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Review and improvement of a method for measuring losses in the dielectric materials by calorimetry

E. Obame**, F. Aitken*, O. Gallot-Lavallée**

Abstract— The power loss plays a significant role in the design, implementation and use components in power electronics. It is therefore important to be able to characterize them using techniques reliable and preferably in the nominal operating conditions. The calorimetric principle seems to be particularly suited to the full characterization of losses. The calorimetric studied in this article was specifically designed to measure the losses in power capacitors. We offer a comprehensive analytical study heat exchange. The surfaces of the calorimetric device are considered insulated, gray, opaque and perfectly diffuse. The exterior wall is supposed adiabatic. The temperature gradients highlighted by this model and the response of the device in case tests show weaknesses in the system. The result is a degradation of measurement accuracy. This could, however, be improved by encouraging exchanges by radiation and using a single temperature regulator. This is the subject of an ongoing study.

Index Terms—Calorimetry, Dielectric, Emissivity, Losses, Modeling, Radiation.

I. INTRODUCTION

THE energy dissipated as heat by electrical components such as capacitors, insulated cables or integrated systems of power electronics are partly due to the phenomena of dielectric losses. Now-day, these losses are measurable under electrical constraints type sinusoidal and in limited ranges of frequencies. However it is very difficult to determine these losses in electrical industry constraints (e.g. modulation pulse width), which are very distant from the limits set by traditional analysis devices. These losses play an important role in the design, construction and the use of components [1]. It is therefore important to be able to characterize these losses with reliable techniques [2]. The calorimetric method is an interesting way for the losses characterization [3]. In 1995, a calorimeter was designed and implemented in our laboratory in order to characterize the losses in the low-voltage capacitors (Fig. 1 and Fig. 2).

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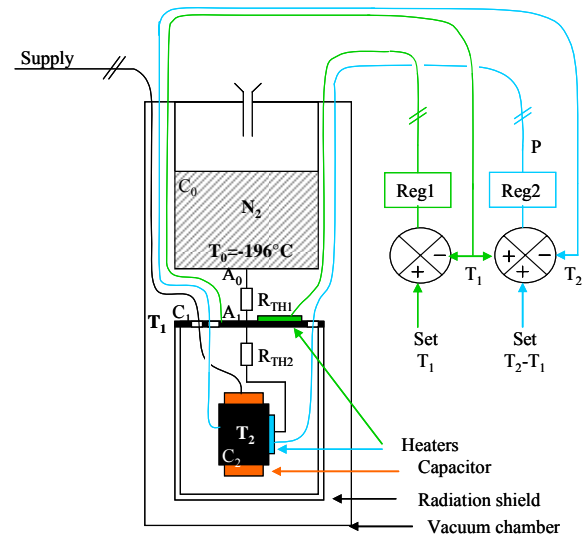


Fig. 1: Experimental set up

This calorimeter has three different levels of temperature. The liquid nitrogen tank C_0 maintains the cold point A_0 at a fixe temperature $T_0 = -196^\circ\text{C}$. The radiation shield, providing protection against thermal radiation, comprises a lid C_1 which centre A_1 , is thermally connected to A_0 by a copper rod (comparable to a thermal resistance R_{TH1}). The lid C_1 , is maintained at a temperature T_1 by a first temperature regulation 1. The measuring cell C_2 , is a copper band, tight around the capacitor. This cell is placed inside of the radiation shield and is connected to point A_1 by a copper rod (also comparable to a thermal resistance R_{TH2}). The fixation point of R_{TH2} on the measuring cell is noted A_2 and its temperature is T_2 . The gap ΔT ($\Delta T = T_2 - T_1$), is stabilized by a second temperature regulation 2 [4]. Sets point T_1 and ΔT being fixed; the measurement is done in two phases. In the 1st phase, (capacitor OFF); the heat flux passing of A_2 to A_1 is stabilized to the value P_0 by the temperature regulation 2. It corresponds ideally to the power delivered by regulation to maintain the gap ΔT constant. In the 2nd phase, (capacitor ON); capacitor dissipates heat power P_C equal to the active power consumed. This dissipated power takes part to heating the cell, and it has the effect of raising the temperature T_2 , and hence ΔT . The regulator gap responds to this disturbance by reducing the power it delivers to the measuring cell. When the steady state is again reached we can measure the heating

