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Development of a calorimetric sensor for medical application

Part I. Operating model

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Abstract A calorimetric sensor has been developed to measure the calorific dissipation through a determined area of the human body surface. An experimental laboratory prototype with a capturing surface of 36 cm^2 has been built, and a functioning model suggesting an operational method that allows to determine the calorific power going through the sensor has been proposed.

Keywords Calorimetric sensor · Calorimetric model · Medical calorimetry

Introduction

Calorimetric instrumentation has been developed mainly within the great area of the thermal analysis. In this area, many devices have been built: one for every need and with characteristics inherent to the process of the intended study [1, 2]. In calorimetry, to measure the calorific energy that is developed in a process, it is necessary for it to be carried out in a closed and controlled area where the influences external to the energetic process that is intended to be studied will be less. The objective of the developed instrument is to measure surface calorific dissipations located in the human body. In this medical use, the application that is to be measured is not inside the measuring instrument, but it is placed outside, this is the reason why this instrument is off the calorimetry standards. However, it has been built a laboratory experimental prototype, and it has been proposed an operational method to measure the heat flow that goes through the sensor. The operation principle of this small instrument is based on the Law of heat transmission by conduction and as its operation requires a thermostat at constant temperature, it can be included within the isothermal calorimeters by heat conduction [3].

The applications of the developed instrument are very varied as they will allow to study, in energy terms, different energetic processes developed in the human body. One of the possible applications is to control the power that is being dissipated when burning malignant cells with different methods. Another application is to measure the calorific dissipation in different parts of the surface of the human body: trunk, limbs, etc. for different activities: sedentary or typical of certain movements or exercises. The developed prototype has a capturing area of 36 cm^2, and it is valid for extensive surfaces. The sensor must be fixed to the skin avoiding any relative movement between the skin and the sensor. In this line of study that we start, we intend to optimize the operation of this device to, subsequently, develop similar devices for smaller capturing areas.

Experimental prototype

The calorimetric sensor is made up of by a thermopile and a thermostat thermally isolated to the exterior. The TEC1-12704 thermopile of 40 × 40 × 5 mm is located between the thermostat and an aluminium plate of 60 × 60 mm and 1 mm of thickness that is leaned against the area where it is intended to determine the calorific dissipation, on this surface, it is placed a Joule calibration resistance. The thermostat is made up of a small aluminium block (40 × 40 × 5 mm) that contains a heating resistance and a RTD sensor; it is also included within the thermostat a

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cooling system based on an aluminium dissipator with its corresponding fan (Fig. 1). A PID control keeps constant the thermostat temperature.

A programmable power supply (Agilent E3631A 80 W Triple Output Power Supply, 6 V, 5 A and ±25 V, 1 A) feeds the fan, the Joule calibration resistance and the resistance that is located in the thermostat. The calorimetric signal, the outside and thermostat temperatures, and the powers dissipated in the resistances are calculated from the measures carried out by a data acquisition system (Agilent 34970A Data Acquisition/Switch Unit and 34901A 20 channel multiplexer). The Agilent 82357B USB/GPIB Interface provides a direct connection from a USB port in our laptop to GPIB instruments.

Operating models and results

The operating model is provided by the system of equations which relate the dissipated powers with the measures variables, in such a way as to be able to reproduce accurately the operation of the device. With this purpose, it has been used the localized-constants model (RC model), that has been normally used to represent the operation of several conduction calorimeters [4–7]. It has been chosen a three domain model (Fig. 2), the first one represents the aluminium plate, and the second one represents the thermopile. The third domain represents the aluminium block that makes the thermostat function of the calorimeter. Each domain has a calorific capacity C_i and it is connected to the neighbouring domains through thermal couplings of thermal conductivity P_{ik}.

