Power consumption modelling of a realistic small scale house; a sustainable development project in electronic engineer school.

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Abstract: This paper relates to a concrete sustainable development project introduced at university. A small scale genuine materials house (1/20 scale) with its green energy sources and electronic circuits management have been designed. The building itself has already been described in a previous paper [1]. Thanks to a modular design, different types of measurements are possible, like in a real house for research and educational purposes. This paper focuses on a mixed electrical/thermal modelling of the small scale house. Global behaviour of a temperature regulation system is simulated. Power consumption computation under various scenarios is performed. Experimental measurements are given to confirm modelling validity. As these results are positive, the 1/20 model kit will be transferred as a educational "multi tool" for practical work in a near future.

Key words: thermal modelling, temperature control, power consumption and saving, sustainable development project,

1. Introduction

This "sustainable development" study was initialized a few years ago at ENSEIRB-MATMECA school: The "Ecole Nationale Supérieure d'Electronique, Informatique et Radiocommunications de Bordeaux".

2. The project short overview

This global project was carried out through national collaboration with "the House of the Nature and the Environment" (MNE) of Bordeaux, national french organism ADEME (Agency of the Environment and the Control of Energy) France, the ENSEIRB-MATMECA (33400 Talence), the colleges Chambéry (33140 Villenave d' Ornon) and Henri Buisson (33400 Talence) (professors and pupils) for the realization of the small scale house.

3. Small scale House project state of art

3.1 Generalities

The project of small scale house model started some years ago [1] from individual initiative of a few researchers and teachers.
A personal sensitivity to sustainable development helped to start the project while respecting obviously the mains scientific fields of our engineering school.

Thus, the « small scale house » project was born. The aim was to build a original fully functional modular model of house (1/20 scale) with genuine construction materials and its "green" energy generation and electronic control system. The finished model is used as:

- demonstrator (exhibition in town halls or local sustainable development events)
- research tool
- educational support for practical lessons and electronic projects, for sensitizing ENSEIRB MATMECA engineering students.

3.2 Originality and interest of the study

3.2.1 Generalities

With the climate change, sustainable development concept introduction and agenda 21 adoption, Kyoto protocol (3rd conference of parties COP 1997) has defined an ambitious goal for France: to divide the French green gasses emission by four. As private houses and buildings represent a significant contribution of the whole emission, French government has decided a progressive renovation program of the French flats and buildings [2]. Reduction of power consumption and gasses emission is becoming a priority.

For that purpose, a thermal cartography of the most important French cities was first decided to determine the main sources of thermal losses and over consumption. Bordeaux was one of the leading cities for such full thermal assessment [3], [4]. A thermal cartography of the Bordeaux and suburb [5] has been done flying over and scanning the city with an infrared camera.

3.2.1 Interest of the presented work

The work presented in this paper has several possible impacts in Research as well as in Education fields.

- From Research point of view, creating a small scale local "tool" can be seen as an attempt to experiment a full scale phenomenon in laboratory conditions. Indeed, the small size of the house and small scale materials allows comparative studies who might be more difficult to make, in true houses.
It is also a preliminary work to check and to validate the possible uses and performances of the small scale house model. Once fully validated, it should be transformed in a pedagogical tool, to be included in practical work in first year of study.

- From a pedagogical point of view, it is an innovative approach: rather than to train our students with the electronic techniques and to apply it to the electronic subject, we chose "to move" the field of application towards sustainable development without modifying or lowering the scientific contents.
At last, showing electronic circuit design and thermal aspect with this small scale house, discussing and measuring thermal insulation efficiency during practical lessons could also act as a kind of unconscious sensitization of the students to the sustainable development concept.

3.3 Scaled house design short overview

The small scale house itself is now achieved. Its building (with true materials) required more than 1500 hours of work including pupils, students and teachers work [1].

The dimensions of the 1/20 scale house model are 50cm x 50cm (external walls included). Useful internal surface is 45cm x 45cm. It consists of 3 independent parts (cf. figure 1) encasable like a "turned over shoes box". External walls are made of Autoclaved Aerated Concrete (AAC) 2.5cm thickness (part 1) coated and painted. There are one door and 4 windows. Interchangeable interior insulation double wall and ceiling (part 2), is encasable from the top, inside the external walls. At last, a removable pitched roof (part 3) is made of pine tree wood parallel roof truss, covered with terra cotta tiles. Attic may be filled with mineral wool insulation. A roof solar panel is integrated on one side of the roof. The "basement" is used for electrical wiring and electronic circuit's installation (heating system, lightning, and "green" power sources management system, and so on).

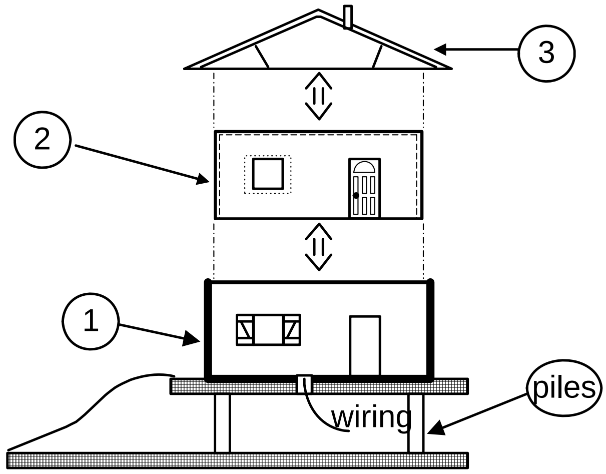

Figure 1: "turned over shoes box" house design

Figure 2 shows the AAC walls during the building phase.


