Design of a low cost thermal impedance measurement tool for practical lesson in engineering school

Ph.Dondon, J.Micouleau

Abstract— We present here a low cost electronic design for a new practical lesson called "thermal characterisation of power transistor thermal impedance". First, we describe the design using COTS components and open source software for practice of temperature measurement and characterisation of electronic component. We explain how we checked and validated the designed tool. Lastly, didactical and financial aspects are discussed within the context of economic difficulties and budget reduction for education.

Keywords— Thermal measurement, low cost electronic design, didactical tool, practical lesson.

I. INTRODUCTION

A. Generalities

ENSEIRB MATMECA high engineering school has several departments of which the electronic ones. In first year of study, we propose to the students their first project which consists in designing and realizing a class AB audio power amplifier. When the schematic is defined, students capture the design, make analogue simulations, PCB routing, wiring and testing of their amplifier. Unfortunately, because of the project duration, thermal considerations are not included within the frame work of the project. However, choosing and calculating heat sink for the push pull stage is obviously very important. That's why we propose here a practical complementary lesson to deal with thermal aspect of electronic. While professional equipment [1], [2] remains very expensive, we have designed a low cost didactical tool to fit to our pedagogical needs.

B. Thermal aspect in electronic design

In our linear power audio amplifier project, the output stage is a classical bipolar push pull stage which can deliver up to 10W.

As our students focus on electronic design they often forget that heat must be correctly dissipated. Thermal impedance is not an obvious notion for most of the students. In order to sensitize students to thermal aspects for a basic approach, equivalence between electrical and thermal quantities is first explained [3], [4], [5]. Then, equivalent schematic of a thermal assembly, using R and C components, is established. And this approach must be illustrated by a practical lesson. In the next paragraph, we describe the board we designed for this purpose.

A lot of methods and works on thermal measurement are already found in literature [6], [7], [8], [9]. So it is quite easy to get the fundamentals and basics in this field.

The most important point in our approach is the low cost and didactical aspect, within the context of reduction of budget and impact of global economic difficulties. Thus, after the pure technical design description, we discuss various aspects of our work.

II. ELECTRONIC DESIGN

A. Technical design

Block diagram of the designed board is given in Figure 1. The Device under Test "D.U.T" (here a TIP 31 NPN bipolar transistor TO 220 package) is placed in a feedback loop to set up a constant voltage value between collector and emitter. A controlled constant current coming from a current source is switched on when pressing a button. Thus a calibrated power pulse (adjustable from 1W to 2W) is applied to the DUT. A second push on the button stops the power pulse. A LED is turned on during the power pulse.

Under these conditions, V_{BE} voltage through base emitter pins decreases linearly (-2mV/°C) when the temperature increases. Thus, V_{BE} is measured thanks to a precision instrumentation operational amplifier AD620 and deliver an image of the temperature of the chip T_{chip}. One thermocouple (K type) with its conditioning circuit AD595 and LM6482, gives image of ambient temperature $T_{ambiant}$. A other one can be placed at the interface between transistor back, sil-pad thermal joint and heat sink [10], [11] to obtained an intermediate temperature $T_{intcase}$. A particular attention has been paid to PCB routing for thermocouple acquisition circuits, to reduce connexion length and to make twinned routing for each thermocouple.

Sensitivity of V_{BE} channel is 10mV/°C.
Sensitivity of thermocouple channels is 28mV/°C.

Manuscript submitted 6 january, 2015:

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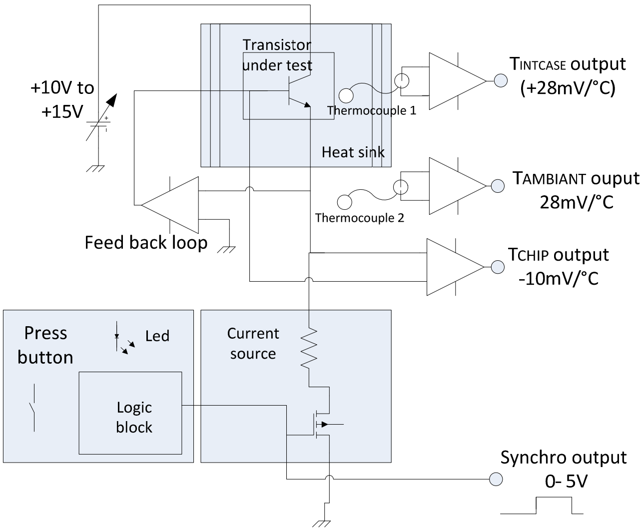

