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EXPERIMENTAL-NUMERICAL DETERMINATION OF THERMAL COEFFICIENTS THROUGH A PHASE-CHANGE PROCESS

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ABSTRACT

The present paper shows the correlation between the analytical formulae for the determination of thermal coefficients of semi–infinite materials through a phase–change process with an overspecified condition on the fixed face and a simple device which determines some auxiliary parameters. The method is approachable for some thermal coefficients because of the dispersion of the theoretical and experimental results.

Introduction

The goal of the present paper is the determination of thermal coefficients (thermal conductivity, specific heat, latent heat of fusion and mass density) of semi–infinite materials through a phase–change process (Stefan problem [25]) with an overspecified condition on the fixed face x=0 of the material. Although there exist various other methods for the experimental determination of thermal coefficients, this is the first time in which a phase–change process is utilized. The corresponding theoretical method to our approach was present in [22, 23, 24]. In these papers (See also Appendix I), analytical formulae for the simultaneous determination of one or two thermal coefficients of semi–infinite materials through a phase change process are presented.

Although there are numerous classical methods for the determination of thermal coefficients [2, 8, 9, 12, 14, 16, 19, 21, 26, 27], the goal of the present paper is to show not the comparison with other well–established methods for measuring thermophysical properties but the goodness of the corresponding mathematical model. One of the characteristics of our method is the simultaneous determination of two thermal coefficients (See Appendix I).

The approach of the present paper consists firstly in constructing a simple device [1] for the experimental determination of some auxiliary parameters (for example: θ_0, H_0, σ) and then in applying those analitycal formulae.

The method is approachable for some thermal coefficients because of the dispersion of the theoretical and experimental results.

The phase–change processes have many applications in science and technology (particularly in solar energy as low temperatures thermal–storage); for more details see [3, 4, 5, 6, 7, 10, 11, 15, 18, 20, 25].

Theoretical Method for the Determination of Thermal Coefficients

A semi–infinite body $x > 0$ made out of some material in its liquid phase and at its fusion temperature θ_f is considered. We want to calculate (for the solid phase) one or two of its thermal coefficients among k, c, l and ρ (See Nomenclature). We carry out a solidification process with a difference in temperature $\theta_0 > 0$ ($\theta_0 = \theta_f - \theta(0,t)$) which is equal to the difference between the fusion temperature and the temperature on the fixed face x=0, and with an overspecified condition at the fixed face x=0, given by

(1) $$k\, \theta_x(0,t) = h_0 / \sqrt{t} \quad (t > 0) \qquad \text{or}$$

(2) $$\theta_x(0,t) = H_0 / \sqrt{t} \quad (t > 0) .$$

In these equations $\theta = \theta(x,t)$ represents the temperature of the point $x > 0$ at the time $t > 0$, H_0 and h_0 are the coefficients which characterize the temperature gradient and the heat flux on the fixed face x=0 respectively. These coefficients are always positive ($H_0 > 0$, $h_0 > 0$), and obey the relation

(3) $$h_0 = k\, H_0 \ .$$

Eq. (3) allows the determination of h_0 in function of H_0, which is experimentally determined. This relation is obviously useful when the thermal coefficient k is known.

The method used for the experimental–numerical determination of a thermal coefficient through the solidification process described above consists of the following steps (An explanation of the theoretical method can be found in [22, 23, 24]) :

(i) Carry out the solidification process by determining $\theta_0 > 0$ and $H_0 > 0$ (or $h_0 > 0$) experimentally.

(ii) Determine numerically an auxiliary coefficient $\xi > 0$ which turns to be the only solution of the intersection of two analytical curves which depend on the thermal coefficients known, the mathematical functions known and the experimental data calculated in step (i) .

(iii) Apply the analytical formulae for the determination of the unknown thermal coefficient in terms of the coefficients obtained in steps (i) and (ii).

(iv) If in step (i) we also determine experimentally the coefficient $\sigma > 0$ which caracterizes the solid–liquid interface $s(t) = 2\sigma\sqrt{t}$ ($t > 0$), then steps (ii) and (iii) may be repeated in order to obtain two unknown thermal coefficients simultaneously .