Figure 2: AAC external walls building

Figure 3 shows the structure of scaled double glazed windows of the house. The space between the two glasses is a simple air gap (of course, no rare gas inside).

All the windows frames have been cut and machined from the same raw material plate (PVC). Small glasses have been cut from a unique wide glass plate. Machining was programmed on a digital milling machine. Thus, it guarantees identical geometrical characteristics (thickness and size) and also homogeneous thermal characteristics.

Floor is made of wood plate (22mm thickness) covered by a 3mm polyurethane insulation film.

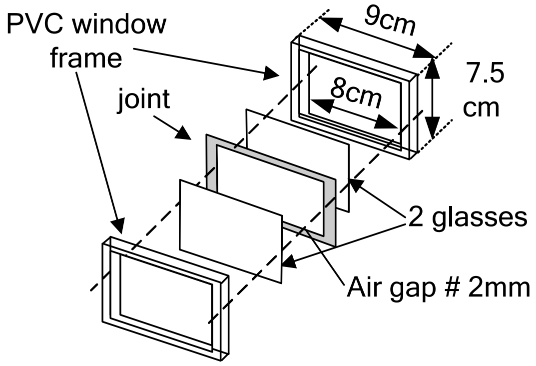

Figure 3: Mini double glazed window assembly.

Figure 4 shows an example of assembled insulation internal walls and ceiling, with window frame and main door. (The “insulation box” has been turned vertically on one side to take an easy picture).
Three “boxes” with three types of insulators have been designed to be able to make practical thermal performances comparison. Each “insulation box” [6] consists of 3 parts:

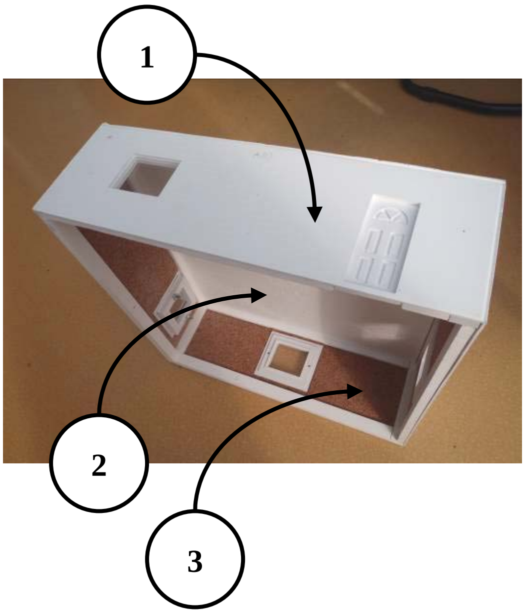

Figure 4: Encasable double wall insulation

Part 1: 3mm thickness Forex frame (walls and ceiling), for mechanical rigidity
Part 2: 5mm polystyrene layer for the ceiling (ceiling internal surface: 41cmx41cm)
Part 3: wall insulation layers. Depending of the chosen“box”, walls are insulated as follow:
- Mineral wool (6mm thickness + thin aluminium sheet to press lightly the wool). The thermal conductivity of mineral wool is around 0,038 W/m.K (insulator n° 1).
- Polystyrene insulator 5mm, with a thermal conductivity # 0,039 W/m.K (insulator n°2).
- Thin cork layer 3mm (thermal conductivity # 0,05 W/m.K) (insulator n°3).

Figure 5 shows a picture of the finished scale modular and evolvable small scale house model.

Figure 5: Finished small scale house.

4. Thermal modelling identification and extraction

4.1 Modelling aims

Thermal modelling is a complex domain which requires high knowledge level and specialists [7], [8], [9].
Firstly, as the major competencies field of ENSEIRB-MATMECA institute is Electronic, the aim of this simplified approach is to obtain a simple and global “image” of the small house thermal behaviour compatible with our electronic culture and approach. Secondly, once this study ended, it will be transferred for educational application and practical sensitizing work with our electronic students. Thus, it must be understandable in a quite short time for non thermal specialists.
Lastly, modelling must be just enough fine to easily understand mains tendencies, effect of double internal or external insulation, thermal inertia and to run simple day/night scenario in order to predict heating power consumption.
For these reasons, we chose to build an equivalent modelling, using analogies between thermal and electrical quantities.

4.2 Modelling identification

The equivalence and analogies between electrical and thermal quantities are given in table 1.

Thermal quantities			Electrical quantities		
T	Temperature	°K	U	Voltage	
J	Heat flux	W/m^2	J	Current density	A/m^2
P	Heat	W	I	Current	A
Q	Heat quantity	J=W.s	Q	Charge	C=A.s
λ_{th}	Conductivity	W/(°K .m)	σ	Conductivity	1/(Ω.m)
R_{th}	Resistance	°K/W	R	Resistance	Ω
C_{th}	Capacitance	W;s/° K	C	Capacitance	F

Table 1: Thermal and electrical equivalence

Thus, each "thermal way" can be classically modelled [10] by R, C electronic network circuits, where R represents the thermal resistance and C the thermal inertia of each raw material used in the building. The heating source (in W) is represented by a current generator and temperature by voltage node values in a SPICE simulation.

The most simple and rough localized time constant equivalent circuit is given in figure 20.

