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Estimation of the Calorific Power of a Heating Element

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Authors' contributions

This work was carried out in collaboration between all authors. All authors read and approved the final manuscript.

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ABSTRACT

The present paper is aimed to determine the calorific power of a heating source, consisting of a laterally isolated aluminum cylinder, which incorporates an internal electrical resistance for controlling the heat, adjusted to a preset temperature. For this, a glass vessel covering the heating surface and containing a certain mass of water is placed on the cylinder, while the thermal evolution of the water, is monitored by means of a thermocouple probe. We describe a simple model, based on the resolution of the differential equation for the heat balance associated with water, incorporating two gain and loss coefficients (the latter directly associated with the heating power required) and its application to the stationary response achieved at a given time with a steady final temperature. In this way and for different preset temperatures ranging from 30 to 70 ° C (in each case, the actual temperature of the source is determined by infrared thermometer), a table of power values is obtained, whose results can be used in other experiments that require it, such as those related to measures heat conductivities in disk shaped samples.

Keywords: Heat capacity; heat balance; losses coefficient.

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1. INTRODUCTION

In thermal physics laboratories, it is sometimes necessary to determine the power of heating sources without prior characterisation, in order to solve the problem of heat conduction in solids. Measurement of the thermal properties of a material is an important issue since the parameters associated with it are extremely relevant both in the laboratory and in industrial design. Direct measurement of heat transfer has been studied by using several techniques [1], including infrared thermography [2,3], the use of circular heat flow disks, as well as comparisons and calibrations of heat flux sensors [4]. In this way, thermal conductivity has been studied for a wide variety of materials using different experimental techniques [5-9].

This paper presents an experimental procedure to obtain the power of the heating source, with controllable temperature for different pre-set values, by means of a simple method based on the calorific balance between the source and a body in mutual contact [10], when the steady state is reached. The model incorporates two coefficients corresponding to gains and losses, respectively, for the heated element, the first being the coefficient directly related to the heating power and whose determination for each temperature allows the thermal characterisation of the heating element. The results of our study can be used for measuring heat conductivities corresponding to metallic materials.

2. THEORY

Let us consider the case of a mass of water contained in a glass vessel on a heating element at temperature θ_c> room temperature θ_a, (see Fig. 1). Taking into account heat gains and losses for the system, expressed by λ_1 and λ_2 coefficients respectively the heating power transferred, is given by

$$\frac{\delta Q}{dt}=\left(mc_a+k\right)\frac{d\theta}{dt}=C\frac{d\theta}{dt}=\left(\frac{\delta Q}{dt}\right)_1+\left(\frac{\delta Q}{dt}\right)_2=\lambda_1\left(\theta_c-\theta\right)+\lambda_2\left(\theta_a-\theta\right) \quad (1)$$

where $\left(\delta Q/dt\right)_1$ is the supplied power to the system by the heated element and $\left(\delta Q/dt\right)_2$ is the power lost by the same, with $C\equiv mc_a+k$ the heat capacity of the calorimetric system, θ its temperature, m the mass of water in the glass vessel, c_a the water specific heat and *k* the water equivalent of the system.

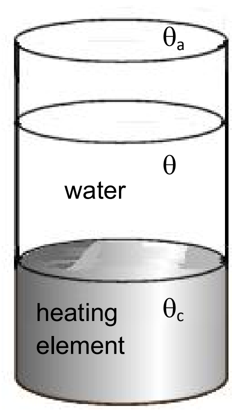

Fig. 1. System scheme: heating element and glass vessel with water

Grouping the terms in the above equation, $-\left(\lambda_1+\lambda_2\right)\theta+\lambda_1\theta_c+\lambda_2\theta_a=C\left(d\theta/dt\right)$, and renaming $\alpha\equiv\lambda_1\theta_c+\lambda_2\theta_a$ and $\beta\equiv\lambda_1+\lambda_2$, gives

$$C\frac{d\theta}{dt}=\alpha-\beta\theta \quad\Rightarrow\quad \frac{Cd\theta}{\alpha-\beta\theta}=dt \quad (2)$$