The phase–change material used in the experience was stearin and the results obtained agree with the data given in [17, 28].

Determination of Thermal Coefficients

For the experimental determination of constant thermal coefficients (of the solid phase) through a phase–change process (Lamé–Clapeyron–Stefan problem) the variants described in [22, 23, 24] will be used. Therefore, the conditions imposed by the model used must be taken into account, that is :

(i) the thermal coefficients k, c, l, ρ of the solid phase are constants;

(ii) A solidification process is carried out. All the substance must be initially in liquid state at the phase–change temperature θ_f;

(iii) The focus temperature (the temperature on the fixed face x=0) must be lower than θ_f . The difference in temperature between θ_f and that of the focus will be noted as $\theta_0 > 0$;

(iv) The semi–infinite body is simulated with a cylinder of finite length which is insulated on the right side (See Fig. 1);

(v) If the solid–liquid interface s(t) is known a priori by the relation $s(t)=2\sigma\sqrt{t}$ $(t \geq 0,\ \sigma > 0)$ (that is, σ is known a priori), then two thermal coefficients of the phase–change material may be calculated simultaneously. In the case where s(t) is unknown only one thermal coefficient may be calculated;

(vi) On the fixed face x=0, we have an overspecified condition given by (1) or (2), namely, the knowledge of the heat flux or the temperature gradient on x=0 (In [3], a mathematical theory for the determination of unknown coefficients is specified).

We will try to verify the experimental (and also numerical, because of step (ii)) results which were obtained in the 6 experiments carried out.

For the sake of convenience, an Appendix I is considered which 17 different theoretical cases. In each case, we give the coefficients calculated by the device, the restriction to be verified by data (theoretical and experimental coefficients) and the formulae for the unknown thermal coefficients. In general, these formulae are given in function of the dimensionless number which solves an equation. Moreover, in cases 1 to 3, 4 to 7, 8 to 13 and 14 to 17 the coefficients (θ_0, H_0, σ), (θ_0, h_0), (θ_0, h_0, σ), (θ_0, σ) must be determined experimentally [24], [22], [23] and [23] respectively.

Experimental Device

In Fig. 1 the general system of the experimental device utilized is shown. It consists of a glass tube (made out of quartz) full with a phase–change material, with a length of 0.60 m and a diameter of 0.018 m. Thermocouples (copper–constatan, standard NBS; $\Delta\theta = 0.1\,^{\circ}K$) are embedded in the material, and placed along the tube axis at various axial locations x, namely : 0.00073; 0.00328; 0.0055; 0.00865; 0.01107; 0.01458; 0.1905; 0.2371; 0.2851 m.

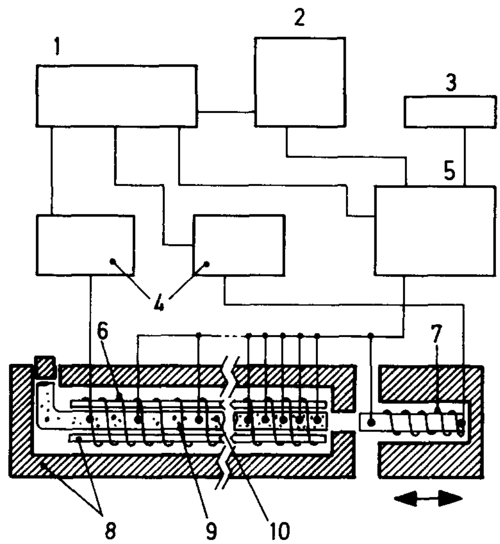

FIG. 1

Experimental device: 1: Voltage source; 2: Microprocessor; 3: printer;
4: Programmable temperature controller; 5: Data Logger; 6: Heater (100 W);
7: Hot focus (240 W); 8: Insulation; 9: Glass tube; 10: Sample
•: Termocuples; ⟷: Mobile section.

The glass tube is heated in all its length so that all the material to be analized be at the phase–change temperature at the beginning of the experiment, being at the same time insulated. The two systems are initially separated and are coupled when both of them verify the conditions of the mathematical model.