The model is obtained from the equations that are the result of the energetic balance of each domain. The power generated or absorbed in the domain with a capacity C_i is the sum of the stored power $C_i(\mathrm{d}T_i/\mathrm{d}t)$ plus those

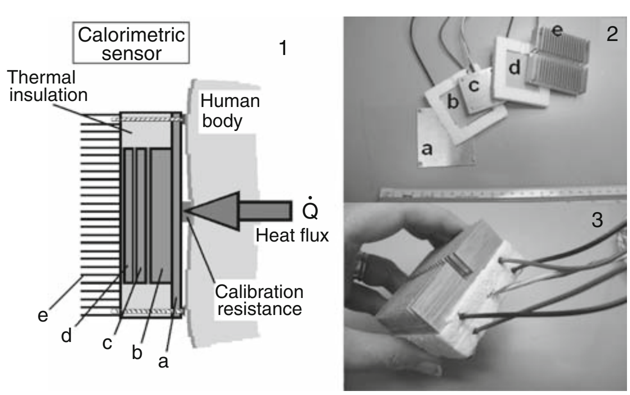

Fig. 1 Diagram (1) and assembly (2–3) of a calorimetric sensor. a—aluminium plate, b—thermopile, c—thermostat, d—Peltier element, e—aluminium dissipater

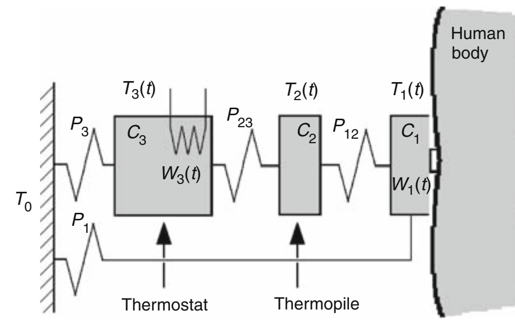

Fig. 2 Model of the calorimetric sensor

transmitted by conduction to the exterior (T_0) and to the neighbouring domains:

$$\begin{aligned} w_1(t) &= C_1\frac{\mathrm{d}T_1(t)}{\mathrm{d}t} + P_{12}(T_1 - T_2) + P_1(T_1 - T_0) \\ 0 &= C_2\frac{\mathrm{d}T_2(t)}{\mathrm{d}t} + P_{12}(T_2 - T_1) + P_{23}(T_2 - T_3) \\ w_3(t) &= C_3\frac{\mathrm{d}T_3(t)}{\mathrm{d}t} + P_{23}(T_3 - T_2) + P_3(T_3 - T_0) \end{aligned} \quad (1)$$

The power developed in the human body and that goes through the sensor is represented by $w_1(t)$, and the dissipated power in the thermostat is $w_3(t)$. The experimental output provided by the thermopile is $y(t) = k(T_2 - T_3)$, and the thermostat temperature is T_3. The outside temperature of the room is T_0. The power $w_3(t)$ is determined by a PID control that keeps constant the temperature T_3 in the thermostat, in stationary state, the temperature fluctuations are ±2 m K. As an example, we want to indicate that if we program a variation of the temperature at the thermostat of +2 K, the PID control will get stability in 5 min.

The model parameters (Table 1) are determined by minimizing a quadratic error criterion between the experimental curves and the ones obtained by the model equations (Eq. 1). In order to do so, it has been used the simplex search algorithm method by Nelder and Mead [8] using the software MatLab [9]. The experimental calorimetric curves used in the adjustment correspond to the known dissipations w_1 and w_3, Fig. 3 shows not only such powers but also the experimental outputs and the calculated curves. In

Table 1 Parameters of the RC model (Eq. 1)