power P issued by the regulator gap. The gap ΔT is kept constant by temperature regulation, the losses generated P_C by the components are in principle, equal to the difference $P_0 - P$ powers previously measured. This measurement principle is valid while P_0 exceeds P at a given temperature T_1 [4].

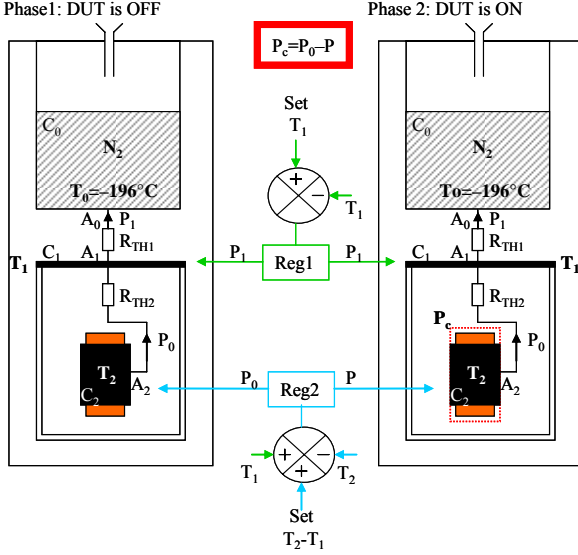


Fig. 2: Measurement principle.

This measurement principle may be interesting to the condition *sine qua non* that the balance of heat flux remains unchanged in both phases of measurement except the power P of regulation 2 and losses P_C produced by the component.

To highlight the measurement inaccuracies, a model relatively complete of heat transfer inside calorimeter was made. This model is compared with experimental measurements performed on the calorimetric device with $\Delta T = 0$ (this does not change the measurement principle while losses generated by the capacitor remains below P_0 (Fig. 2); i.e. $P_0 - P > 0$) and other measurement system in order to highlight weaknesses of the calorimeter.

II. MODELING IN PERMANENT THERMAL MODE.

The aim of modeling is to build a model as simple as possible in order to highlight potential weaknesses of the system. Calorimeter operates under vacuum, two modes of heat transfer dominate; radiation heat transfer between different surfaces areas and conduction heat transfer through the thermal resistances R_{TH1} and R_{TH2} of calorimeter (Fig. 1).

A. Simplified model component-measuring cell

A thermal model of system component-measuring cell was conducted to highlight the change in heat flux radiated by the component between phases OFF and ON (Fig. 3). The system being under vacuum, the component-measuring cell contact was seen as a mid to low thermal conductivity equal to that of air and low thickness equal to e . The component and the cell are supposed isotherm. This represents the worst case for the average temperature change of component. For heat flux of

1W by conduction between component and cell-C2 with $e = 1\text{mm}$, temperature variation of component $\Delta T_C = T_{C2} - T_{C1}$ (Fig. 3) corresponding east 7K. An $e = 0.5\text{mm}$ thickness is $\Delta T_C = 3.5\text{K}$.

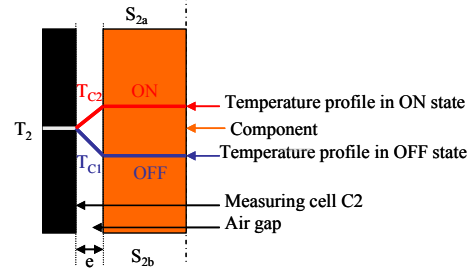


Fig. 3: Thermal model of component-measuring cell C2.

