Thermal transient behaviour and insulation efficiency analysis of a realistic small scale house model.

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Abstract: This project was initialized at ENSEIRB-MATMECA. It started a few years ago by the design of a small scale genuine materials house (1/20 scale) and its surroundings. The handmade realization has already been described in a previous paper. The design is based on a modular structure. This work is a sequel intending to address some issues of thermal transient behaviour and insulation efficiency at the small scale sustainable house. Several types of measurements and simulations are possible, like in a real house. This paper focuses on thermal behaviour and modelling of the small scale house. Transient behaviour is firstly investigated by experimental measurements and various wall insulation scenarios are tested. Experimental results are analyzed and compared. Finally, extraction of a thermal modelling is presented using thermal/electrical equivalences followed by the results discussion and conclusion.

Key words: Thermal measurement, equivalent SPICE modelling, insulation efficiency, Sustainable development

1. Introduction

This study was initialized at ENSEIRB-MATMECA school: “Ecole Nationale Supérieure d’Electronique, Informatique et Radiocommunications de Bordeaux”.

It was carried out with the participation of several local and national partners listed below: “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 colleges Chambéry (33140 Villenave d'Ornon) and Henri Buisson (33400 Talence).

The project of small scale house model started three years ago [1] from the individual initiative of a few researchers and teachers. A personal sensitivity to sustainable development helped to start the project while respecting obviously the main scientific fields of the institute ENSEIRB-MATMECA.

The aim was to build an original fully functional modular model of house with genuine construction materials and its “green” energy generation system. Once completed and fully characterized, the model will be used as:

- demonstrator (exhibition in town halls or local sustainable development events)
- educational support for practical lessons and electronic projects, in order to raise awareness of sustainable achievements with respect to energy savings for sensitizing ENSEIRB-MATMECA engineering students.

With the climate change, the sustainable development concept introduction and agenda 21 adoption, the Kyoto protocol has defined an ambitious goal for France: to divide French green gasses emission by four. As private houses and buildings represent a significant contribution of the global emission, French government has decided a progressive renovation program of the French flats and buildings [2].

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. This strategy will from French politic representative shows the new importance given to thermal measurements.

Thus, the work presented in this paper shows a possible ways, among others, to illustrate these new goals within the Sustainable Development concept framework. It is an original work as it was the first and unique fully functional small scale prototype built in France.

Moreover, this cross disciplinary study can be secondly 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 experimental studies who might be difficult to make in true houses.

Lastly, once validated, this work can be easily transferred to educational applications: Indeed, the small scale house model will offer the possibility to perform “indoor measurements” in the school for a small group of students without the need for heavy infrastructure. It could be a good opportunity to introduce sensitization to sustainable development. Thus, it will be an innovative approach in ENSEIRB-MATMECA school.

2. Small scale house short description

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

The dimensions of the 1/20 scale house model are 50cm x 50cm (external walls included). 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.

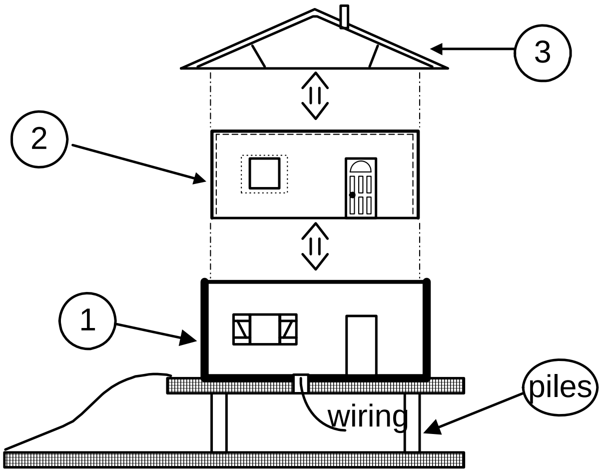

Figure 1: “Turned over shoes box” house design

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 polyurethane insulation film.

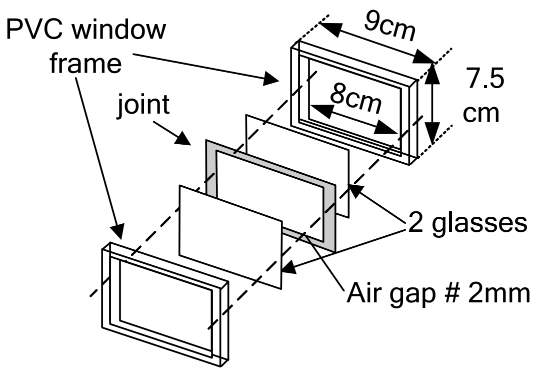

Figure 3: Open view of mini double glazed window assembly.

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:

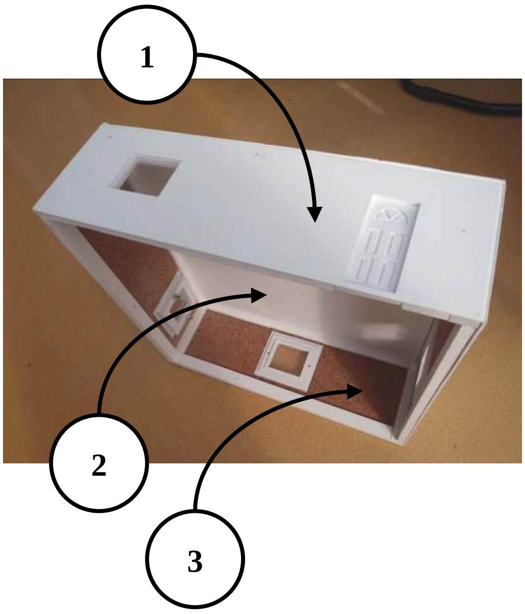

Figure 4: Encasable double wall insulation

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 “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.