RC model	$P_1 = 0.0368\ \mathrm{W\ K^{-1}}$
$C_1 = 13.72\ \mathrm{J\ K^{-1}}$	$P_{12} = 0.3203\ \mathrm{W\ K^{-1}}$
$C_2 = 14.63\ \mathrm{J\ K^{-1}}$	$P_{23} = 0.4605\ \mathrm{W\ K^{-1}}$
$C_3 = 61.91\ \mathrm{J\ K^{-1}}$	$P_3 = 0.3804\ \mathrm{W\ K^{-1}}$
Calorimetric signal $y(t)$	
$y(t) = k(T_2 - T_3)$	$k = 40.34\ \mathrm{mV\ K^{-1}}$

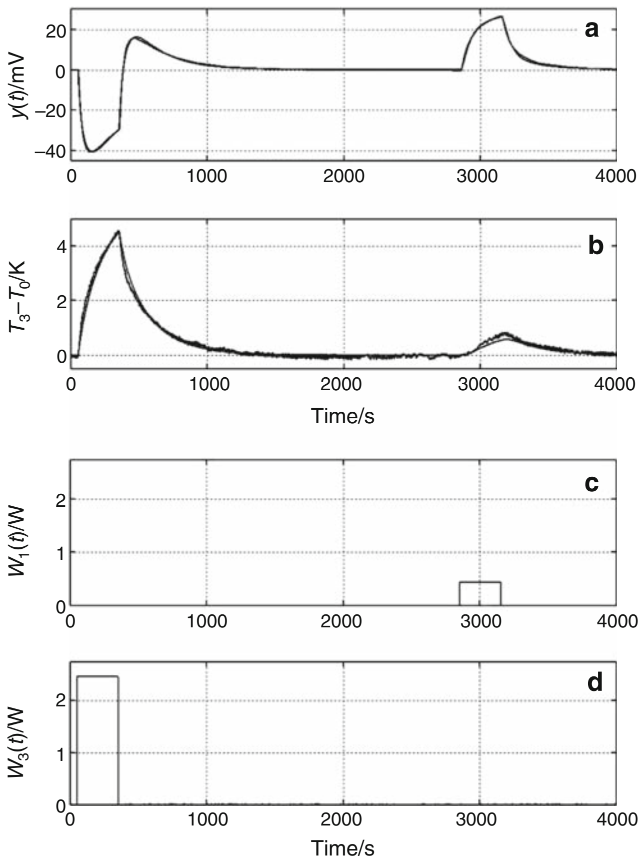

Fig. 3 Calibration measures. The figures show the experimental outputs and calculated $y(t)$ (**a**) and $T_3 - T_0$ (**b**)for the dissipated powers in the calibration resistance (w_1; **c**)and in the thermostat (w_3; **d**)

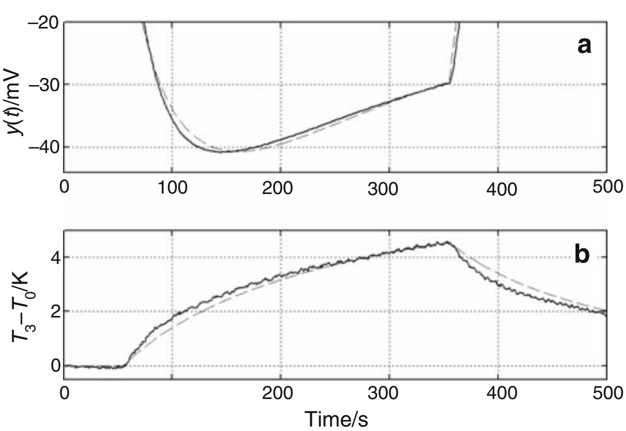

Fig. 4 Graphic detail shows the adjustment between the experimental curves (*solid line*) and those calculated (*dashed line*) using the model. **a** Expansion of the Fig. 3a. **b** Expansion of the Fig. 3b

Fig. 4, the adjustment between the experimental curves and those calculated by the model can be observed.