Fig. 1: Simplified block diagram

To make our thermal test system autonomous and low cost, (no extra voltmeter, oscilloscope required to manipulation), we added a simple acquisition board to record temperature during pulse power application as explained in §3.2.

B. Acquisition hardware and software

Acquisition system is based on open source Arduino kit: Uno board with and Ethernet/SD card shield) and a RTC module DS1307 for dating the acquisitions. Analogue inputs are converted by a 10 bits ADC which is enough for accuracy and resolution of the system (less than 0.5 degree).
A "C language" program has been implemented in the Arduino micro controller:
After initialisation, acquisition is triggered by the start button. Analogue values are sampled and dated with the Real Time Clock (RTC) every 5 seconds which is enough for a slow thermal phenomenon. Voltage are converted in temperature value though a calibration formula, data are converted in text format and recorded on a local SD card as text file.
Acquisition is ended by a second push on button, recording file is closed and ready for transferring data in a spread sheet.

A view of the designed board is given in Figure 2. DUT has been elevated above the electronic board to facilitate observation by an Infrared camera if necessary and available.

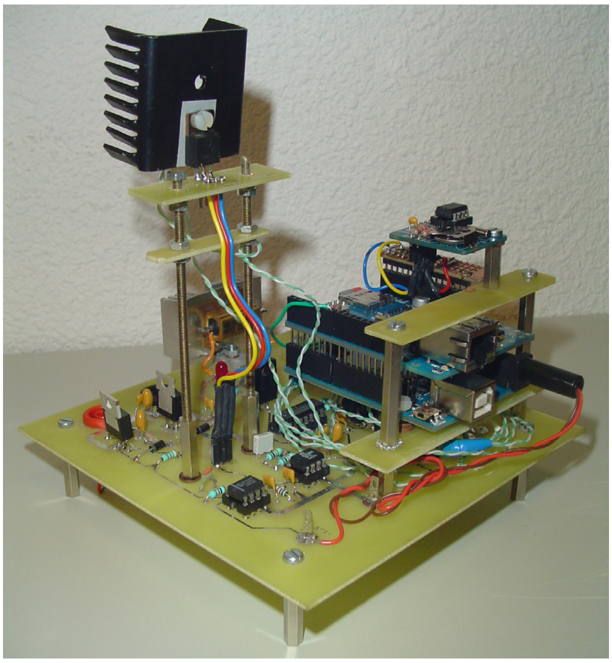

Fig. 2: View of the testing board.

III. VALIDATION OF DESIGNED TOOL

There is no preliminary calibration of the chip in Fluorinert liquid for example like with professional equipment. So, our tool must be as well as possible checked before being "ready to use" for the students.

Thus, several test have been performed as described in next §A to check integrity, fidelity and accuracy of recorded data. Validation test required extra apparatus such as voltmeter, digital oscilloscope and infrared camera.

A. Results from acquisition

Three different tests were performed under the same operating conditions:
- Power pulse 1.1W, 7 minutes duration.
- Close "ambient" temperature measured by thermocouple located at 3mm far from the back of the D.U.T; (ambient temperature in electronic means temperature quite close to the heating component).
- Data are imported in Excel spreadsheet to draw graphics.
- Horizontal scale format time in hh:mm:ss

All the results given in this paragraph will be discussed and commented in § IV, from a technical point of view.

First test is done without heat sink. Thus, only chip and ambient temperatures are recorded as indicated in figure 3.

