state  $D$  is steady. In the meantime, the Nusselt number increases to its final value 1.47 at the steady state  $D$ .

Table 1 summarizes the different behaviours of the system during the different time intervals.

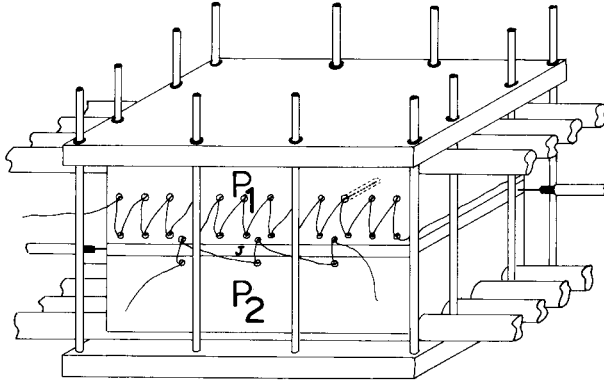


Fig. 5: Constant temperature gradient apparatus.

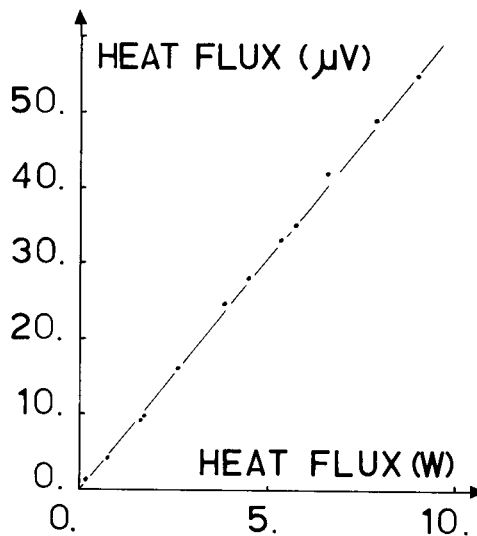


Fig. 6: Heat-flux meter calibration.

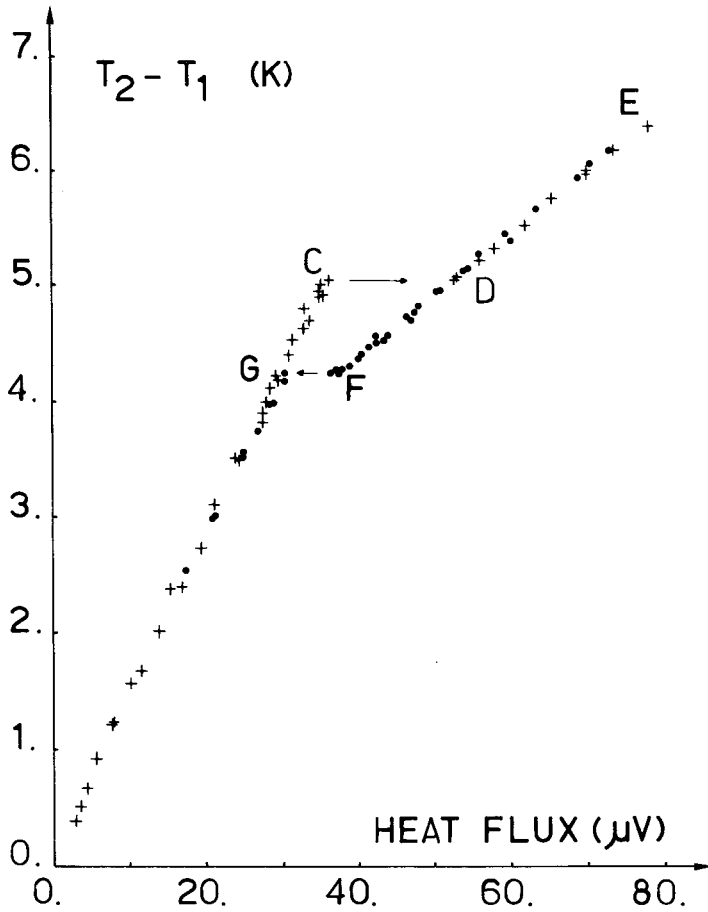


Fig. 7: Schmidt-Milverson plot in the constant temperature gradient apparatus.  
 +: results with temperature gradient increasing.  
 ·: results with temperature gradient decreasing.