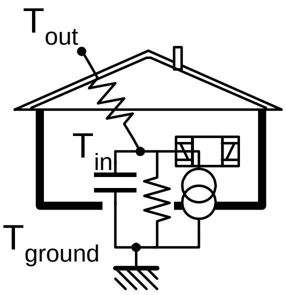

Figure 6: Intuitive ultra simple modelling

Between this ultra simple modelling given in figure 20 and a fine 2D or 3D ANSYS finite element modelling, we suggest here a medium complex modelling enough detailed to understand the major thermal aspects.

4.3 Modelling parameters

Six main and parallel kinds of thermal ways are identified (cf. figure 7):

- Four through the vertical walls (single glazed windows, double glazed window, door and insulated wall)
- One through the ceiling,
- One through the basement.

A typical thermal "equivalent" electrical schematic for one path is given in figure 7. R_{int} and R_{ext} represent the "in" and "out" thermal resistance of superficial exchange. And each layer is represented by a R, C network.

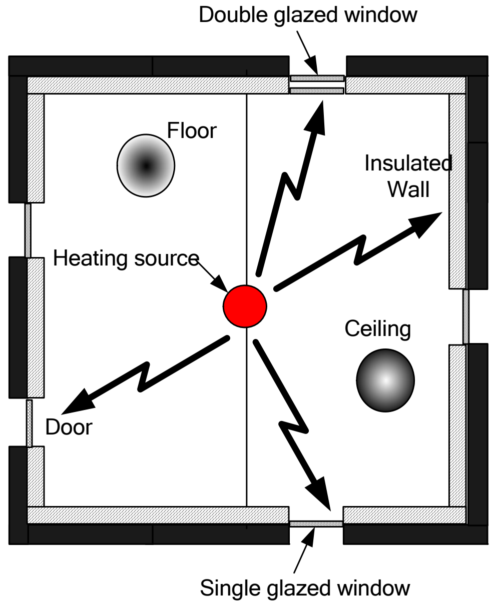

Figure 7: Identified thermal paths

R (°C/W), C (W.s/°C) values are estimated from materials thermal characteristics given in literature (Louvain catholic university (Belgium) database [11]) and from the geometrical characteristics of the each small house parts (surface and thickness).

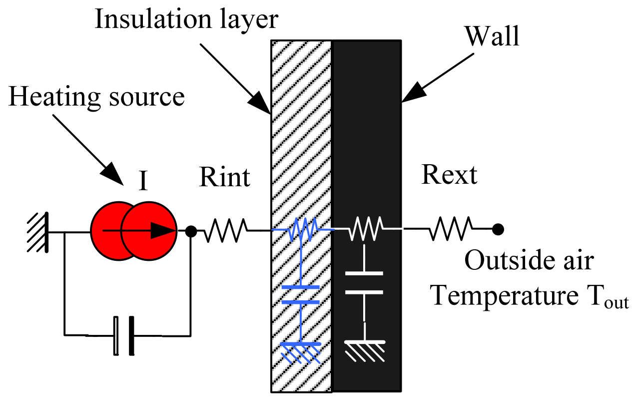

Figure 8: Typical equivalent path

For example, the thermal resistance and capacitance of external Autoclaved Aerated Concrete (AAC) walls is computed as follow:

- One wall average surface: S1= 47cm x 15cm,
- Four identical walls,
- Wall thickness: e =2.8cm,
- Window surface: W=6cm x 5cm,
- Door surface: D= 5cm x 10cm,

Thus, total AAC wall surface is:

$$S = 4.S1- (4.W+D) = 0.280m^2$$

And wall volume is:

$$V= 8.4\ 10^{-3}\ m^3$$

As thermal conductivity λ of AAC is 0.13W/m.°C and thermal capacity per volume unit is 112 W.h/m^3.°C, we obtain the equivalent thermal resistance:

$$R= (1/\lambda)e/S \quad = 0.76°C/W$$

And an equivalent thermal capacitance:

$$C = 3386\ W.s/°C$$

Thus, the AAC walls thermal time constant τ is:

$$\tau = R.C = 2537s\ (\#\ 42\ minutes)$$

The scaled heating source is sized to 20W. It corresponds to a classical installed power of 6kW for an 80/90m^2 "average" house in South France. This source (here, a halogen small spotlight) is thus modelled by a 20A current generator with a parallel capacitor representing its thermal inertia.

4.4 Final modelling

The equivalent thermal/electrical schematic (figure 9) is then built, considering the 6 paths identified previously. We added a current source to simulate the power heating source, a reference DC voltage source to simulate the ground temperature, and a second variable voltage source to simulate outside air temperature.

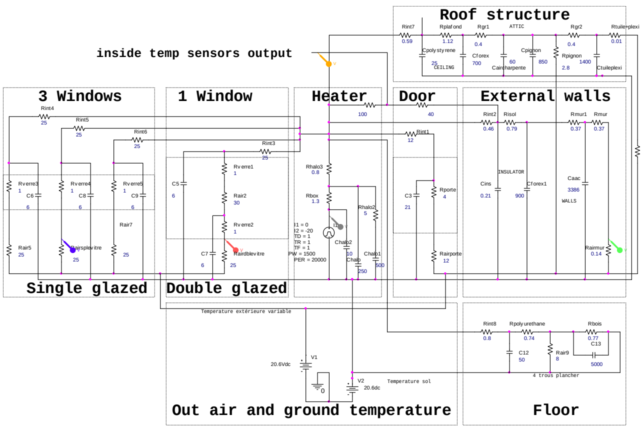

Figure 9: Equivalent thermal /electrical schematic

This house modelling can be seen as a linear box with 3 inputs: heating source P, T_{out} and T_{ground}, one output T_{in} and with a "low pass filter" behaviour. (See §5.3.2)

4.5 Modelling validation

A set of experiments, described in [12], [13], were performed to validate the modelling.