Once the phase change temperature is reached (which has been determined in a previous solidification experiment [10], the heater resistence is approached at a constant temperature lower than the melting temperature to the closed end and at this moment the experimental process begins. The experimental device is connected to a tension stabilizer. Both heating systems are assisted by a proportional electronic regulator ($\Delta\theta = \pm\ 0.3\ ^\circ K$). The measuring data are registered by a Fluke 2240–B data logger system. The data logger is connected to a digital PC computer system with printer. The phase–change material used was stearin (stearic acid), whose table theoretical coefficients [10, 17, 28] are given by :

$$(4) \qquad \rho = 8.47 \times 10^2\ Kg/m^3\ , \qquad l = 1.99 \times 10^5\ J/\ Kg\ , \qquad \theta_f = 342.39\ ^\circ K\ ,$$
$$c = 1.67 \times 10^3\ J/(Kg\ ^\circ K)\ , \qquad k = 1.6 \times 10^{-1}\ W\ m/(m^2\ ^\circ K)\ .$$

We shall indicate these theoretical values with the subscript t , that is l_t , ρ_t , c_t and k_t respectively. A detailed descripcion of the collection of experimental data obtained through the experimental device which was described before can be found in Appendix II.

According to the results in Appendix II, in each experiment the average value of the coefficient wich its corresponding standard deviation is found (See Figures 2 through 6).

For the computation of the coefficients H_0 and σ, the data up to a time of 360s was considered since for a greater time a very significant desviation was observed. The temperature taken for the focus was the one that the thermocouple located in the nearest position to the focus would have at the end of the experiment (360s).

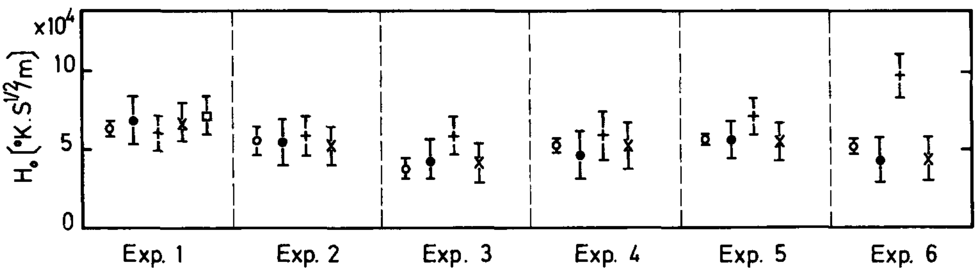

FIG. 2
The experimental values of H_0 obtained by :
o: from experience; •: case 14 ; +: case 15 ; x: case 16 ; □ : case 17.

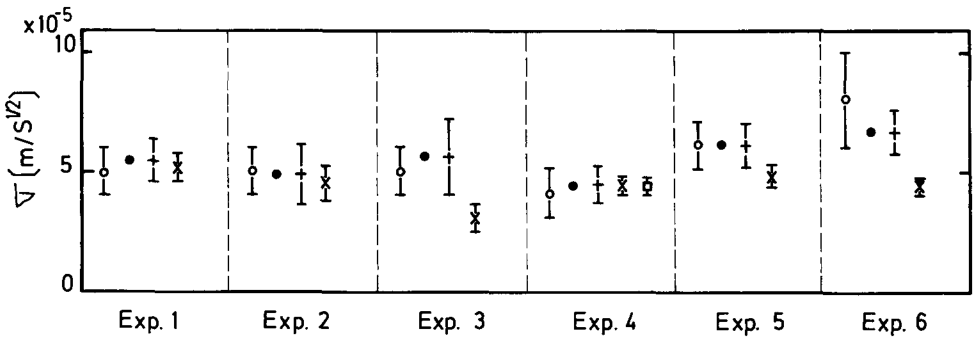

FIG. 3
The experimental values of σ are shown by appluing analytical formulae :
o: from experience; •: case 4 ; +: case 5 ; x: case 6 ; □ : case 7.