The change of power radiated by the component $\Delta \Phi_R$ calculated from the equation (1) in steady state is shown in Fig. 4.

$$\Delta \Phi_R \approx 4 \epsilon_C \sigma \Delta T_C T_{Cm}^3 S_C \quad (1)$$

Where ϵ_C is the surfaces emissivity of the component; T_{Cm} is the average temperature of the component taken as equal to T_2 ; $S_C = S_{2a} + S_{2b}$ and σ is the Stephan-Boltzmann constant.

$\Delta \Phi_R$ increases with temperature T_2 of the measuring cell. This variation is even more important than contact resistance or ΔT_C is great.

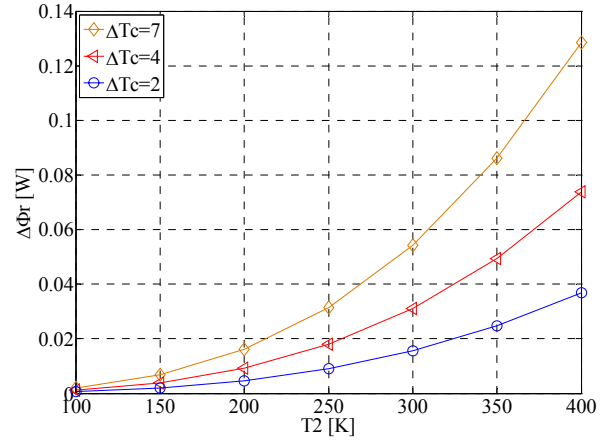


Fig. 4: Change in power radiated by component vs. T_2 of measuring cell

Thus, the power radiated by the component is different between the two phases of measurement. Therefore a portion of the power generated by the component is not measure by our calorimetric device.

B. Simplified model calorimeter.

1) Description model.

The calorimeter modelled consists in a vacuum chamber of $L_1 = 780\text{mm}$ in length and $\Phi_1 = 280\text{mm}$ in diameter, assumed insulated from external (i.e. adiabatic) where the various constituents (electrical component, liquid nitrogen tank, vacuum chamber walls, radiation shield) exchange energy by radiation and by conduction. The calorimeter model is

depicted Fig. 5.

For modeling radiation exchanges, the system has been divided into eight areas. All surfaces are considered isotherms, opaque gray and perfectly diffuse. All constituents being in cylindrical geometry, view factors (i.e. form factors between black bodies) were calculated according to references [5], [6] and [7]. The hemispherical total emissivities of metal surfaces are considered as equal to 0.1, and those of dielectric material (made of polymer materials) as equal to 0.9. These emissivities are supposed constant.

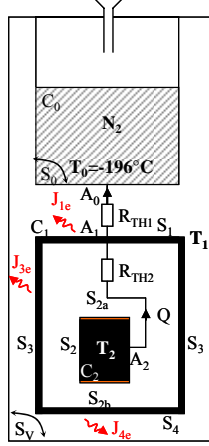


Fig. 5: Calorimeter model, S_0 reservoir of liquid nitrogen to 77K; S_1 lid of radiation shield, at T_1 , S_2 sheer electrical component T_2 ; S_{2a} and S_{2b} base surfaces component; S_3 lateral surface of the radiation shield; S_4 base area bottom of the radiation shield; S_V surface of the vacuum enclosure. J_{1e} , J_{3e} and J_{4e} represent radiosities surfaces S_1 , S_3 and S_4 sharing of power with S_V and S_0 .

The liquid nitrogen tank, $L_2 = 450\text{mm}$ in length and $\Phi_2 = 240\text{mm}$ in diameter, is maintained at reference temperature ($T_0 = 77\text{K}$).

The electrical component is considered as a cylinder 60mm in length and 30mm in diameter, and then it is divided into three areas: S_2 is copper while the other two surfaces base (S_{2a} and S_{2b}) are a polymer material.