5. Temperature control

Once the thermal equivalent modelling of the small house defined, the electronic temperature control system was included in the schematic.

5.1 Electronic system and schematic

The principle of temperature control loop in given in figure 10. T_s is the inside 'comfort' temperature set point, tuneable by the user, like in a real house. The measured "in" temperature T_{in} is compared to T_s and heating source is turned "on" or "off", according to a chosen hysteresis of 1°C around the T_s value.

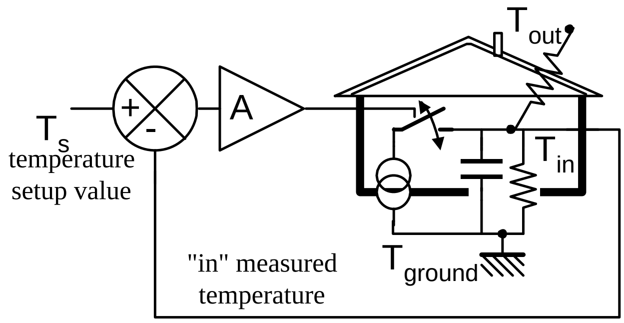

Figure 10: Temperature control principle

The heating source and switch are simulated by a Voltage Current Controlled Source (VCCS Spice component) while comparator stage is a simple LM311 circuit with 2 resistances to make a temperature hysteresis. Control circuit is merged with the previous schematic presented in §4.4, to built a complete equivalent circuit (cf. figure 11).

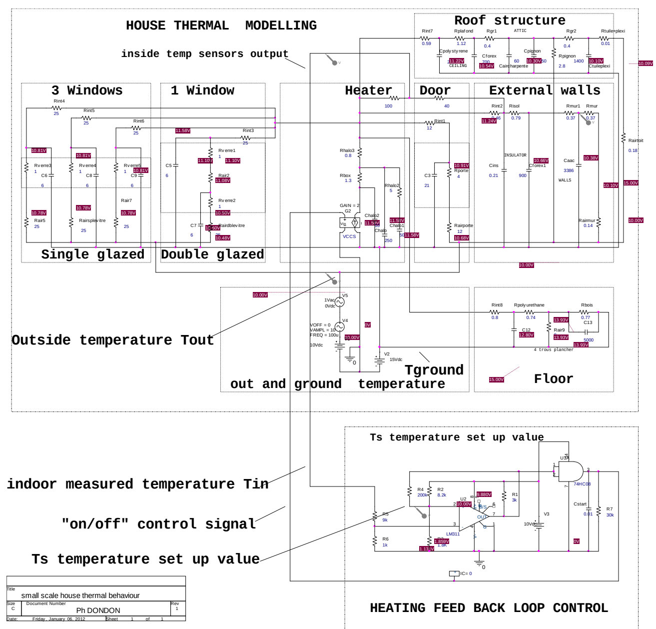

Figure 11: Temperature feed back loop control

5.2 SPICE Simulations

A complete set of simulations has been done under various conditions for T_s, T_{out} and T_{ground}, without or with various internal insulation (cf. §3.3). We give hereafter only the most significant simulation results.

5.2.1 Steady state simulation

Figure 12 shows the regulation efficiency under the following conditions:

- Temperature T_s set up value: 18°C
- Outside Air T_{out} : 12°C
- Ground temperature T_{ground}: 15°C
- House double wall insulation: insulator n°2.

Upper trace: regulated T_{in} temperature 18°C +/- 0.5°C (Hysteresis)
Lower trace: heating "on/off" control signal
Horizontal scale total time: 10.000s
Vertical scale: 0V to 20V (i.e. 0°C to 20°C, thanks to analogy and equivalence given in table 1)

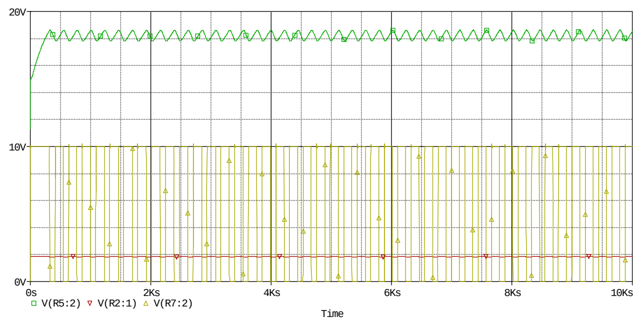

Figure 12: Steady state simulated response

T_{in} is well regulated between the two threshold levels 18°C and 19°C, fixed by the hysteresis circuit.

5.2.2 AC analysis

Figure 13 shows the AC response T_{in}/T_{out} of the house itself, under the following conditions:

- Temperature feed back loop circuit disabled.
- Outside Air temperature: Amplitude variation 1°C around 12°C
- Ground temperature T_{ground}: 15°C
- House double wall insulation: insulator n°2.