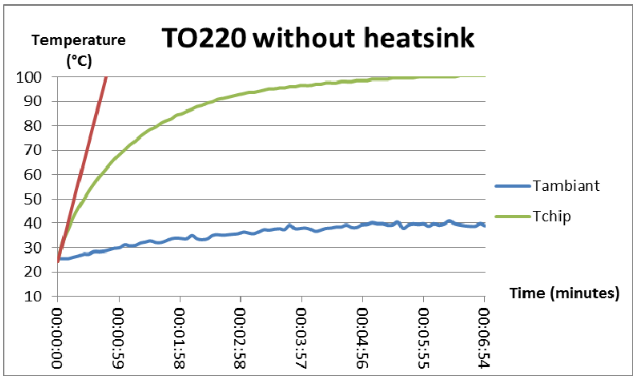

Fig. 3: Temperature vs. time without heat sink

Second test is performed by adding a heat sink (reference multicomp - MC33278 - heatsink 7.6°C/W) and a sil pad thermal conductive sheet between TO220 package and heat sink.

Fig. 4a: Heat sink for TO220 package

A thermocouple is inserted between the heat sink and the Sil pad in a small trench as indicated in figure 5. Then, the temperature $T_{intcase}$ at interface is given by this second thermocouple.

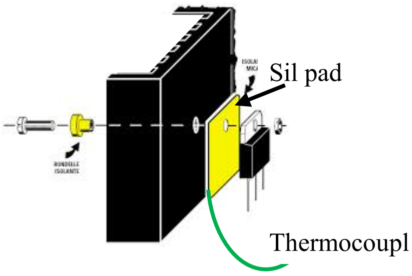

Fig. 4b: Insertion of thermocouple

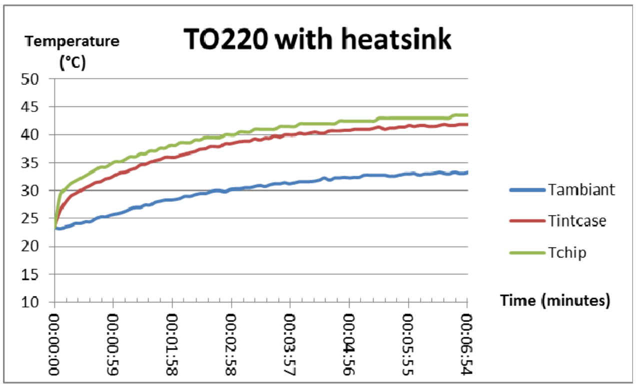

Fig. 5: Temperature vs. time with heat sink

The last test is performed with the same assembly, and a small fan (Matsushita panaflo DC brushless 12V, 0.16A, 80mm x80mm). It is located at 15cm from the DUT on the side; It obviously increases the air convection around the heat sink. Result is given in figure 6.

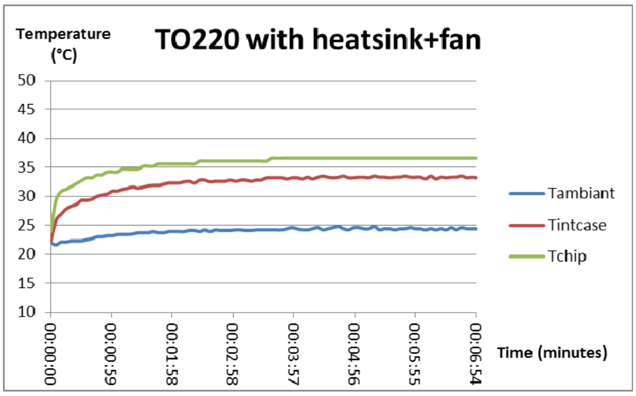

Fig. 6: temperature vs. time with heat sink and fan

In order to validate the results, comparison with oscilloscope acquisition and infrared observation has been done.

B. Oscilloscope measurement comparison

Chronograms have been directly recorded on a 4 channels digital oscilloscope, in single shot mode, with horizontal scale 50s/div.
CH1 (orange): image of power pulse
CH2 (blue): voltage image of Tambiant (1V/div)
CH3 (violet): voltage image of Tintcase (1V/div)
CH4 (green): 5*VBE voltage image of Tchip (1V/div)

The correct conversion from voltage to temperature values is done by comparing the recorded data on SD card with the curve recorded with digital oscilloscope.
Minimum, maximum and some intermediate values were taken on each curve.
They were manually converted in temperature values and compared with values recorded in SD card to check correct offset compensation and coefficient implemented in the program.