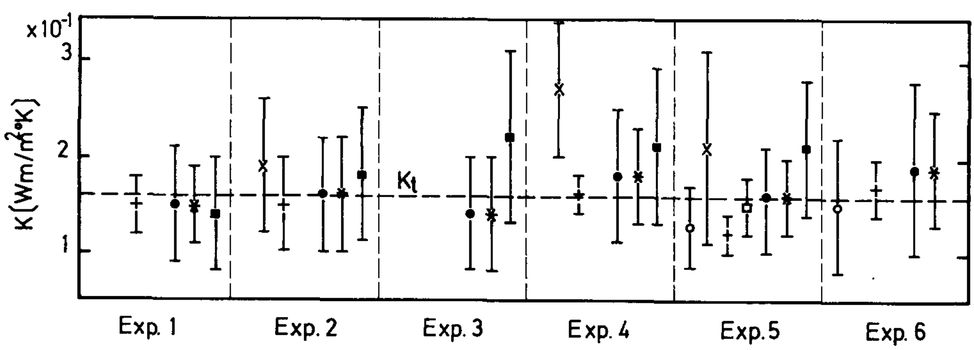

FIG. 4
Determination of the thermal conductivity k through different cases :
o: case 1; •: case 9 ; +: case 6 ; x: case 2 and 3 ; □ : case 8 ;
□ : case 15; x: case 10; ----- : table value .

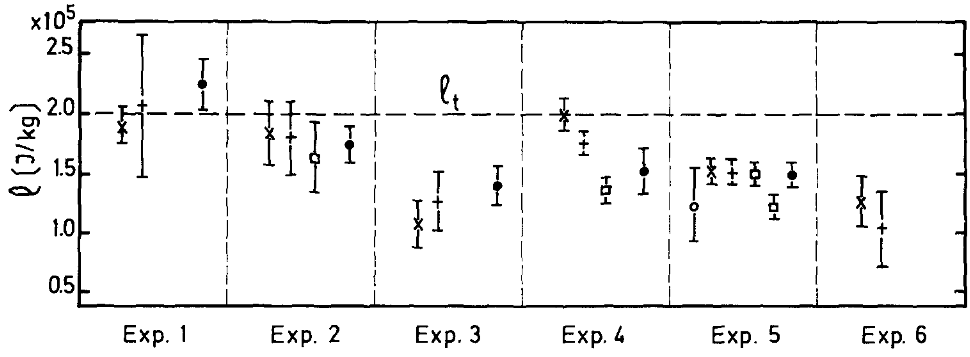

FIG. 5
Determination of the latent heat of fusion l through different cases :
o: case 1; •: case 14 ; +: case 9 ; x: case 4 ; □ : case 11 ;
□ : case 12 ; ----- : table value .

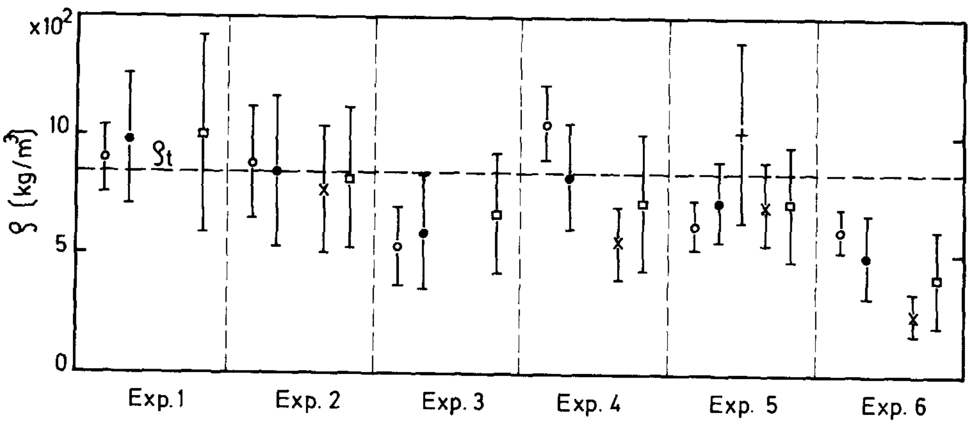

FIG. 6
Determination of the mass density ρ through different cases :
o: case 5; •: case 10 ; +: case 12 ; x: case 13 ;
□ : case 16 ; ----- : table value .