Horizontal scale: 1µHz to 100Hz
Vertical scale linear: 0.1/div

Trace: transfer function module (i.e gain) $|T_{in}/T_{out}|$

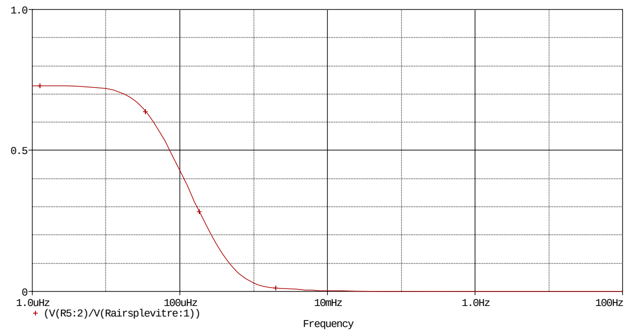

Figure 13: Simulated T_{in}/T_{out} AC response

The small scale house looks like a low-pass filter which represents the thermal inertia. The dominant cut-off frequency is around #100µHz (i.e. dominant time constant # 26 minutes), partially due to the high time constant of the wall (see §4.3).

5.2.3 Closed loop response

Figure 14 shows the response in closed loop to a T_s pulse value under the following conditions:

- Initial temperature T_s set up value: 18°C
- Final temperature T_s set up value: 20°C
- Outside Air T_{out}: 10°C
- Ground temperature T_{ground}: 15°C
- House double wall insulation: insulator n°2.

Upper window: T_s set up value 18°C, switched to 20°C at time 4000s. Small square undulations on the curve represent the two levels due to hysteresis.
Lower window:
Upper trace: regulated T_{in} temperature
Lower trace: heating "on/off" control signal
Horizontal scale total time: 10.000s
Vertical scale: 0V to 25V (i.e. 0°C to 25°C)

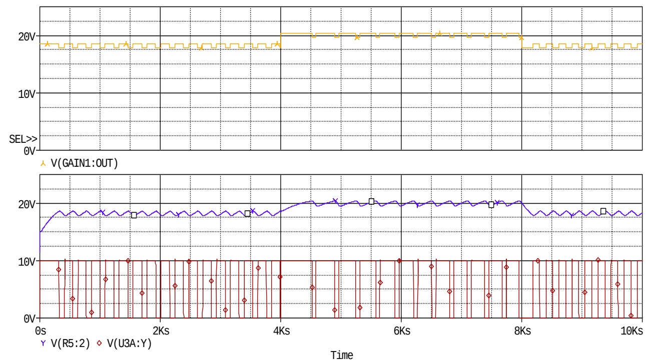

Figure 14: Closed loop transient response to a T_s temperature set up value pulse.

The T_{in} temperature switches correctly from 18° to 20° following T_s temperature set up value, with a settling time of around 1000s.

System stability in closed loop is obtained without correction needs.

5.2.4 Simple night and day scenario

Figure 15 shows the regulation efficiency under the following scenario:
- Temperature T_s set up value: 18°C
- Ground temperature T_{ground}: 15°C
- House double wall insulation: insulator n°2.
- Outside Air T_{out}: medium day/night amplitude temperature from 17°C to 3°C with a sine waveform representing a scaled day night cycle

Vertical scale: 0 to 20V (i.e. 0°C to 20°C)
Horizontal scale: time 0 to 10.000s
Upper trace: regulated T_{in} temperature 18°C +/- 0.5°C (Hysteresis)
Middle trace: outside air temperature simulated variation
Lower trace: heating "on/off" control signal

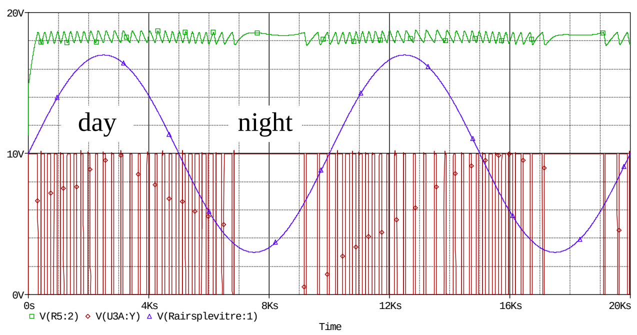

Figure 15: Moderate amplitude outside air temperature variation

T_{in} is well regulated between the two threshold levels fixed by the hysteresis circuit.

Figure 16 shows the regulation efficiency under the following scenario:
- Temperature T_s set up value: 18°C
- Ground temperature T_{ground}: 15°C
- House double wall insulation: insulator n°2.
- Outside Air T_{out}: high day/night amplitude temperature from 20°C to 0°C with a sine waveform representing a scaled day night cycle.

Vertical scale: 0 to 20V (i.e. 0°C to 20°C)
Horizontal scale: time 0 to 20.000s
Upper trace: regulated T_{in} temperature
Middle trace: outside air temperature simulated variation
Lower trace: heating "on/off" control signal

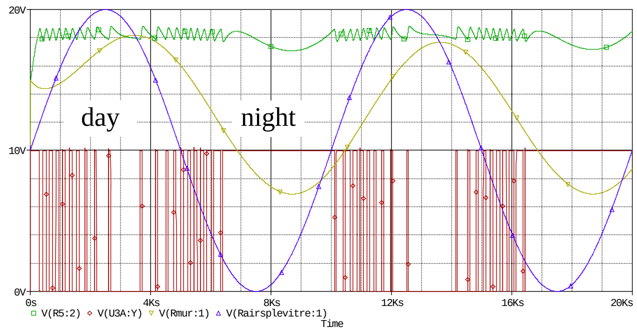

Figure 16: High amplitude outside air temperature variation

T_{in} is no more well regulated at the end of the night: The feed back control system do not work anymore correctly at the end of the night because the installed heating power (20W) is no more sufficient despite a permanent 'on' state during low outside temperature.