Figure 7 shows the transient response corresponding to the first test (cf. figure 3). Only chip temperature and ambient temperature are displayed. Thus, the noise B is high pass filtered while the input signal V_{in} is low pass filtered with the same time-constant T_c of the integrator (Cf. figure 6). One must thus choose T_c to let pass the maximum frequency F_{max}, of the input signal V_{in}.

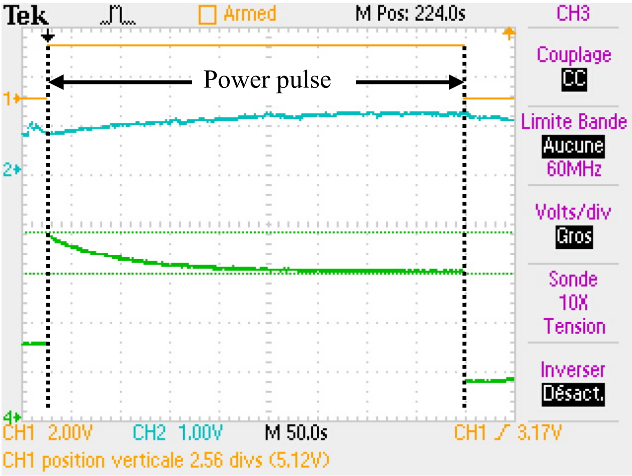

Fig. 7: TIP31 without heat sink

Figure 8 shows the transient response corresponding to the second test (cf. figure 5).

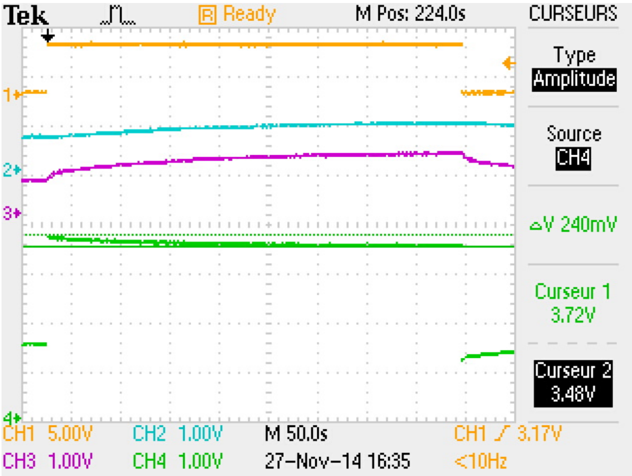

Fig. 8: TIP31 with heat sink

Figure 9 shows the transient response corresponding to figure 6.

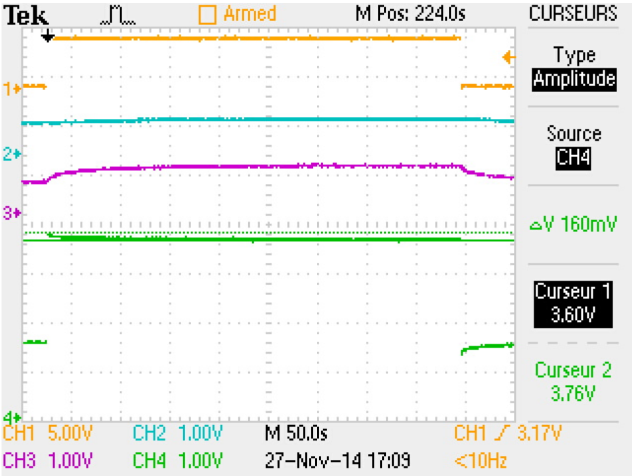

Fig. 9: TIP31 with heat sink and fan

C. *Infrared camera*

To complete experiments, some infrared pictures were recorded under the previous test conditions, using a B335 FLIR camera.

