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

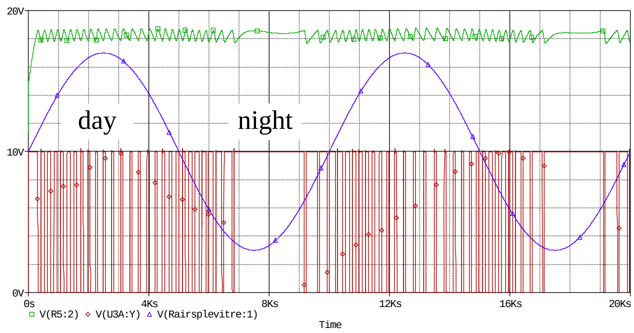

Figure 15: Moderate amplitude outside air temperature variation

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

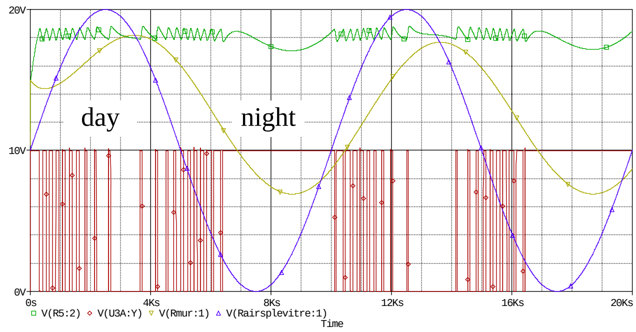

Figure 16: High amplitude outside air temperature variation

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)

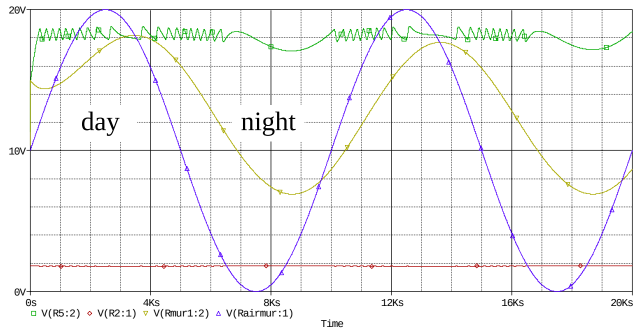

Figure 16: Thermal inertia of the walls

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.

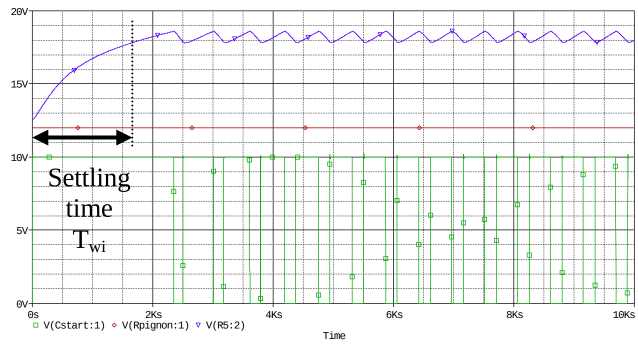

Figure 17: Transient and steady state without internal insulation

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)

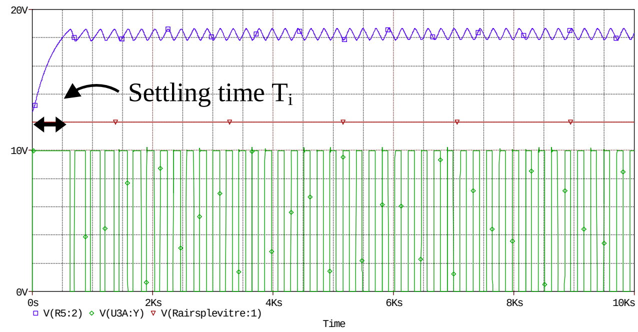

Figure 18: Transient and steady state response with internal insulation n°2 (polystyrene)

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.

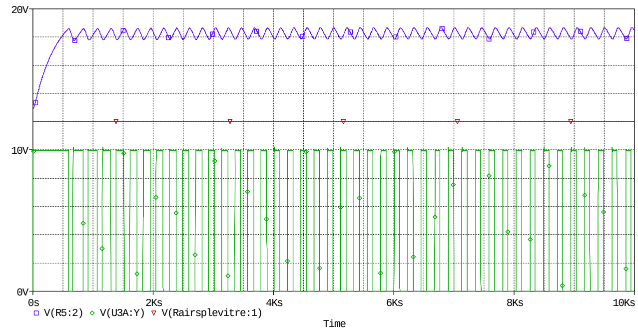

Figure 19: Steady state response with internal insulation and external insulation.