Integrating between the initial temperature of the liquid (θ_o) and temperature (θ) at instant t, gives:

$$\int_{\theta_o}^{\theta}\frac{C\cdot d\theta}{\alpha-\beta\theta}=t \quad\Rightarrow\quad \ln\left[\frac{\alpha-\beta\theta}{\alpha-\beta\theta_o}\right]=-\frac{\beta t}{C} \quad\Rightarrow\quad \alpha-\beta\theta=\left(\alpha-\beta\theta_o\right)\exp\left(-\gamma t\right) \quad \left(\gamma=\frac{\beta}{C}>0\right) \quad\Rightarrow$$
$$\Rightarrow\quad \theta=\frac{\alpha}{\beta}-\left(\frac{\alpha}{\beta}-\theta_o\right)\exp\left(-\gamma t\right) \quad (3)$$

Therefore and according to the boundary conditions applicable to the system, ($t\rightarrow 0$, $\theta=\theta_o$ (initial temperature) and $t\rightarrow\infty$, $\theta=\theta_f=\left(\alpha/\beta\right)$ (final temperature)), equation (3) can be rewritten as

$$\theta=\theta_f-(\theta_f-\theta_o)\exp(-\gamma t)=A-B\exp(-\gamma t)\quad \begin{cases} A=\theta_f=\dfrac{\lambda_1\theta_c+\lambda_2\theta_a}{\lambda_1+\lambda_2}, \\ B=\theta_f-\theta_o=\dfrac{\lambda_1(\theta_c-\theta_o)+\lambda_2(\theta_a-\theta_o)}{\lambda_1+\lambda_2}, \\ \gamma=\dfrac{\beta}{C}=\left(\dfrac{\lambda_1+\lambda_2}{C}\right) \end{cases} \tag{4}$$

and consequently

$$(\lambda_1+\lambda_2)\theta_f=\lambda_1\theta_c+\lambda_2\theta_a \quad\Rightarrow\quad \frac{\lambda_2}{\lambda_1}=\frac{\theta_f-\theta_c}{\theta_a-\theta_f}=\theta_f^* \tag{5}$$

where a final reduced temperature θ_f^* has been introduced. In addition

$$C\cdot\gamma=\lambda_1+\lambda_2 \tag{6}$$

both equations (5) and (6) allow λ_1 and λ_2 coefficients to be obtained from adjustable parameters γ and θ_f, giving

$$\left.\begin{aligned} \lambda_1&=\frac{C\gamma}{1+\theta_f^*} \\ \lambda_2&=\lambda_1\theta_f^* \end{aligned}\right\} \tag{7}$$

According to (1), equations (7) show the energy gain and loss coefficients of the system, as well as the value of the power supplied by the heating element. It sufficient time elapsed to reach the steady state ($\theta=\theta_f$), the net heat exchange is cancelled out and, consequently, $(\delta Q/dt)=0$. Then, the power supplied by the heat source is

$$\left(\frac{\delta Q}{dt}\right)_1=\lambda_1(\theta_c-\theta_f) \tag{8}$$

2.1 Obtaining the k Value: Mixing Method

To calculate the power supplied by the heating element, as described above, it is necessary to know the value of the water equivalent of the system, corresponding to the heat capacities of the surrounding vessel, as well as of the measuring device (e. g., thermo-probes). To do this, we use the mixing method [11], which consists of introducing into the water contained in the glass vessel at room temperature, a known metal body previously heated in a recipient of boiling water (100 °C at normal atmospheric pressure) [12]. In this way, when the body is introduced into the problem system, the water temperature increases. After a time interval Δt, the body is removed from the system and the water cools down towards environment temperature. Fig. 2 outlines the process with its three stages: preheating, heating and post-heating. In our case the duration of these stages was 20, 1 and 20 minutes, respectively, for which the corresponding thermogram is shown in Fig. 3.