The electrical component is located inside of thermal radiation shield, $L_3 = 130\text{mm}$ in length and $\Phi_3 = 80\text{mm}$ in diameter, which objective is to limit thermal exchanges with the vacuum chamber. This radiation shield is also divided into three areas isotherms: lid S_1 , lateral surface S_3 and bottom S_4 .

Heat flux radiated by resistances R_{TH1} and R_{TH2} with other elements of the system are neglected ($Bi \approx 8 \cdot 10^{-3}$).

Influence of electric wires of temperature regulator and capacitor are taken into account by thermal resistances R_{TH1} and R_{TH2} .

2) Setting equations :

Consider a gray-walled enclosure of arbitrary geometry made up of N isotherm surfaces, as a general, for a surface S_i exchanging the heat flux with other surfaces of this enclosed space, balance heat radiated is given by (2)

$$\sum_{j=1}^N F_{ij} (J_i - J_j) = \frac{\varepsilon_i (\sigma T_i^4 - J_i)}{1 - \varepsilon_i} \quad (2)$$

Where F_{ij} represents the view factor between surfaces S_i and S_j , i.e. the ratio between the amounts of heat radiated leaving S_i and reached S_j on total power radiated by S_i . The form factor depends on the surface geometry exchanging thermal power by radiation [8].

The term J_i represents radiosity (Wm^{-2}) of the surface S_i . By definition, radiosity is the resulting intensity of two terms: a term associated to emission of surface S_i and a term associated to reflection of the irradiation onto the S_i (3):

$$J_i = \varepsilon_i \sigma T_i^4 + (1 - \varepsilon_i) E_i \quad (3)$$

Where, E_i is the irradiation (Wm^{-2}) onto the surface S_i , i.e. the radiative heat flux per unit area from other surfaces that reached S_i , including that of S_i , if this surface is concave. In our model, only surfaces S_3 exchanging with the component and S_V are concave.

The application of relations (2) and (3) allows us to establish the equation of heat flux on the electrical component (i.e. each isotherm area of component exchanges heat flux with radiation shield surfaces, by radiation, moreover, the electrical component exchange heat power by conduction toward the lid of radiation shield), such as:

$$\sum_{j=1,3,4} F_{2j} S_2 (J_2 - J_j) + \sum_{j=1,3} F_{2aj} S_{2a} (J_{2a} - J_j) + \sum_{j=3,4} F_{2bj} S_{2b} (J_{2b} - J_j) + \frac{T_2 - T_1}{R_{TH2}} = \Phi_2 \quad (4)$$

Where Φ_2 represents the total heat dissipated by the electrical component and / or regulation 2.

On the lid (i.e. surface S_1) taking into account the power Φ_1 issued by the regulator 1; a heat flux balance for component is given by (5):

$$\sum_{j=2,2a,3,4} F_{1j} S_1 (J_1 - J_j) + \sum_{j=0,V} F_{1j} S_1 (J_{1e} - J_j) + \frac{T_1 - T_2}{R_{TH2}} + \frac{T_1 - T_0}{R_{TH1}} = \Phi_1 \quad (5)$$

J_{1e} means radiosity of the surface S_1 of radiation shield exchanging heat flux radiated with S_V and S_0 .

The net heat flux received by S_3 and S_4 from the electrical component may be stated as:

$$\Phi_{h=3,4}^{net} = S_h (E_h - J_h) = \sum_{j=1,2,2a,2b,3,4} F_{hj} S_h (J_j - J_h) \quad (6)$$

The net heat flux issued by S_3 and S_4 to the vacuum

enclosure S_V and nitrogen liquid tank S_0 is calculated as:

$$\sum_{j=0,V} F_{hj} S_h (J_{he} - J_j) = \Phi_{h=3,4}^{net} \quad (7)$$

Applying the principle of conservation of net heat flux, the flux entering in S_h , is equal to that coming out (8):

$$\sum_{j=1,2,2a,2b,3,4} F_{hj} (J_j - J_h) - \sum_{j=0,V} F_{hj} (J_{he} - J_j) = 0_{(h=3,4)} \quad (8)$$