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.

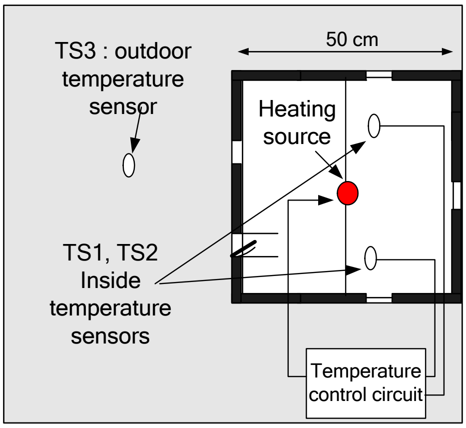

Figure 19: Experimental plateform

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%).

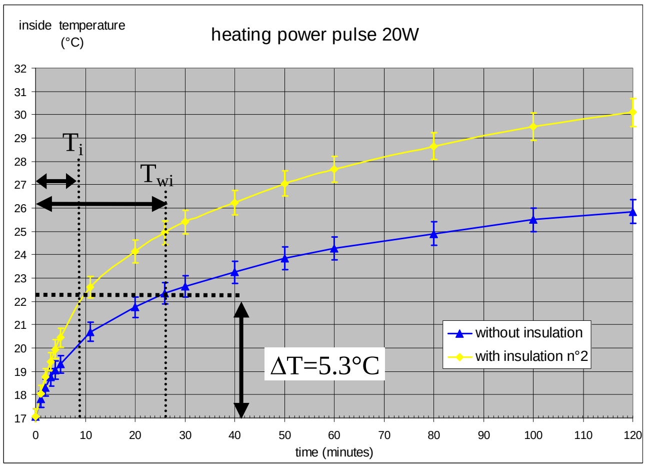

Figure 20: Transient experimental response

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)

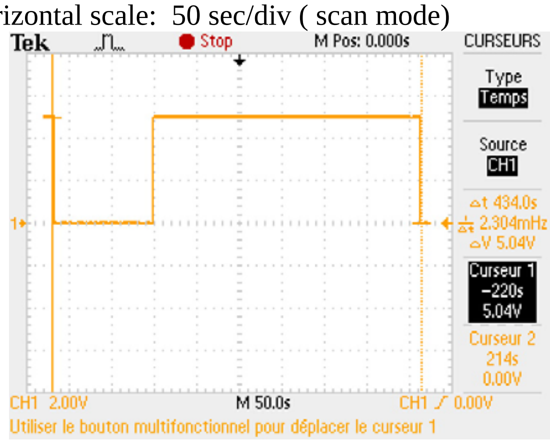

Figure 21: Control signal in steady state situation without insulation

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.

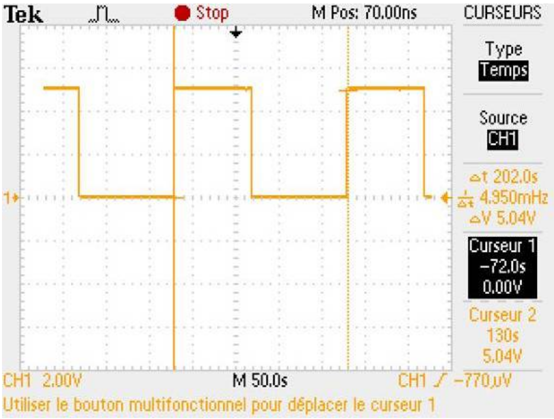

Figure 22: Control signal with insulator n°2

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).

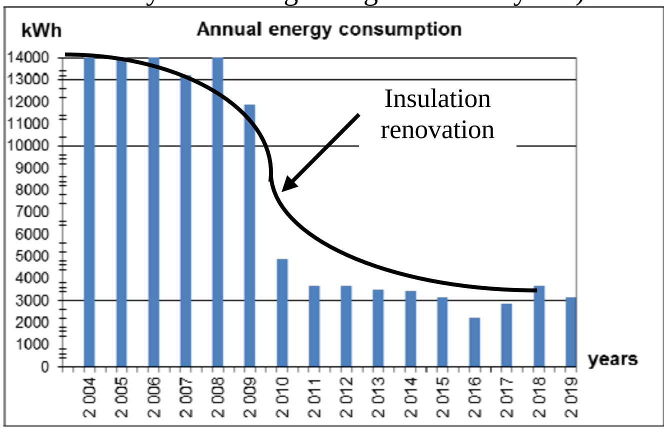

Figure 22: Annual heating energy real consumption (kWh) of the tested apartment

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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