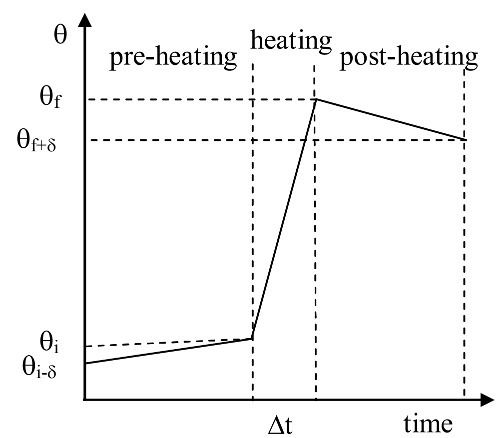

Fig. 2. Thermal evolution diagram of the water in a mixing process

θ_i: initial temperature, θ_f: final temperature, δ: pre and post-heating time interval

The energy balance for the heating stage is described by the equation

$$Mc_M(\theta_f-\theta_i)=(m_a c_a+k)(\theta_f-\theta_i)+\dot{Q}_p\Delta t \tag{9}$$

where M is the metal body mass (copper in our case), c_M is its specific heat [13], m_a is the water mass, c_a its specific heat, θ_i and θ_f are the initial and final temperature corresponding to the time interval Δt, and $\dot{Q}_p$ refers to heat losses per unit

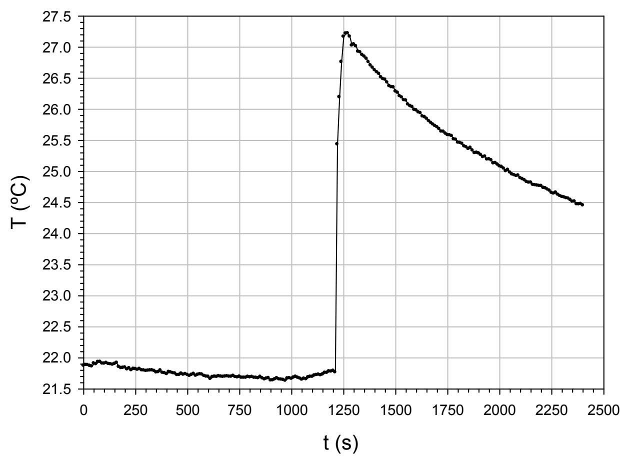

Fig. 3. Thermogram obtained to calculate the water equivalent value of our system, obtained by introducing a pattern metal body at 100ºC

of time in this stage, which can be determined as the arithmetic mean of the losses in the pre and post-heating stages:

$$\dot{Q}_p = \left[\left(\dot{Q}_p^{pre} + \dot{Q}_p^{post} \right) / 2 \right]$$

Preheating stage: thermal stabilisation of the system tending to temperature θ_a,

$$\dot{Q}_p^{pre} = (m_a c_a + k) \left[\frac{[(\theta_i - \theta_{i-\delta})]}{20} \right]$$

where $\theta_{i-\delta}$ and θ_{ι} are the initial and final temperature of this stage.

Post-heating stage: after removing the metal body and monitoring cooling process of the water,

$$\dot{Q}_p^{post} = (m_a c_a + k) \left[\frac{[(\theta_{f+\delta} - \theta_f)]}{20} \right]$$

where θ_f and $\theta_{f+\delta}$ are the initial and final temperature of this stage.

Thus, the energy balance given by equation (9) is

$$Mc_M(\theta_f - \theta_i) = (m_a c_a + k) \left[(\theta_f - \theta_i) + \frac{[(\theta_f - \theta_{i-\delta}) + (\theta_{f+\delta} - \theta_i)]}{40} \right] \quad (10)$$

This equation allows us to determine the value of the equivalent k, when the mass M of the metal used and its specific heat c_M are known.