Since it is difficult to determine finely the emissivity of the target, emissivity value was set up, from tables given in literature for the aluminium anodised and black coated heat sink. Figure 10 shows the DUT during the transient phase with heat sink and without fan. The temperature of the heat sink is not still homogeneous.

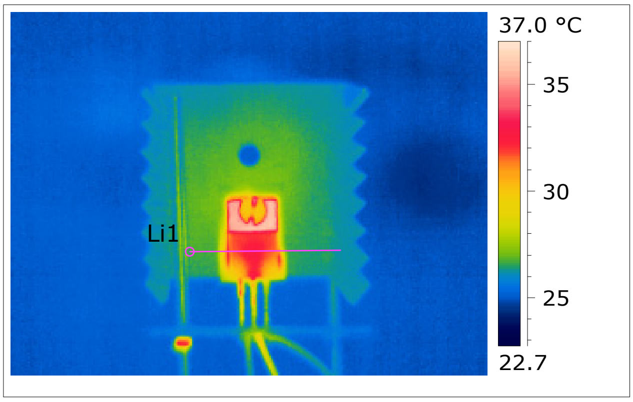

Fig. 10: Infrared Transient image after 3 minutes

Figure 10 and 11 shows the assembly when steady state is reached after 7 minutes. Surface temperature rises up to 40°C and is quite homogeneous on the whole heat sink surface. This value is coherent with the value given by $T_{intcase}$ at the same instant.

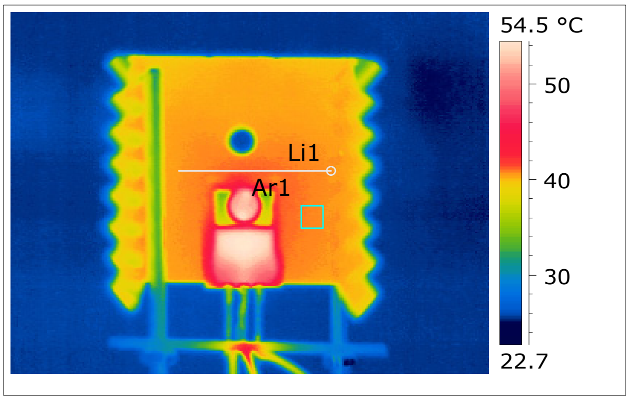

Fig. 11: Infrared image after 7 minutes

IV. EXPLOITATION OF THE RESULTS

A. *Extraction of thermal modelling*

The main goal of this test system is to extract thermal resistor and thermal time constant values. However, the measurements are not performed according to JEDEC Standard. Our test conditions are close to the true operating conditions. Thus, it is not possible to extract extremely precisely the thermal impedance of the assembly and to compare them to the theoretical values given in data sheet.

Nevertheless, order of magnitude, impact of heat sink and tendencies can be easily checked. In most of the cases, it is enough for discrete electronic designer since there are a lot of uncertainties on ambient temperature value, interface pressure on sil-pad, air flow around the board... It can be done from the previous measurement as indicated hereafter:

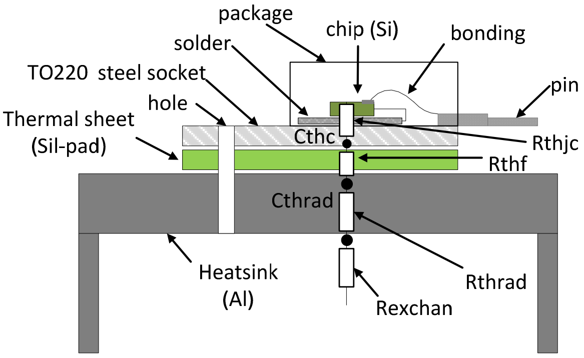

Fig. 12: Assembly cross section

As defined on figure 12:
-Rthjc is thermal resistance between chip and case,
-Rthf is thermal resistance of sil-pad sheet,
-Rthrad is thermal resistance between heat sink and ambient,
-Rthja is thermal resistance between chip and ambient when no external heat sink.
-Rexchan is superficial exchange resistance with room.