Figure 17 highlights the thermal inertia (or delay) of the walls. The conditions are similar to the previous ones used to obtain figure 16.
Vertical scale: 0 to 20V (i.e. 0°C to 20°C)
Horizontal scale: time 0 to 20.000s
Upper trace: regulated T_{in} temperature
Medium trace (yellow): wall temperature variation
Lower trace (blue): outside air temperature simulated variation (0°C to 20°C)

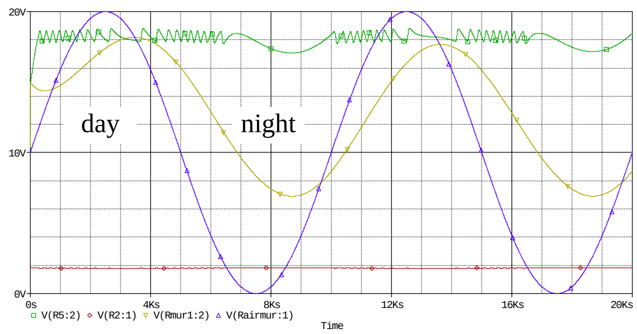

Figure 16: Thermal inertia of the walls

Peak temperature variations in the wall are reduced compared to outside air variations and phase difference represents the effect of thermal inertia of the wall.

5.2.5 Small scale house energy consumption

Energy efficiency of the house is obviously related to insulation efficiency.

A comparison can be easily done by placing or removing R,C components corresponding to insulator layers on SPICE house modelling given in §4.4.

For these simulations, we set up the following conditions:

- Temperature T_s set up value: 18°C
- Outside Air T_{out} : 12°C
- Ground temperature T_{ground}: 15°C
- Initial T_{in} temperature: 12.7°C

Average power consumption in each situation is then evaluated considering the duty cycle of the "on/off" control signal in steady state situation.

Upper trace: regulated T_{in} temperature
Middle trace outside air temperature (12°C)
Lower trace: heating "on/off" control signal

Horizontal scale total time: 10.000s
Vertical scale: 0V to 20V (i.e. 0 to 20°C)

Figure 17 shows the house behaviour when internal wall and ceiling insulation is totally removed.

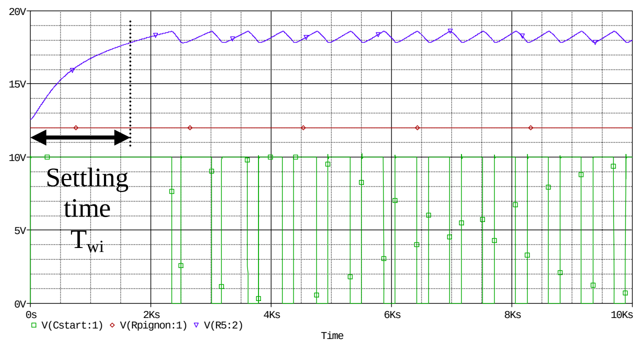

Figure 17: Transient and steady state without internal insulation

In this first case, the duty cycle is 0.75 in steady state situation: Thus, an average heating power of 20W*0.75 = 15 W is required.

The required settling time T_{wi} to reach steady state (i.e. ΔT=5.3°C rise from 12.7°C to 18°C) is around 1620s (i.e 27 minutes).

Figure 18 shows the house behaviour when equipped with internal wall and ceiling insulation n°2 (i.e. polystyrene layer).

In this second case, the duty cycle becomes 0.481 in steady state situation. Thus, it requires an average heating power of 20W*0.481 # 9.62 W.
And the required settling time T_i to reach the same steady state (i.e. from 12.7°C to 18°C) is roughly 3 times less than in the first case for the same temperature elevation (510s against 1620s)

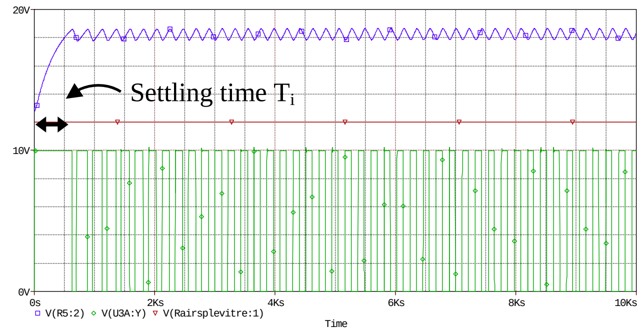

Figure 18: Transient and steady state response with internal insulation n°2 (polystyrene)

At last, the insulation efficiency can be extrapolated to an external wall insulation [12] and wool insulation in attic by adding R, C on outside external wall surface and in attic path. In this last situation, we obtain the figure 19.

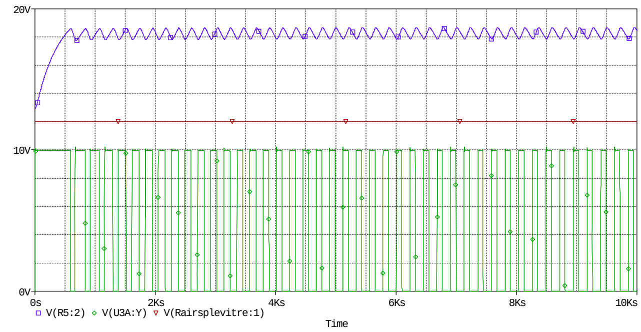

Figure 19: Steady state response with internal insulation and external insulation.