3. EXPERIMENTAL DEVICE

We have designed a device (Fig. 4) with an isolated aluminium cylinder of 2 cm thickness as a heating element, containing an electrical resistance as a heating element. The control temperature θ_c (temperature setting) is measured with a type J thermocouple probe (iron–constantan, with - 210 to 1200 °C range) incorporated into the cylinder. The resistance and thermocouple are connected to a control device, equipped with display showing the instantaneous values of θ_c^* (nominal control temperature). This temperature is the magnitude controlling the heat flow, while the heating element directs and regulates the heating process of the system. At every instant, another type J thermocouple records the temperature θ of the deionised water (40 cm^3) contained in a glass vessel (wall 2 mm), placed on top of the heater cylinder. In the steady-state, the temperature reaches a value θ_f for each considered θ_c^*. The real temperature values on this surface of the heating cylinder (θ_c), for each of the nominal control values selected (θ_c^*), were measured with an infrared thermometer of configurable emissivity (Optris® LS with dual focus infrared light) [14], provided with a laser marking device, which points to the upper part of the cylinder (or element whose surface temperature is required) projecting a cross. This acts as a guide for the measurement distance (distance of the object (D) and size of the area of focal measurement (S), whose d:s ratio is in our case 75:1 for the considered disk) (Fig. 5).

4. RESULTS AND DISCUSSION

Appling eq. (10) to 40 cm^3 water permits the determination of the water equivalent of the calorimetric system (k = 14.623 g) and taking into account that $C \equiv mc_a + k$, it follows that C = 64.623 cal g^{-1} $°C^{-1}$. This value, together with the γ parameter of the exponential fitting of the corresponding thermograms for the system, (over a range of temperatures θ_c^* from 30 to 70ºC, at 5ºC intervals) allows calculation of the coefficientsλ_1 and λ_2 (eq. (7)), and, consequently, according to eq. (8) determination of the corresponding heating power. Fig. 6, shows the thermogram corresponding to the value θ_c^* = 50°C.

Table 1 shows thevalues of measured temperature for every control temperatureθ_c^* considered [30-70ºC]. In all cases, 4000 s was sufficient to reach the steady state.

Fig. 7 illustrates the different thermograms for the θ_c^* values shown in Table 1.

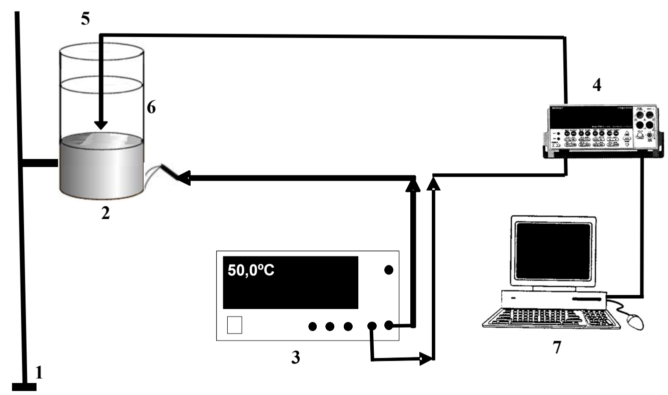

Fig. 4. Experimental set up for monitoring the evolution of the heating power of the heater element: 1) Support. 2) Heater cylinder with insulation wrap. 3) Thermal control device (temperature of the heating element). 4) Keithley 2700 multimeter. 5) Type J thermocouple probe in water. 6) Glass vessel. 7) PC

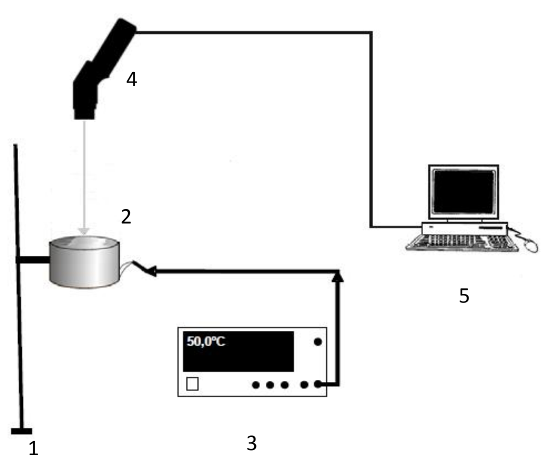

Fig. 5. Experimental set up for the measurement of the surface temperature of the heating element (θ_c): 1) Support. 2) Heater cylinder with insulation wrap. 3) Thermal control device of temperature setting (temperature of the heating element). 4) Infrared thermometer. 5) PC