Nominal data given by manufacters are:
-Rthja= 62.5°C/W, for TO 220 case
-Rthjc= 3.1°C/W
-Rthf between 1 to 4°C/W, depending on interface pressure,
-Rthrad= 7.6°C/W.
Thermal capacitances are not specified.

From the first test, (figure 3, without heat sink) we obtained in steady state condition a temperature difference $\Delta T = T_{chip}\text{-}T_{ambiant}$ of 63°C for 1.1W power pulse. However, this value is obviously greatly dependant of the location of $T_{ambiant}$ thermocouple. Thus, our test leads to an experimental value of Rthja around 57 To 62°C/W. Thus, estimation of Rja is correct.

From the second test (figure 5, with heat sink)
The absolute chip temperature is greatly decreased from 100°C to 45°C which prove the qualitative efficiency of the heatsink.
We obtained in steady state condition a temperature difference $\Delta Trad = T_{intcase} - T_{ambiant} = 8.6°C$
It gives a Rthrad around 7.8°C/W. Thus, estimation of Rthrad is correct.
If we take the room temperature T_{room} as reference, (far from the component), $\Delta T2 = T_{ambiant} - T_{room}$ reaches 10°C. So, that our estimation of R_{exchan} (exchange coefficient with air) is around 8 to 9°C/W.

From the last test (figure 6, with heat sink and fan), The absolute chip temperature is decreased from 45°C to 36°C, which prove the efficiency of the fan (improvement of air exchange).
We obtained, in steady state conditions a temperature difference $\Delta T1 = T_{chip}\text{-}T_{intcase} = 3.4°C$. Our estimation of Rthjc+Rhf is around 3°C/W, (a little underestimated compared to manufacturer values).
The difference $\Delta Trad = T_{intcase} - T_{ambiant}$ is always equal to 8.8°C and confirms the Rthrad value obtained in the previous test.

Time constants can be extracted from the same curves.
From Figure 3, we get the time constant without heat sink, around τ= 45 to 50s. Extracted value of thermal capacitance is thus Cthja = τ /Rthja around 0.8 to 0.6 W.s/°C.
This thermal inertia comes essentially from the steel alloy (AISI 4340) socket of the TO220 back side package. We can check this value using physical properties given by TO220 manufacturer:
- heat capacity of AISI 4340 alloy : 477 J/kg.°C
- weight of the socket is around 1.5g

So, we get a thermal capacitance Cthja of 0.7W.s/°C. Order of magnitude is thus correct.

From Figure 5, (with heat sink) we can also extract time constant. In fact, as we added the heat sink, the global thermal equivalent circuit becomes second order with two capacitances. The second time constant is around 100 seconds. So, thermal capacitance Crad of the heat sink is around 11W.s/°C.

B. Spice equivalent thermal modelling

It leads to the following equivalent thermal/electrical network [3] given in figure 13:
Green probe : T_{chip}
Red probe :$T_{intcase}$
Blue probe :$T_{ambient}$

Yellow probe: room temperature (23°C)

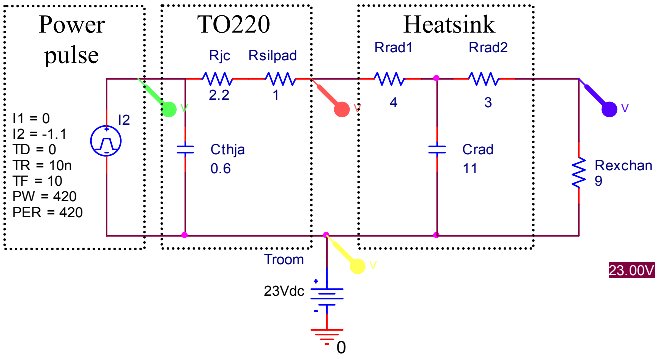

Fig. 13: Equivalent schematic

Corresponding simulation is given in figure 14, with the following set up:
- Conversion factor 1V⇔1°C
- Heat power pulse 1.1W⇔current source 1.1A
- Horizontal scale 420s (7min)

Spice simulation must be compared to figure 5.