Temperatures of electrical component (T_2 , T_{2a} and T_{2b}) and lid (T_1) are imposed by the temperature regulations; therefore heat flux by conduction through R_{TH1} and R_{TH2} are automatically determined. Ultimately, the equations to solve this problem are as follows:

- Electrical component: equation (4);
- Surface S_2 : equation (2) with $i=2$ et $j=1, 3, 4$;
- Surface S_{2a} : equation (2) with $i=2a$ et $j=1, 3$;
- Surface S_{2b} : equation (2) with $i=2b$ et $j=3, 4$;
- Surface S_1 : equation (5) inwards and outwards of the heat radiation shield;
- Surface S_3 : equation (2, 8) with $h=3$ and $j=1, 2, 2a, 2b, 3, 4$;
- Surface S_4 : equation (2, 8) with $h=4$ such as:

$$\sum_{j=1,2,2b,3} F_{4j} (J_j - J_4) = F_{4V} (J_{4e} - J_V) \quad (9)$$

- Liquid nitrogen tank S_0 : equation (2) with $i=0$ and $j=1, 3, V$;
- Vacuum chamber S_V :

$$\sum_{j=1,3,4,0} F_{Vj} (J_V - J_{je}) = 0 \quad (10)$$

Temperatures T_1 and T_2 being imposed, the above equations admit as unknown the radiosities of isotherm surfaces. The heat flux Φ_2 and Φ_1 are determined by equations (4) and (5). It is noted that variations Φ_2 or T_2 have the same influence on the calorimetric system. Thus studies were conducted by considering one of these parameters (T_2 temperature of the measuring cell).

C. Theoretical results

We determined the changing temperatures of the system versus electrical component temperature T_C , that is considered as uniform (i.e. $T_C = T_2 = T_{2a} = T_{2b}$). The temperature T_1 is set at 300K (27 ° C), and theoretical analysis has been conducted within the limits of experimental temperature measurement (i.e. $\Delta T \leq 10K$).

Fig. 6 shows that temperatures of surfaces S_3 and S_4 , remain very similar, and increases slightly with the electrical component temperature (slope = 5%) and there is a steep

gradient compared S_1 . This trend is also observed in S_V temperature (slope = 4%), but the temperature of this surface remains logically lower than that of radiation shield.

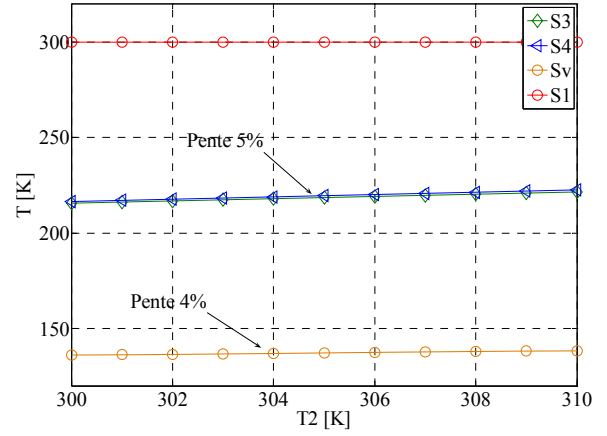


Fig. 6: Temperatures surfaces calorimeter vs. temperature of electrical component T_C .

We also calculated the change in power electric of regulator 1, against temperature T_1 of lid S_1 for $T_2 - T_1 = 10K$. It appears in Fig. 7 that, this variation increases with temperature lid.

From behaviour described above, although the temperature of the lid is fixed, component, and / or the temperature regulator 2 provide additional heating power to the lid, leading to a decrease of that of regulator 1. This variation is even more important than T_1 is high.