Analysis of the Results

Taking into account the melting–freezing curve we have obtained the value of (328 ± 2)°K for the melting temperature. We remark that the material used is commercial. Six experiences were carried out (See Appendix II). Owing to the experimental data obtained from the six experiments, the results will be analyzed through diagrams. In Fig. 2 and 3 the values of H_0 and σ are plotted by using the experimental values and the different cases. In Fig. 4, 5 and 6 the correlation from the different cases is shown. In all figures, the values of the different coefficients are plotted with the corresponding estimated uncertainties. Taking into account the six experiments the average values obtained are the following:

$$k = (0.181 \pm 0.008)\ \mathrm{W\ m/(m^2\ ^\circ K)},$$
$$\rho = (7.5 \pm 0.3)\ 10^2\ \mathrm{Kg/\ m^3},$$
$$l = (1.5 \pm 0.7)\ 10^5\ \mathrm{J/Kg}.$$

Conclusions

We can predict that the theoretical method is approachable for the determination of some thermal coefficients because of the dispersion of the theoretical and experimental results. In experiments 1 and 2 the relation among the different thermal coefficients is nearer than in experiments 3 to 6. This fact is due to the chemical reaction between the acid stearic with thermocouples.

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Nomenclature

- a root square of the thermal diffusivity, $\sqrt{\frac{k}{\rho c}}$, [m/s],
- c specific heat , [J/Kg °K] ,
- l latent heat of fusion, [J/Kg] ,
- h_0 coefficient which characterizes the heat flux on the fixed face x=0, [Ws/m^2] ,
- H_0 coefficient which characterizes the slope of the temperature on x=0, [°K $\sqrt{s}$/m],
- k thermal conductivity, [W m/(m^2 °K)] ,
- s position of phase change location , [m] ,
- t time variable , [s] ,
- x spatial variable , [m] ,

Greek symbols :

- α thermal diffusivity , $\frac{k}{\rho c}$, [m^2/s] ,
- σ coefficient which characterizes the moving boundary, [m/$\sqrt{s}$] ,
- ρ mass density, [Kg/m^3] ,
- θ temperature, [°K] ,
- θ_0 temperature on the fixed face x=0, [°K],
- θ_f phase–change temperature, [°K] ,
- ξ dimensionless parameter, [$\frac{\sigma}{a}$] ,