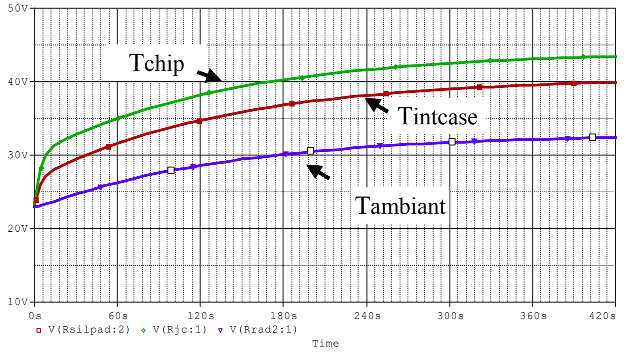

Fig. 14: Spice simulation (heat sink)

From figure 6, when fan is in action, R_{exchan} is reduced from 9 to 2°C/W. The Spice simulation becomes as indicated in figure 15 (to be compared to figure 6).

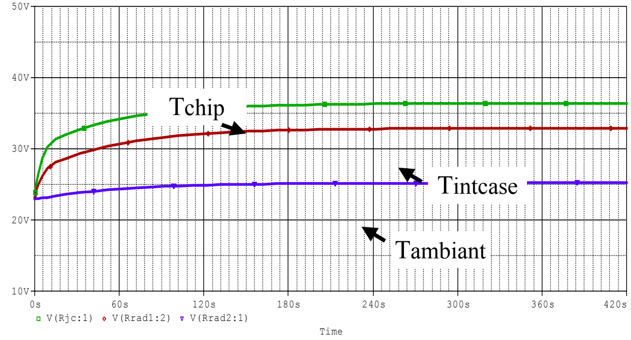

Fig.15: Spice simulation (heat sink+ fan)

C. *Application to our student's project*

Once extracted, this modelling can be used in our didactical project for studying the thermal behaviour of the push pull stage (MOS in TO220 package) of the audio amplifier:
Indeed, thanks to Special Spice elements "multiplication function" (EMult) and "Voltage controlled current source" (VCCS) (from ABM library ORCAD/CADENCE software), the instantaneous power dissipated in output transistors can be calculated in real time during a transient simulation. Then, it is applied to the network in figure 13 included on the same schematic sheet, to get an image of thermal behaviour of the output stage.

Figure 16 shows a basic output push pull stage, supplied under Vcc= +15/-15V, associated to the previous thermal equivalent modelling. Audio speaker is represented by a resistance R_{HP}= 8 ohms. Room temperature is set up to 23°C by the equivalent DC voltage source T_{room}.

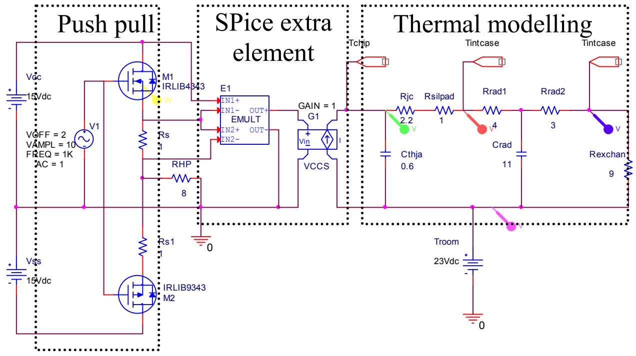

Fig. 16: Thermal modelling included in push pull electronic schematic

Transient simulation can be run in worst case with a classical sinus input stimuli waveform at 1 kHz. When input signal amplitude is 2.Vcc/π, the average dissipated power P_d in one transistor is maximum:

$$P_{dmax} = Vcc^2/(\pi^2.R_{HP})$$

The result of full simulation is shown in figure 17 (Without fan). Vertical scale 1V⇔1°C. Full horizontal scale : 720s (7min)

Figure 18 represents a zoom on instantaneous dissipated power P_d waveform. (Horizontal scale : 5ms. Vertical scale in W).