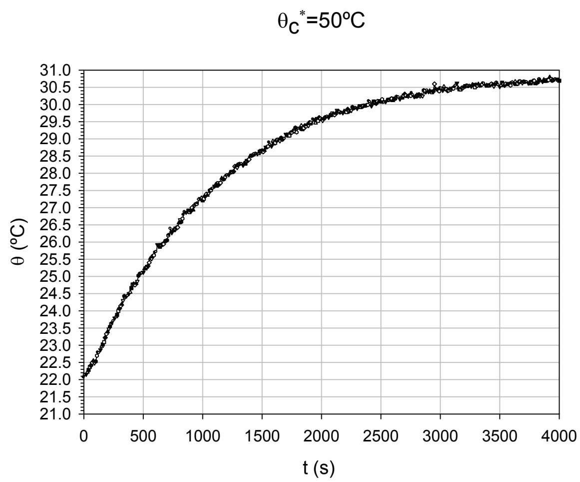

Fig. 6. Thermal evolution of the calorimetric ensemble at a nominal temperature θ_c^*=50ºC

Table 1. Thermal evolution of the system for the different control temperatures θ_c^* considered

	Nominal control temperature θ_c^* (ºC)								
	30	35	40	45	50	55	60	65	70
t (s)	**Temperature θ (ºC) as a function of the time**								
0.00	22.43	21.36	21.17	22.00	22.06	23.23	23.11	23.45	23.19
500.00	22.57	22.75	23.35	24.44	25.12	26.65	27.13	28.18	28.84
1000.00	22.69	23.61	24.78	26.02	27.14	28.94	29.74	31.01	31.99
1500.00	22.78	24.20	25.70	27.06	28.49	30.42	31.42	32.79	33.90
2000.00	22.85	24.61	26.29	27.73	29.37	31.38	32.51	33.90	35.06
2500.00	22.90	24.88	26.66	28.17	29.94	32.01	33.22	34.59	35.75
3000.00	22.94	25.00	26.90	28.46	30.32	32.41	33.67	35.02	36.20
3500.00	23.00	25.13	27.06	28.65	30.56	32.67	33.97	35.17	36.48
4000.00	22.98	25.19	27.17	28.80	30.69	32.81	34.16	35.41	36.64

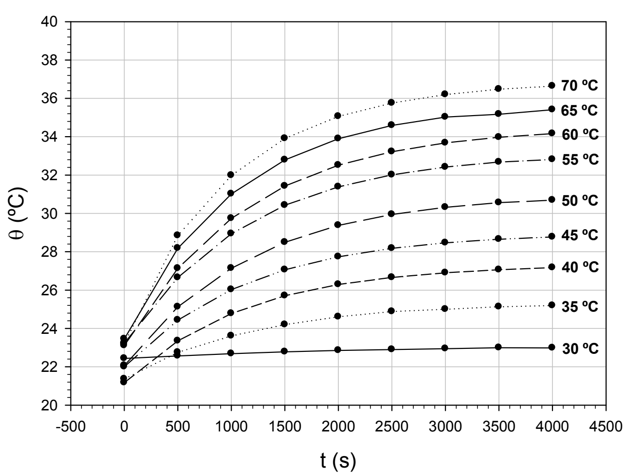

Fig. 7. Fitting experimental curves (eq. (3)) for every control temperature θ_c^*. The shown experimental points correspond to 500 s intervals between 0 and 4000 s

Table 3 shows experimental results for characteristic temperatures, initial (θ_o), room (θ_a) and final (θ_f), as well as the loss and gain coefficients, and heating power calculated from eq. (8).

Fig. 8 shows the final temperature (θ_f) *versus* control temperature values (θ_c) of the heating source and the straight line fitted by less squared analysis.

Behaviour of calculated powers versus final temperature θ_c when steady state is reached, is shown in Fig. 9.