### 3. Discussion of results

As stated in Sect. 1, the linear theory gives the critical points (using numerical techniques such as the local potential) in the cases of exchange of stabilities and overstability, and in this last case the pulsation  $\sigma_I$  of the oscillations as well, once known all the relevant parameters: the Prandtl number, the Schmidt number, the Soret number etc. and also  $N_1^{in}$ , the initial mass fraction of component 1. Unfortunately, a precise value of the ratio  $D'/D$  is not available. Therefore, for fixed values of  $Pr$ ,  $Sc$ ,  $R_{th}$ ,  $N_1^{in}$  relevant to the present experiments (see appendix), we run the computer program for different values of  $\mathcal{L}$ , searching for the value of  $\mathcal{L}$  that produces, within an error of one unit, a theoretical value of  $Ra^{crit}$  identical to the experimental one. Also we found the value of the pulsation  $\sigma_I$ . The numerical technique used, was described some time ago by Legros, Platten and Poty [9] in the case of dilute solution ( $N_1^{in} \ll 1$ ). Straightforwardly, we have extended the theory to the general case ( $0 \leq N_1^{in} \leq 1$ ), and the details may be found elsewhere (Villers [11]). The results are listed below.

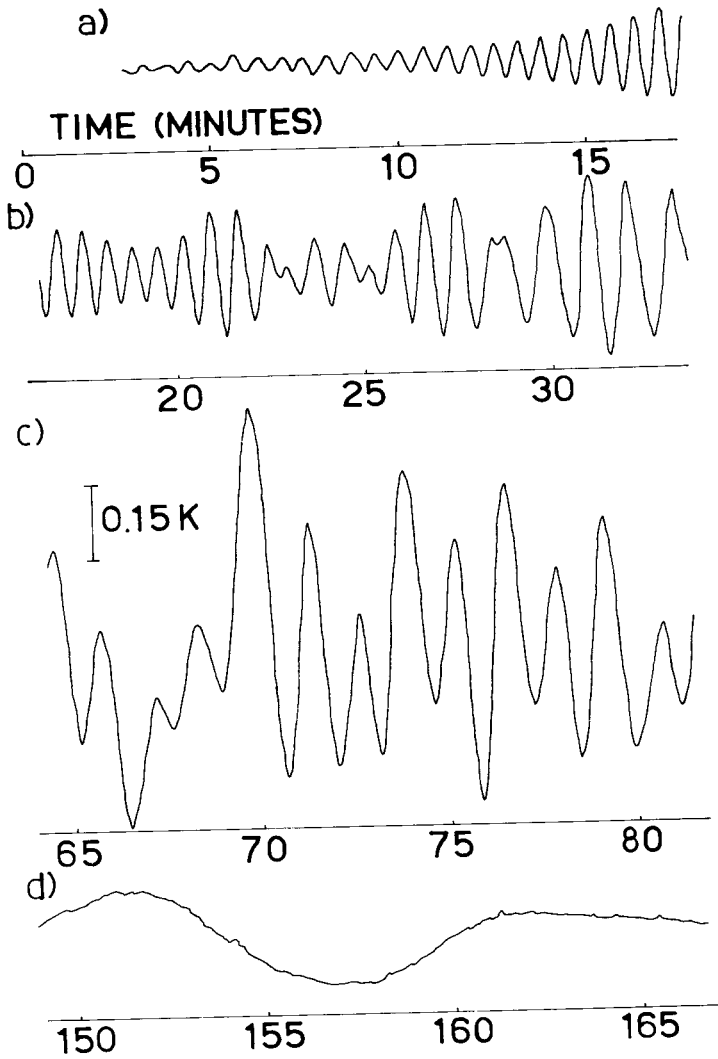


Fig. 8: Transient oscillations in the imposed temperature gradient apparatus.

*First apparatus:*

heat flux imposed.

$$\Delta T^{\text{crit}} = 6.02 \text{ K}$$

$$d = 3.07 \text{ mm} \quad T^0 = 21.8 \text{ C}$$

$$Ra^{\text{crit}} \text{ experimental} = 2591$$

The set  $Pr = 11.11$ ,  $Sc = 1100$ ,

$$N_1^{\text{in}} = 0.9091, R_{\text{th}} = 178217,$$

$$\mathcal{S} = -5.102 \cdot 10^{-3}$$

produces theoretically

$$Ra^{\text{crit}} = 2591.2$$

$$\text{and } \sigma_I = 1.068$$

From the definition of  $\mathcal{S}$ ,

we compute

$$D'/D = -9.3 \cdot 10^{-3}$$

and a period

$$\left(\frac{d^2}{\nu}\right) 2\pi/\sigma_I = 41.2 \text{ s}$$

*Second apparatus:*

temperature gradient imposed.