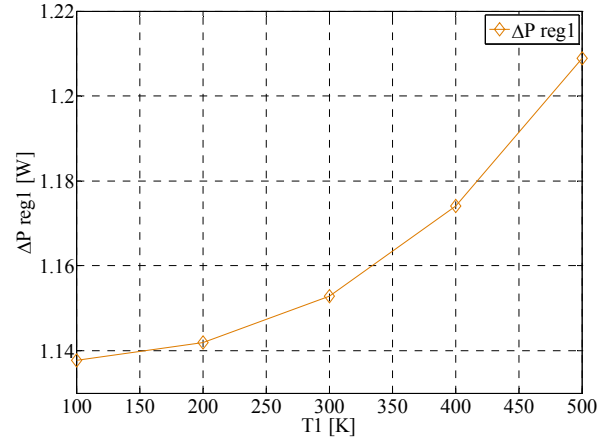


Fig. 7: Change in power regulation 1 vs. T_1 , corresponding to $T_2 - T_1 = 10K$.

The variation of ratio between the total heat flux radiated by component (Φ_r) on flux issued by conduction through R_{TH2} (Q) based on the difference $T_2 - T_1$ is illustrated by Fig. 8. It notes that from $T_1 = 300K$, this ratio is no longer negligible ($\Phi_r/Q=40\%$). Therefore, it is expected that under these conditions, the power measured by the calorimeter is less and less the total heat flux emitted by the electrical component.

The variation of ratio in percentage of heat flux $\Delta\Phi_r/\Delta Q$ ($\Delta\Phi_r$: variation of heat flux radiated by the electrical component, ΔQ : variation of flux emitted by conduction through R_{TH2}) for $T_2 - T_1 = 10K$, depending on the temperature T_1 , is shown in Fig. 9. This ratio is low for values of T_1 below

300K and takes significant values beyond that temperature.

The heat radiated is proportional to the emitting surface; the change in power observed previously will be even larger than the ratio diameter length of the capacitor is important (i.e. surface radiation $S_{2a} + S_{2b}$ /surface conduction S_2).

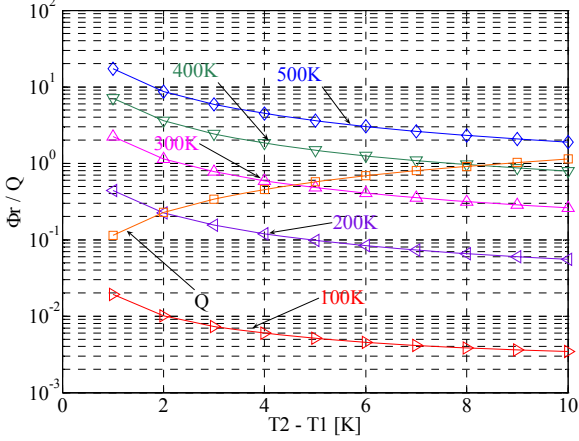


Fig. 8: Changes in the ratio Φ_r/Q (Φ_r total net heat flux exchanged by radiation, Q heat flux emitted by conduction through R_{TH2}) vs. $T_2 - T_1$ at different values of T_1 .

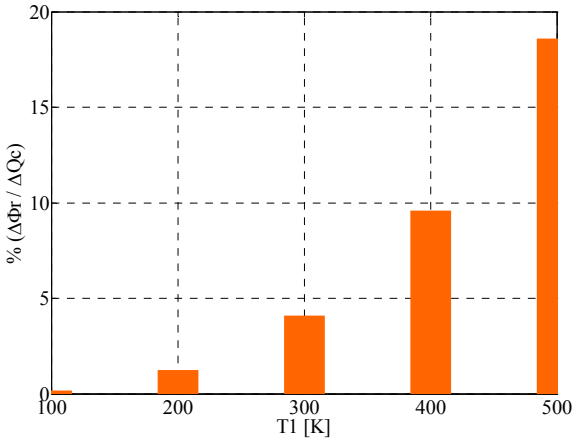


Fig. 9: Ratio $\Delta\Phi_r$ (heat radiated variation by the component) on ΔQ (heat flux conducted through R_{TH2}) for $T_2 - T_1 = 10K$, vs. T_1 .