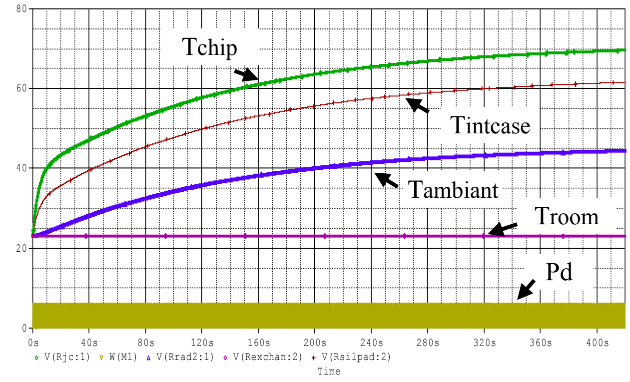

Fig. 17: Global Spice simulation

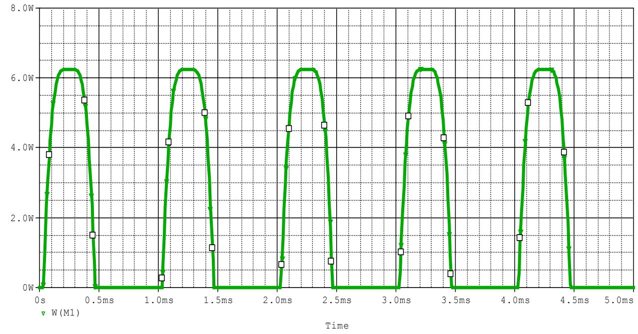

Fig. 18: Zoom on dissipated power chronogram

V. General comments

Generally, electronic designers do not take into account Rexchan. Indeed Rexchan is a very variable value depending on complex geometrical, physical, and thermal and room environment considerations. For heat sink estimation, they prefer to assume room temperature is between 30 to 40°C. Our practical approach allows to better know this parameter for a given situation and to get a more realistic value of chip temperature. So, it is a way to integrate the effect of Rexchan.

VI. Financial Aspects

The design of this basic thermal measurement board is quite cheap. We give in table the cost of raw materials, excluding labour cost of the teacher. It is obviously greatly cheaper than professional equipment [3].

materials	price
thermocouples	6€
Electronic components	55€
Arduino uno	24€
Arduino SD card shield	30€
Arduino RTC module	6€
SD card USB adapter	10€
Total	131€

Table 1: Cost of the design

VII. Pro and con's

A. *Advantages*

Our board is “Easy to use”, and perfectly matches to our didactical needs. But the most important is the “low cost” design. It shows that it is possible to do “something with nothing” within a difficult economic context.

B. *Disadvantages*

This design is obviously not professional equipment: There is no preliminary calibration of junction and it is able to test only bipolar transistors.

VIII. Didactical aspects

The global project “design of an audio amplifier” represents around ten sessions of 3 hours by group of 12 students.

During the first session, teachers give specifications. Then, a few sessions are dedicated to the electronic design and simulation. 2 practical lessons are used for testing parts of testing sub parts of the design. When

PCB design and routing is ended, 2 final sessions remains for wiring, and final test of the audio amplifier.

For time table reasons, our thermal characterization practical lesson is included in the “measurement practical lesson” unit which operates in parallel with our project. During this 3 hours lesson, all the measurements and analysis presented in this paper are performed and reported by the students.

IX. Future work

Arduino Ethernet SD card allows to work as internet server. So, recorded data on SD card can be transferred automatically through an internet browser to a PC computer. It could be a possible improvement of our system without extra fees.

X. Conclusion

The design of a low cost thermal measurement board has been described and successfully validated. Didactical aim and uses have been explained.

This tool is now used by the students in first academic year of the electronic department. It is included in our analogue power audio amplifier design project, and may be also included in a practical lesson cycle called « Instrumentation and Measurements », a part of the Physics Unit of Value.

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Dr Ph. Dondon became active reviewer in World Scientific and Engineering Academy and Society (WSEAS) in 2006, then, editor within "WSEAS transaction journal in 2010. He is organizer and chair of many international conferences.