$$\Delta T^{\text{crit}} = 5.05 \text{ K}$$

$$d = 3.32 \text{ mm} \quad T^0 = 21.5 \text{ C}$$

$$Ra^{\text{crit}} \text{ experimental} = 2688$$

The set  $Pr = 11.27$ ,  $Sc = 1100$ ,

$$N_1^{\text{in}} = 0.9091, R_{\text{th}} = 222586,$$

$$\mathcal{S} = -4.555 \cdot 10^{-3}$$

produces theoretically

$$Ra^{\text{crit}} = 2687.9$$

$$\text{and } \sigma_I = 1.113$$

From the definition of  $\mathcal{S}$ ,

we compute

$$D'/D = -9.9 \cdot 10^{-3}$$

and a period

$$\left(\frac{d^2}{\nu}\right) 2\pi/\sigma_I = 37.2 \text{ s}$$

The two computed values of  $D'/D$  are within an error of 6%. That shows that precise determinations of negative Soret coefficients are possible from experimental critical Rayleigh number. In the determination of  $D'/D$  for the system water-isopropanol reported above, we need the values of physical parameters for the mixture, such as viscosity, density, thermal conductivity, at a particular composition and temperature, and they were obtained, as explained in the appendix, by experimental measurements or by interpolations.

For the imposed temperature gradient apparatus, we compute  $\sigma_I = 1.113$ , and thus the dimensional period  $T = (d^2/\nu)2\pi/\sigma_I = 37.2 \text{ s}$  is in perfect agreement with the experimental value 37 s. On the other hand, the *sustained* oscillations of period 72 s (a value also observed previously by Platten and Chavepeyer) observed in constant heat flux apparatus (Fig. 4), cannot be compared with the linear theory. This is not surprising, since at point *A* (Fig. 3) where the oscillations were recorded, we are far from the critical point ( $Ra/Ra^{\text{crit}} = 0.87$ ;  $Nu = 1.14$ ). However in the first stage of the transition *C* to *A* we also observed oscillations of increasing amplitude of period  $\simeq 30 \text{ s}$ . Thus, the reasonings made by Platten and Chavepeyer [8] are wrong. They claimed to have found agreement between the observed period (70 s) of *sustained* oscillations and the calculated one from the linear theory. This agreement which they claimed to have shown is fortuitous and only due to a bad knowledge *at that time* of the value of  $D'/D$  found in the existing literature, and that they used in order to compute the pulsation  $\sigma_I$ .

The mechanism of sustained oscillations is not elucidated in the present case. A general mechanism for sustained oscillations has been proposed by Busse [12] with possible application to Rayleigh-Bénard convection in the presence of rotation or temperature-dependent viscosity. It may be that this general mecha-

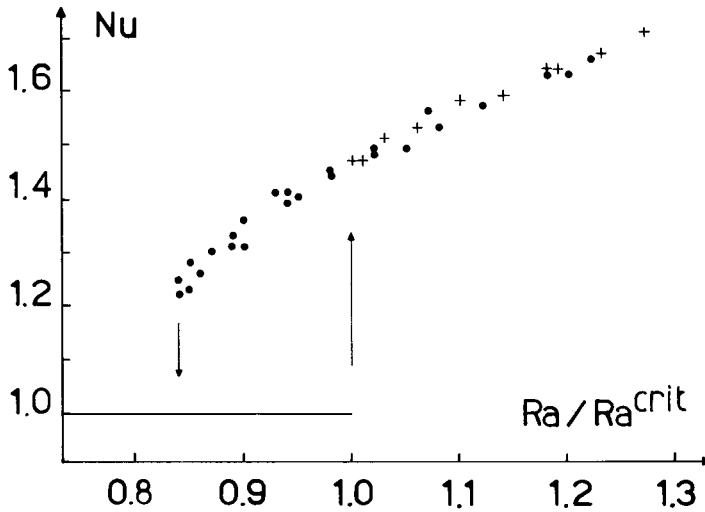


Fig. 9: Experimental values of the Nusselt number versus  $Ra/Ra^{crit}$  at the convective steady states.