III. EXPÉRIMENTATIONS

A. Samples Description

1) Condensator

The first type of sample is a capacitor-type PEK235 designed to operate under nominal voltage and nominal current of 330V-12.5A ac. Its capacity typical at 1 kHz/25 °C is 481nF.

2) Standard component

The standard component is made up of the same capacitor which we added two resistance heaters coated polyimide to produce artificial losses. These heaters have the following characteristics: electrical resistance: 157Ω; Voltage: 28V; rated power: 5W; operating temperature: -32°C to +100°C (Fig. 10).

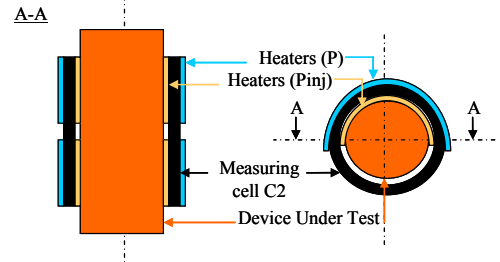


Fig. 10: Standard component constitutes of resistances heaters pasted outside (Reg2) and inside (Pinj) of the measuring cell C_2 .

B. Experiment

1) Calorimetric measurement

The measurements of losses artificially produced by the "standard component" were made using calorimeter. These measurements were performed in primary vacuum. The temperature T_1 of radiation shield lid was regulated on a range of -50°C to +100°C. The power losses measured ($P_{meas} = P_0 - P$) by calorimeter were compared with that artificially produced (P_{inj}) by heaters in the standard component.

A characterization in ac of capacitor test (PEK235) equivalent series resistance (ESR) has also been carried out using the same device. These measurements were performed in primary vacuum. The temperature T_1 was regulated to 50°C. This characterization was carried out on a frequency range from 1 kHz to 1MHz and in an apparent power of 10VA corresponding to a range of voltage and current from 23V–0.42A à 35V–0.28A. These measurements was performed with $\Delta T = 0$ respecting the condition $P_0 - P > 0$.

2) Impedance analyzer measurement

A characterization in ac of equivalent series resistance (ESR) of the same capacitor test (PEK235) was carried out using an impedance analyzer (Novocontrol ® BDS20) [9]. These measures were performed under atmospheric pressure in oven at 50°C in a frequency range of 1 kHz to 1MHz and under ac voltage of 3Vrms.

C. Results

The measurements on the standard component show that power measured (P_{meas}) by calorimeter remains lower than the standard component dissipated power (P_{inj}). It also notes that the gap between P_{meas} and P_{inj} increases with temperature T_1 (Fig. 11). This shows that the power measured by the calorimeter is even more underestimate that T_1 is great. Indeed, it is likely that a part of thermal power conduct by electrical wires differs between the two phases of measures. It is also likely that heat flux radiated by the system composed of the measuring cell C_2 and capacitor is not constant in both phases of measures. But the differential measurement principle is valid only if the balance of heat flux between the system component–measuring cell and radiation shield remains unchanged: *condition sine qua non*.

The results of current measurement of regulation 1 (Reg1) before and during power-up of standard components are presented in Fig. 12.

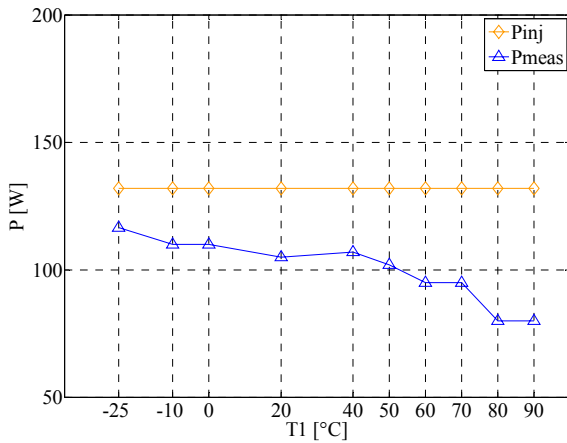


Fig. 11: Comparison between injected power and the power measured by the calorimeter.