In this last case, the duty cycle is reduced to 0.415 in steady state situation. It requires only an average heating power of 20W*0.415 # 8.3W.

Thus, between a "non insulated" house and a full well insulated house, a heating power significant reduction of around 40 to 45% can be predicted by simulation.

6. Experimental

Validity of our modelling must be obviously checked by experiments. Since the small scale house is inside a normally heated experimentation room in our office, it is not possible to reproduce all the simulated operating conditions (outside air temperature). However, we give hereafter the most significant experimental results in order to validate the thermal behaviour of the small house.

6.1 Experimental plateform

The small scale house is equipped as indicated on figure 19. As said before, the heating source is a 20W halogen lamp powered under 10VDC voltage. It can be considered as a punctual source located in the middle of the house. Temperature control circuit is done by two averaged temperature sensors TS1, TS2 and a simple electronic board located under the house.

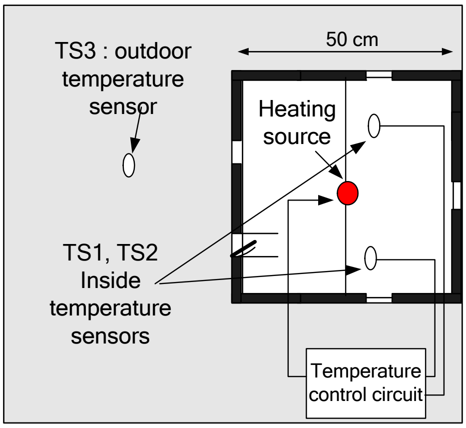

Figure 19: Experimental plateform

Measurements were performed during winter in a "non heated" experiment room of ENSEIRB school. Thus, the initial ambient temperature (given by TS3), was 17°C for all the experiments.

6.2 Experimental results

6.2.1 Thermal transient behaviour

Thermal transient behaviour is obtained by submitting the small house to a heating power pulse of 20W with insulator n°2 and without any insulation (cf. figure 20).

These curves have to be compared with figure 17 and 18 during the initial transient state (temperature rise between 12.7°C and 18°C).

Initial temperature in simulation and experiment are not the same but quite close, due to operating conditions. However, assuming a linear behaviour of the system, temperature evolution is similar, with a simple vertical axis offset of 4.3°C. Relative and differential comparison is possible.

Thus, we compare the necessary time to obtain the same temperature rise of 5.3°C. From figure 20, it is roughly T_{wi} =1580s when there is not internal insulation and T_i =490s when house is insulated with insulator n ° 2.

Comparative results are summarized in table 2.

We observe a correct matching between measurements and simulation (with a reasonable error margin of 5%).

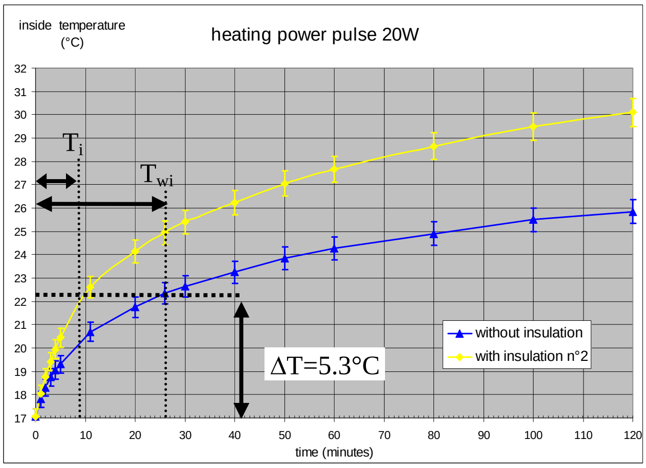

Figure 20: Transient experimental response

Required time for a ΔT rise of +5.3°C	Without insulation	
T_{wi}	simulation	experiment
(in second)	1620	1560
	With insulation n°2	
T_i	simulation	experiment
(in second)	510	490

Table 2: Transient simulation/experiments comparison

6.2.2 Steady state power consumption measurement

Figure 21 shows the "on/off" heating power control logical signal 0/5V in steady state, always for the same temperature rise without insulation.

Duty cycle is close to 0.7 like simulated.

Digital Oscilloscope Tektronix Tek32004
Vertical scale : 2V/div
Horizontal scale: 50 sec/div (scan mode)

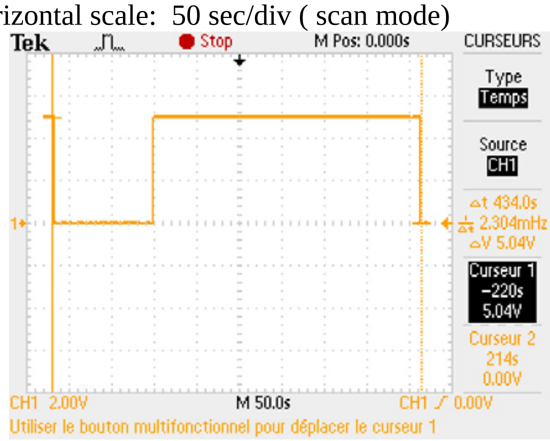

Figure 21: Control signal in steady state situation without insulation

Figure 22 shows the on/off heating power control logical signal 0/5V in steady state always for the same temperature rise without insulation. Duty cycle is close to 0.45 like simulated.