The values obtained from eq. (7) for the gain (λ_1) and loss (λ_2) coefficients *versus* the control temperature (θ_c) of the heating element are shown in Fig. 10. Note the existence of plateau for values 35<θ_c<60°C, with an average value (<λ_1>= (170±2)·10^{-4} w/ºC) based on data of

Table 2. Experimental values for the fitting parameters corresponding to different control temperature θ_c^* shown in Table 1. r, correlation coefficient

θ_c^* (ºC)	A (s)	B (s)	$\gamma\times10^4$ (s^{-1})	r^2
30	24.890	0.6605	5.006	0.9969
35	25.334	3.964	8.420	0.9998
40	27.355	6.185	8.772	0.9999
45	29.000	7.000	8.555	1.0000
50	31.027	8.977	8.405	0.9999
55	33.167	9,947	8,576	0.9999
60	34.510	11.400	8.708	1.0000
65	35.640	12.180	9.728	0.9999
70	36.810	13.570	10.38	0.9998

Table 3. Characteristic temperatures, gain and loss coefficients and heating power for each control temperature θ_c (nominal θ_c^*)

θ_c^*	θ_c	θ_a	θ_o	θ_f	$\Delta\theta$= (θ_c-θ_f)	γC= (λ_1+λ_2)	θ_f^*= (λ_1/λ_2)	λ_1 (w/ºC)	λ_2 (w/ºC)	Pot (w)
30	29.5	18,9	22.4	23.0	6.5	0.0324	1.5854	0.0125	0.0198	0.3400
35	34.1	21.3	21.4	25.2	8.9	0.0544	2.2821	0.0166	0.0378	0.6168
40	39.4	21.9	21.2	27.2	12.2	0.0567	2.3019	0.0172	0.0395	0.8755
45	44.4	22.0	22.0	28.8	15.6	0.0553	2.2941	0.0168	0.0385	1.0944
50	49.5	21.9	22.1	30.7	18.8	0.0543	2.1364	0.0173	0.0370	1.3609
55	54.3	23.1	23.2	32.8	21.5	0.0554	2.2165	0.0172	0.0382	1.5485
60	59.1	23.1	23.1	34.1	24.9	0.0563	2.2727	0.0172	0.0391	1.7969
65	63.7	23.5	23.5	35.4	28.3	0.0629	2.3782	0.0186	0.0443	2.2014
70	68.4	23.5	23.2	36.6	31.8	0.0671	2.4275	0.0196	0.0475	2.6014

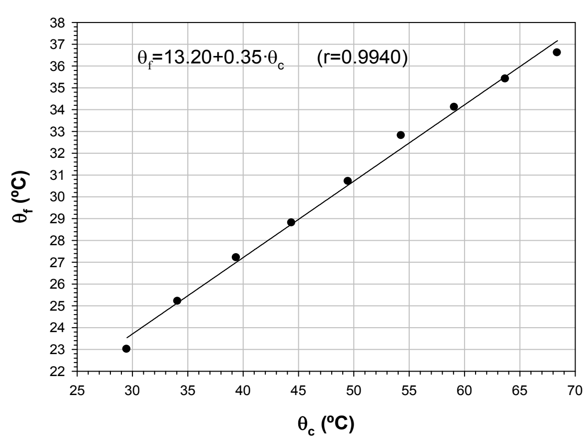

Fig. 8. Final temperature (θ_f) *versus* control temperature (θ_c) of the heating element

Table 3. The mean power for the plateau according to eq. (8) and taking into account the equation in Fig. 8, gives

$$< Pot > = < \lambda_1 > [0,65 \cdot \theta_c - 13,20] \quad (11)$$

This equation allows determination of <Pot> for every control temperature θ_c. The results are listed in Table 4 and illustrated in Fig. 11.