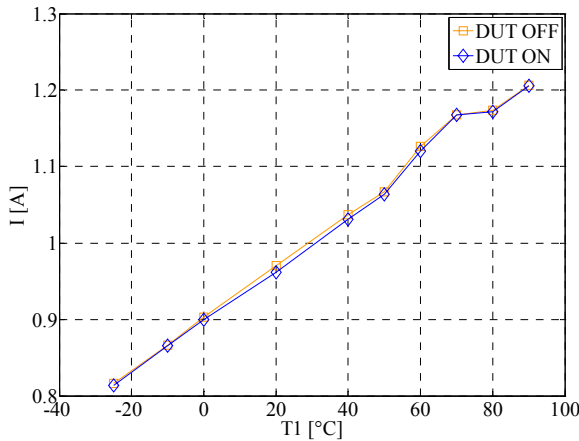


Fig. 12: Current measure against temperature regulator 1 before and during the power-on standard component.

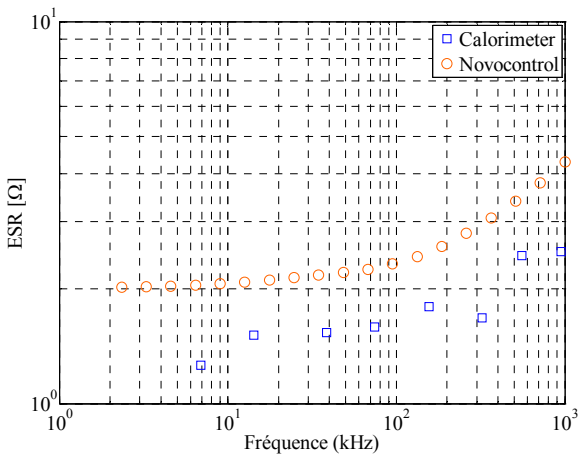


Fig. 13: Comparing spectra of the equivalent series resistance (ESR) issues calorimeter and the impedance analyzer.

These results show a small decrease in heat current of regulator 1 when the standard component is switched on. However, the gap between the two currents which fluctuate is in order of magnitude of 10^{-3} am across the range of measurement. The power provided by Reg1 east of 25W for $T_1 = -20^\circ\text{C}$ while variations by modeling (Fig. 7) are around

1W (4% of the power supplied by Reg1). Therefore, it is difficult to estimate the variation in amount of heat transmitted to lid between two phases of measurement.

Finally, Fig. 13 shows the characteristics of ESR measured from the calorimetric device and that measured by the impedance analyzer. It is observed that the spectrum measured by calorimetry remains below that measured by the Novocontrol®. This result confirms once again that the losses (and therefore ESR measured from calorimeter) are underestimated.

IV. DISCUSSIONS

The modeling calorimeter has revealed temperature gradients in the calorimeter. These gradients reflect power dissipation by radiation which escapes to R_{TH2} . Heat flux radiated is even more important than the temperature applied on the lid is high ($T_1 \geq 300\text{K}$). Under such circumstances, it seems unlikely that all the amount of heat generated by component-measuring cell remains constant in both phases of measures. Hence, the power characteristic measured by the device represents only a part of the real power dissipated by the electrical component. This description is consistent with experimental measurements performed on the capacitor and the standard component where it is observed the degradation of the measure when the temperature T_1 increases.

This calorimeter could however be improved by making the heat flux radiated very paramount against heat conduction through R_{TH2} . This new device would allow testing components with various forms. This is the subject of ongoing study.

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