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APPENDIX I

CASE N°	COEFFICIENTS GIVEN BY EXPERIMENTAL CALCULUS	RESTRICTION	FORMULAE FOR UNKNOWN COEFFICIENTS	ξ IS THE UNIQUE SOLUTION OF THE EQUATION
1	Θ_0, H_0, σ	$\frac{\Theta_0}{2\sigma H_0} < 1$	$k = \frac{\rho \mathcal{C} \sigma^2}{\xi^2}$, $\ell = \mathcal{C}\sigma H_0 \frac{\exp(-\xi^2)}{\xi^2}$	$\begin{cases} \frac{\mathrm{erf}(x)}{x} = \frac{\Theta_0}{\sigma H_0 \sqrt{\pi}} \\ x > 0 \end{cases}$
2	Θ_0, H_0, σ	As in Case N°1	$k = \frac{\rho \ell \sigma}{H_0}\exp(\xi^2)$, $\mathcal{C} = \frac{\ell}{\sigma H_0}\xi^2 \exp(\xi^2)$	As in Case N°1
3	Θ_0, H_0, σ	As in Case N°1	$k = \frac{\rho \ell \sigma}{H_0}\exp(\xi^2)$, $\alpha = \frac{\sigma^2}{\xi^2}$	As in Case N°1
4	Θ_0, h_0	$\frac{\Theta_0}{h_0}\sqrt{\frac{k\rho\mathcal{C}}{\pi}} < 1$	$\begin{cases} \sigma = \xi\sqrt{k/\rho\mathcal{C}} \\ \ell = \frac{h_0}{\rho}\sqrt{\rho\mathcal{C}/k} \cdot \frac{\exp(-\xi^2)}{\xi} \end{cases}$	$\begin{cases} \mathrm{erf}(x) = \frac{\Theta_0}{h_0}\sqrt{\frac{k\rho\mathcal{C}}{\pi}} \\ x > 0 \end{cases}$
5	Θ_0, h_0	———	$\begin{cases} \sigma = k\Theta_0 / h_0\sqrt{\pi} \cdot \xi / \mathrm{erf}(\xi) \\ \rho = \pi h_0^2 / k\mathcal{C}\Theta_0^2 \cdot \mathrm{erf}^2(\xi) \end{cases}$	$\begin{cases} x \exp(x^2)\,\mathrm{erf}(x) = \frac{\mathcal{C}\Theta_0}{\ell\sqrt{\pi}} \\ x > 0 \end{cases}$
6	Θ_0, h_0	———	$\begin{cases} \sigma = h_0/\rho\ell \cdot \exp(-\xi^2) \\ k = \pi h_0^2/\rho\mathcal{C}\Theta_0^2 \cdot \mathrm{erf}^2(\xi) \end{cases}$	As in Case N°5
7	Θ_0, h_0	$\frac{k\rho\ell\Theta_0}{2h_0^2} < 1$	$\begin{cases} \sigma = h_0/\rho\ell \cdot \exp(-\xi^2) \\ \mathcal{C} = \pi h_0^2/\rho k\Theta_0^2 \cdot \mathrm{erf}^2(\xi) \end{cases}$	$\begin{cases} \mathrm{erf}(x)/x = k\rho\ell\Theta_0/h_0^2\sqrt{\pi} \cdot \exp(x^2) \\ x > 0 \end{cases}$
8	Θ_0, h_0, σ	$\frac{h_0}{\rho\ell\sigma} > 1$	$\begin{cases} \mathcal{C} = h_0\sqrt{\pi}/\rho\sigma\Theta_0 \cdot \xi\,\mathrm{erf}(\xi) \\ k = \sigma h_0\sqrt{\pi}/\Theta_0 \cdot \mathrm{erf}(\xi)/\xi \end{cases}$	$\xi = \sqrt{\log\left(\frac{h_0}{\rho\ell\sigma}\right)}$
9	Θ_0, h_0, σ	———	$\ell = \frac{h_0}{\rho\sigma}\exp(-\xi^2)$, $k = \frac{\rho\mathcal{C}\sigma^2}{\xi^2}$	$\begin{cases} x\,\mathrm{erf}(x) = \rho\mathcal{C}\sigma\Theta_0/h_0\sqrt{\pi} \\ x > 0 \end{cases}$
10	Θ_0, h_0, σ	———	$\begin{cases} \rho = \frac{h_0}{\ell\sigma}\exp(-\xi^2) = \frac{h_0\sqrt{\pi}}{\mathcal{C}\sigma\Theta_0}\xi\,\mathrm{erf}(\xi) \\ k = \frac{h_0\mathcal{C}\sigma}{\ell}\frac{\exp(-\xi^2)}{\xi^2} = \frac{\sigma h_0\sqrt{\pi}}{\Theta_0}\frac{\mathrm{erf}(\xi)}{\xi} \end{cases}$	As in Case N°5
11	Θ_0, h_0, σ	$\frac{k\Theta_0}{2\sigma h_0} < 1$	$\mathcal{C} = \frac{k}{\rho\sigma^2}\xi^2$, $\ell = \frac{h_0}{\rho\sigma}\exp(-\xi^2)$	$\begin{cases} \frac{\mathrm{erf}(x)}{x} = \frac{k\Theta_0}{\sigma h_0\sqrt{\pi}} \\ x > 0 \end{cases}$
12	Θ_0, h_0, σ	As in Case N°11	$\rho = \frac{k}{\mathcal{C}\sigma^2}\xi^2$, $\ell = \frac{\mathcal{C}\sigma h_0}{k}\frac{\exp(-\xi^2)}{\xi^2}$	As in Case N°11
13	Θ_0, h_0, σ	As in Case N°11	$\rho = \frac{h_0}{\ell\sigma}\exp(-\xi^2)$, $\mathcal{C} = \frac{k\ell}{\sigma h_0}\xi^2\exp(\xi^2)$	As in Case N°11
14	Θ_0, σ	———	$h_0 = \frac{k\Theta_0}{\sigma\sqrt{\pi}}\frac{\xi}{\mathrm{erf}(\xi)}$, $\ell = \frac{\mathcal{C}\Theta_0}{\sqrt{\pi}}\frac{\exp(-\xi^2)}{\xi\,\mathrm{erf}(\xi)}$	$\xi = \sigma\sqrt{\frac{\rho\mathcal{C}}{k}}$
15	Θ_0, σ	———	$h_0 = \rho\ell\sigma\exp(\xi^2)$, $k = \frac{\rho\mathcal{C}\sigma^2}{\xi^2}$	As in Case N°5
16	Θ_0, σ	———	$h_0 = \frac{k\ell}{\mathcal{C}\sigma}\xi^2\exp(\xi^2)$, $\rho = \frac{k}{\mathcal{C}\sigma^2}\xi^2$	As in Case N°5
17	Θ_0, σ	$\frac{k\Theta_0}{2\ell\rho\sigma^2} > 1$	$h_0 = \rho\ell\sigma\exp(\xi^2)$, $\mathcal{C} = \frac{k}{\rho\sigma^2}\xi^2$	$\begin{cases} \mathrm{erf}(x)\exp(x^2) = \frac{k\Theta_0}{\ell\rho\sigma^2\sqrt{\pi}}x \\ x > 0 \end{cases}$