nism could apply in the present case. Indeed, the results of Fig. 7 showing the possible steady states may be graphically transformed into a graph giving the Nusselt number  $Nu$  versus the ratio  $Ra/Ra^{crit}$  (Fig. 9). A theoretical explanation of this curve is available. Indeed in their nonlinear theoretical analysis of the two-component Bénard problem, Platten and Chavepeyer (1975) have used a truncated double Fourier series, and at the lowest order have derived a generalized Lorenz system for thermal convection. At the steady state they obtained a figure similar to Fig. 9, except that the values for  $Nu$  were computed for free boundaries. We see in Fig. 9 that stable stationary solutions do not exist for all values of the heat flux, even when there are stable stationary solutions for all  $Ra$  numbers. Thus, if the heat flux is imposed corresponding to a value such that there is no steady solution, heat is transported by a nonstationary convection. A possible mechanism is the following: the convective motion grows until the effective Rayleigh number is lowered so far that the convection dies away. Then heat is transported by conduction only and as a result the temperature gradient increases to such a value that convection will start growing again. On the other hand, the Busse mechanism could be incorrect in the present case. The main argument is that the sustained oscillations of Fig. 4 do not look like relaxation oscillations. Therefore one has also to search for a possible limit cycle behaviour of the starting differential equations.

#### 4. Conclusion

In this paper we have shown that:

- (i) heating curves in two-component fluid layers present hysteresis loops and oscillations for negative Soret coefficients.
- (ii) The experimental procedure is important.

- (iii) When the temperature gradient is imposed, the obtained period of *transient* oscillations is in agreement with the computed value from the linear theory and the hysteresis loop is qualitatively identical to the theoretical curve obtained for free and pervious boundaries.
- (iii) When the heat flux is imposed, the hysteresis loop is different, and *sustained* oscillations are obtained, confirming precedent experimental results.

### Appendix

The physical values for the mixture 90.9 wt % water- 9.1 wt % isopropanol were obtained by experimental measurement or by interpolation. In particular, the viscosities are determined at three temperatures with a Poiseuille viscosimeter:

$$\begin{aligned} T = 25.2^\circ\text{C} & \quad \nu = 1.35 \text{ cSt} \\ T = 22.0^\circ\text{C} & \quad \nu = 1.48 \text{ cSt} \\ T = 19.7^\circ\text{C} & \quad \nu = 1.59 \text{ cSt}. \end{aligned}$$

The density is determined by a Paar densimeter at different temperatures and compositions with an accuracy of approximately 5 digits. These determinations provide us computed values for the "solutal" expansion coefficient  $\gamma = 0.138$  and the thermal expansion coefficient  $\alpha = 0.300 \cdot 10^{-3} \text{ K}^{-1}$  at  $T = 21.5^\circ\text{C}$ . The density is 0.983 at the mean temperature considered.

The specific heat of our mixture is computed by a weight linear interpolation between the values for pure water and isopropanol ( $C_v$  mixture =  $4.04 \text{ J gr}^{-1} \text{ K}^{-1}$ ).

The thermal conductivity is also computed by interpolation with a formula provided by Reid and Sherwood (Chemical Engineering Series, Mc Graw Hill):

$$\lambda_m = \lambda_1 N_1 + \lambda_2 N_2 - 0.72 |\lambda_1 - \lambda_2| N_1 N_2.$$

We found thus  $\lambda_m = 5.31 \cdot 10^{-3} \text{ Watt cm}^{-1} \text{ K}^{-1}$ .

From all these values, we can compute  $Ra$ ,  $R_{th}$  and  $Pr$  at the desired temperature. We need also the values of the Schmidt number  $Sc = \nu/D$ . The isothermal diffusion coefficient  $D$  is in liquid phase approximatively of the order of

Tab. 2: Influence of the Schmidt number on the critical Rayleigh number and on the pulsation ( $Pr = 11$ ;  $R_{th} = 200000$ ;  $N_1^{in} = 0.9091$ ;  $\mathcal{S} = -0.5 \cdot 10^{-2}$ ).

$Sc$	$Ra^{crit}$	$\sigma_I$
700	2680	1.13
900	2676	1.13
1100	2674	1.13
1300	2673	1.13
1500	2671	1.13

$10^{-5} \text{ cm}^2 \text{ s}^{-1}$ . Therefore, the Schmidt number is taken to be equal to 1100. Fortunately, the incidence of the bad knowledge of  $Sc$  on the computed values for the critical point is negligible (i.e. less than the experimental error) (see Tab. 2).

### Acknowledgements

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