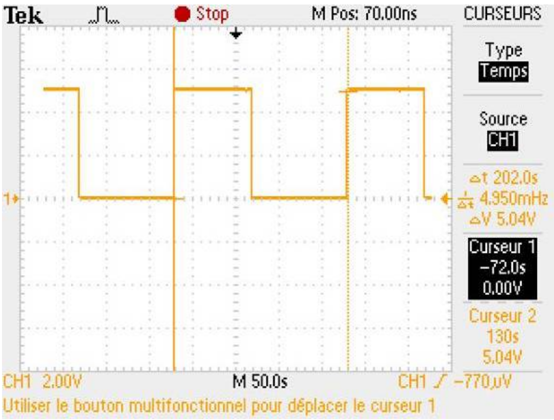

Figure 22: Control signal with insulator n°2

7. Discussion

7.1 Result analysis

Coherence between experiment and small scale house simulation is correctly checked. Order of magnitude is respected at 1/20 scale. Coherence between the small scale house model and a real house is more difficult to do. However, main tendencies have been checked on a true example. Measurements and data collection over 6 years (4 before and 2 after renovation), were performed in a renovated apartment in Bordeaux. It was located at the 5th floor, just under the flat roof, on east and north side of a building, built in 1984, with poor initial wall insulation and no ceiling insulation, heated by natural gas. This apartment was fully renovated in 2009: global insulation of the flat roof (12 cm of polyurethane foam + bituminous watertightness), external wall insulation (12 cm thickness polystyrene tiles) and replacement of old windows by double glazed windows (4cm/16cm/4cm) has divided by more than 2 the annual heating power consumption for the same comfort temperature (around 18.5°C) as shown on figure 22. (Results confirmed by monitoring along the last 15 years).

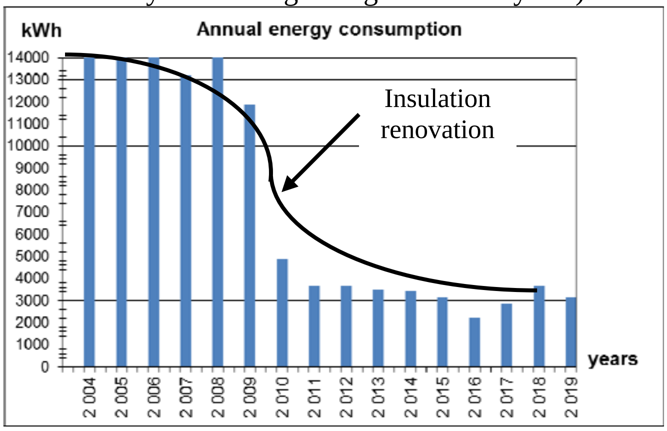

Figure 22: Annual heating energy real consumption (kWh) of the tested apartment

This reduction rate is coherent with result obtained on the small scale house.

At last, the new French standard RT2005 and RT2012 for new buildings aim to reduce by 2 the consumption compared to old buildings using the same kind of insulation techniques and materials than those used in our small scale house.

7.2 Interest and limits of the modelling

7.2.1 Avantages

The main advantages of our approach are given hereafter:

-Easy understanding of thermal problems for non thermal specialists,

- Once modelling built, quick and fast Spice simulation (a few seconds). Simulation by finite element commercial software such as ANSYS/SILVACO could take a few hours depending on mesh size and mesh number,

- "Mixed" thermal and electronic simulation for temperature loop control design and checking.

- Possible use for initiation of electronic students during a standard 4 hours practical lesson.

7.2.2 Limits

The main limits are given below:

-The modelling is a simple 1D linear modelling. It does not take into account surface and volume effect,

- Natural air movement or forced air ventilation are not simulated,

- This not a parametric modelling. Changing size of the house or material properties requires a recalculation of each R, C cells,

- No possible occupation rate scenario [14],

- No fine weather conditions possible simulations.

7.2.3 Comparaison with commercial software

In fact, no comparison can be done. Our approach was mainly a research and didactical study for electronic students and engineer who want to understand thermal phenomenon by analogy with electrical world.

Existing professional and commercial software such as Pleiades (Izuba company)[15] or Design builder[16] are dedicated to architects and house builders. They include a macroscopic building approach with predefined raw material characteristic data base and drawing tools to design real houses. The heater power source can be sized taking into account various parameters such as aspect of the building (face to South or North), annual weather forecast, occupation rate… However, since the size of raw materials (thickness, width, length is predefined according to existing industrial standard and not changeable), they were not suitable for our small scale house.

8. Future work

Some improvement can be done to refine and complete the modelling. For example auxiliary heating source (such as fire chimney or stove) could be included to analyse impacts of peak power value and inertia of the heating source.

Then, we will adapt this research study and transfer it for introducing practical lesson and students projects in our electronic engineering school.

9. Conclusion

Three years were necessary for ENSEIRB-MATMECA school and its academic partners, to design a fully functional realistic small scale house, built in genuine materials. It was completed successfully within the framework of an innovative sustainable development project. An equivalent thermal modelling was built to make easy and simple power consumption prediction. Validity of modelling was checked by experimental thermal measurement. Relative tendencies are demonstrated by a comparative approach like in a true house.
This work should be now adapted and converted for creating a practical lesson on thermal measurement techniques. It could be included in the “measurement techniques” module in first year of study at ENSEIRB-MATMECA.

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