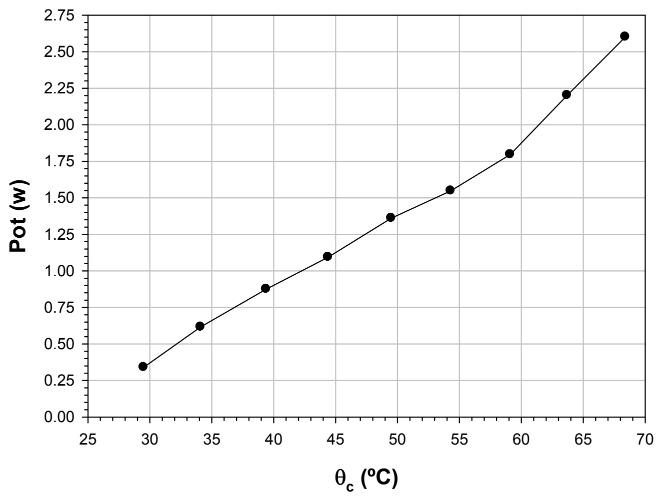

Fig. 9. Power for the heating system *versus* control temperature θ_c

Table 4. Mean heating power for the different control temperatures considered. Also, the final associated temperatures are shown

θ_c	34.1	39.4	44.4	49.5	54.3	59.1
θ_f	25.2	27.2	28.8	30.7	32.8	34.1
<Pot> ± 0,03 (w)	0.64	0.88	1.12	1.35	1.57	1.80

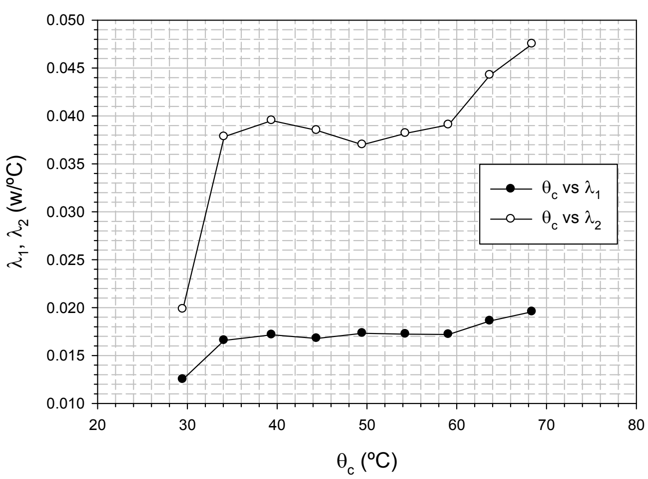

Fig. 10. Gain (λ_1) and loss (λ_2) coefficients *versus* control temperature of the heating source

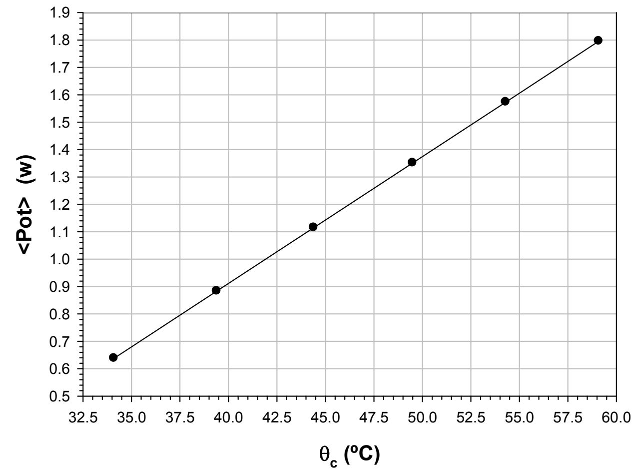

Fig. 11. Mean power values <Pot> as a function of the control temperature θ_c

5. CONCLUSIONS

A new procedure has been designed to measure the power of a no characterised heating source, in order to the use in the determination of thermal conductivities, corresponding to metallic disk samples. The method is based on a mathematical model constructed upon the heat balance equation for the system (source + problem disk + accessories), whose resolution allows us the determination of the gains and losses coefficients, the first of them is directly associated with the required power. For different control temperatures (30-70 ºC), the device was calibrated, so that an equation for the evaluation of the corresponding heat power was obtained, in the range of the considered temperatures.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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