APPENDIX II

t	$\Delta x . 10^4$	Exp.1 (θ_0=6,7 ± 0,3)		Exp.2 (θ_0=5,2 ± 0,3)		Exp.3 (θ_0=4,2 ± 0,3)		Exp.4 (θ_0=4,6 ± 0,3)		Exp.5 (θ_0=6,6 ± 0,3)		Exp.6 (θ_0=6,7 ± 0,3)	
		$\Delta\theta$	H_0	$\Delta\theta$	H_0	$\Delta\theta$	H_0	$\Delta\theta$	H_0	$\Delta\theta$	H_0	$\Delta\theta$	H_0
60	7,3	5,7	60482	4,5	47749	3,3	35016	4,0	42444	5,7	60482	4,6	48810
120	7,3	4,9	73530	4,1	61525	2,9	43518	3,7	55522	4,3	64526	4,0	60024
180	7,3	4,1	75352	3,5	64325	2,5	45946	3,3	60649	3,5	64325	3,3	60649
240	7,3	3,3	70032	2,9	61543	2,0	42444	2,9	61543	2,8	59421	2,7	57299
300	7,3	2,4	56944	2,1	49826	1,5	35590	2,3	54571	2,1	49826	2,0	47453
360	7,3	1,5	38987	1,4	39303	0,9	23392	1,6	41586	1,4	36388	1,3	33789

TABLE 1: Experimental values of temperature gradient on fixed face. Computation of H_0.

t	Exp.1 (θ_0=6,7 ± 0,3)		Exp.2 (θ_0=5,2 ± 0,3)		Exp.3 (θ_0=4,2 ± 0,3)		Exp.4 (θ_0=4,6 ± 0,3)		Exp.5 (θ_0=6,6 ± 0,3)		Exp.6 (θ_0=6,7 ± 0,3)	
	$s(t).10^4$	$\sigma.10^5$	$s(t).10^4$	$\sigma.10^5$	$s(t).10^4$	$\sigma.10^5$	$s(t).10^4$	$\sigma.10^5$	$s(t).10^4$	$\sigma.10^5$	$s(t).10^4$	$\sigma.10^5$
60	3,6	2,324	3,6	2,324	3,6	2,324	3,6	2,324	3,6	2,324	7,3	4,712
120	7,3	3,333	7,3	3,333	3,6	1,643	3,6	1,643	7,3	3,333	7,3	3,333
180	7,3	2,720	7,3	2,720	7,3	2,720	3,6	1,342	7,3	2,720	32,8	12,224
240	20,0	6,455	7,3	2,356	7,3	2,356	7,3	2,356	32,8	10,586	32 8	10,586
300	32,8	9,468	32,8	9,468	32,8	9,468	32,8	9,468	32,8	9,468	32,8	9,468
360	32,8	8,643	32,8	8,643	32,8	8,643	32,8	8,643	32,8	8,643	32,8	8,643

TABLE 2 : Experimental values for s(t). Computation of σ.

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