The experimental device can be considered as a system with two inputs and two outputs, where the inputs are the powers w_1 and w_3, and the outputs are the calorimetric signal $y(t)$ and the temperatures difference $\Delta T_3 = T_3 - T_0$:

$$\begin{pmatrix} Y(s) \\ \Delta T_3(s) \end{pmatrix} = \begin{pmatrix} TF_1 & TF_2 \\ TF_3 & TF_4 \end{pmatrix} \begin{pmatrix} W_1(s) \\ W_3(s) \end{pmatrix} \quad (2)$$

where $Y(s)$, $\Delta T_3(s)$, $W_1(s)$ and $W_3(s)$ are the Laplace transforms of the outputs and the inputs. Each Transfer Function (TF_i) has the form:

$$TF_i(s) = \frac{G_i(s+s_{i1}^*)(s+s_{i2}^*)}{(s+s_1)(s+s_2)(s+s_3)} = K_i\frac{(1+s\tau_{i1}^*)(1+s\tau_{i2}^*)}{(1+s\tau_1)(1+s\tau_2)(1+s\tau_3)} \quad (3)$$

All the TF_i have the same poles s_1, s_2 y s_3; but the zeros s_1* y s_2* of each TF_i are different depending on the position of the dissipation and detection. In Eq. 3, K_i are the sensitivities for each TF_i, $\tau_i = -1/s_i$ and $\tau_i^* = -1/s_i^*$.

In Table 2, it is presented the characteristic parameters of each transference function TF_i. The static response of the system is given by the sensitivity (K_i). The dynamic response of the system is given by the time constants (τ_i, τ_i*), we compare the dynamics of the different transfer functions through the representation of their magnitudes versus frequency (Fig. 5). In Fig. 5, we can see that the dynamic response of the calorimetric signal (TF_1 and TF_2) is faster than the one of the RTD temperature sensor located inside the thermostat (TF_3 and TF_4).

Table 2 Parameters of the TF_i of the system (Eqs. 2 and 3)

	TF_1	TF_2	TF_3	TF_4
K_i	67.826 mV/W	−6.562 mV/W	2.035 K/W	2.432 K/W
τ_1 (s)	229.0	229.0	229.0	229.0
τ_2 (s)	51.9	51.9	51.9	51.9
τ_3 (s)	14.4	14.4	14.4	14.4
τ^*_{i1} (s)	162.7	794.6	0.0	75.3
τ^*_{i2} (s)	0.0	21.4	0.0	15.1

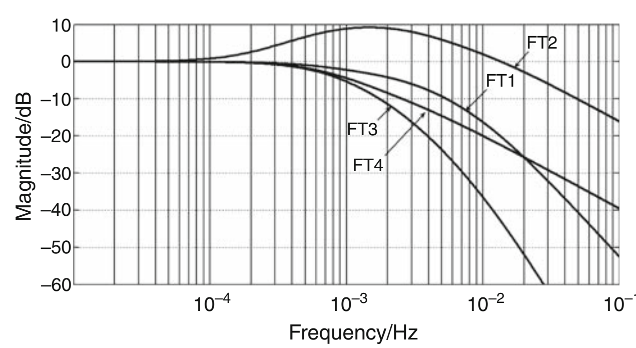

Fig. 5 Variation of magnitude (in dB) and phase (in rad) for the normalized transfer functions, $TF(jw)/TF(0)$, versus frequency. Magnitude (in dB) = 20 $\log_{10}$(magnitude)

Once we know the model parameters, the determination of the power $w_1(t)$ that goes through the sensor is made from the model equations (Eq. 1) The proposed model represents acceptably the operation of the calorimetric sensor allowing the determination of the dissipated power through the detection zone from the following experimental data: calorimetric signal $y(t)$, dissipated electrical power $w_3(t)$ and thermostat and room temperatures: $T_3(t)$ and $T_0(t)$. If the dissipation w_1 is constant and permanent, the determination of the developed power is inmediate as the PID control of the thermostat temperature is capable of reaching thermal equilibrium in the three domains, and for this situation, $w_1 = w_3 \, P_1/P_3$.

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