3. Experimental study of the thermal behaviour of the small scale house

3.1 General operating conditions

Small scale house model is located in a workroom inside the ENSEIRB-MATMECA School. Real conditions (outside measurements) are obviously not respected. However, the small house can be heated more than the room temperature to produce a significant temperature gradient between inside and outside.
Only comparative measurements will be performed to obtain credible results.

3.2 Test bench preparation

The small scale house model can be opened from the roof. It is thus possible to install heating power sources sensors… and to remove double internal insulation or to change the insulation materials.
Test bench is prepared as indicated in Figure 6. The heating power source, placed into the house, is a 12V DC 20W halogen small spotlight.
Inside and outside temperatures of the small scale house are displayed and checked during all the experiments by temperature sensors.
Working room is closed, shutters are closed and measurements are performed early morning to lower the parasitic effects.

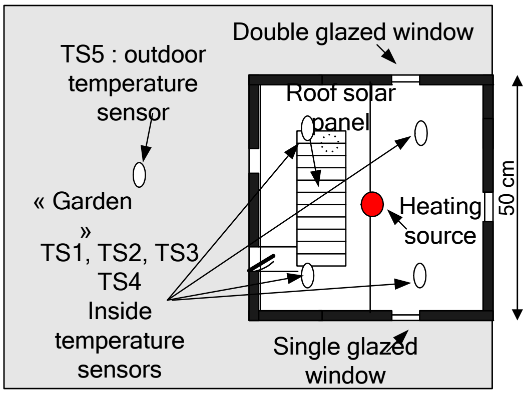

Figure 6: Experimental platform

4. Thermal experiments

4.1 General test operating conditions

Absolute errors on temperature measurement are always possible especially with temperature sensors. Thus, to make realistic and reliable analysis, the study is done only by taking comparative and differential measurements to guarantee representative results. Moreover, strong measurement conditions are set up as follows:

- As indicated in paragraph 2, insulation boxes have exactly the same size to guarantee identical physical properties.
- The heating source is located exactly in the middle of the small scale house equally spaced from the walls. The heating power source is set up at 20W to increase the temperature difference between indoor and outdoor.
- The two temperature sensors TS1 and TS2 are two K thermocouples associated to two channels thermometer Keithley 871A. They are located in the house at 5cm from the wall and at 3 cm high to measure the indoor temperature. TS3 and TS4 are PT100 temperature sensors.

For each set of measurements, the reported inside temperature is the average between the four values.

- The initial ambient temperature is checked by temperature sensor TS5.
- Initial surface external wall temperature identical on the four walls (checked by contactless IR thermometer MO297).
- An infrared camera FLIR B335 takes pictures at a regular rate during each experiment [7], [8], [9], [10].

4.2 Preliminary checking before thermal measurements

4.2.1 Heating source checking

The halogen lamp behaviour has been preliminary checked. The shape of the applied electrical power pulse is shown on Figure 7.

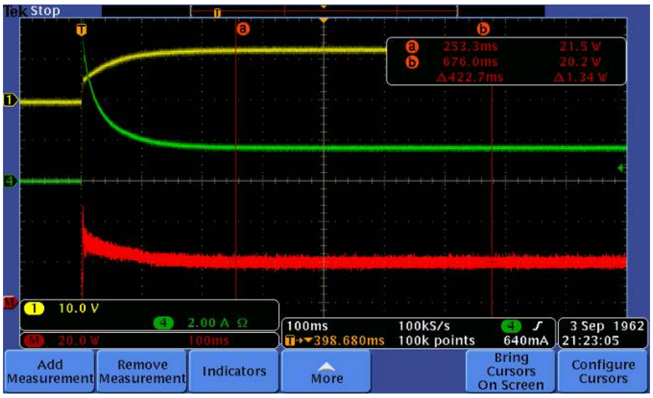

Figure 7: Power pulse settling time (Horizontal scale: 100ms/div)

The upper trace shows the 12V DC voltage applied to the lamp (Vertical scale 10V/div). The middle trace (curve 2) shows the current across the lamp (Vertical scale 2A/div). The lower trace (curve 3) show the power pulse shape (Vertical scale 20W/div), obtained by scope internal mathematical functions.

The transient peak current at the beginning of the pulse is obviously due to the temperature change of the lamp filament bulb. Electrical power pulse reaches a stable value after roughly 200ms. Thus, this settling time is very short compared to thermal time constant of the small scale house; Electrical power pulse can be considered as a “perfect” power pulse.

4.2.2 Calibration and relative accuracy

Relative accuracy between the temperature sensors and IR camera has been checked as follows:
The temperature sensors have been stuck firstly on the sample brick of AAC. The ACC sample was heated over the useful range (from 0°C to 40°C) by an external calibrated heating source while Infrared camera was recording IR images. So, relative accuracy of all sensors has been checked. If needed, offset has been added manually, to match each response curves. Relative matching is better than 0.5°C.
During this preliminary test, Infrared camera calibration was also checked as well as emissivity of the different raw materials. All raw materials used in the small scale house have an homogeneous emissivity close to 0.95. Thus, a direct reading of surface

temperature on infrared image is possible without heavy correction for the present application.
Lastly, from specifications, thermal resolution (NETD) of the camera is better than 0.5°C.

4.3 Transient measurements strategy

Four successive series of measurements are performed: the first one without insulation and the next three one's with a different insulation box (numbered 1, 2, 3) described before.

After switching « on » the 20W heating source, temperature measurements are reported each minute, during 22 minutes (long enough to see differences in thermal behaviour). Between each series, a dead time of 30 minutes is required to decrease temperature and to return exactly to initial condition. A new insulation box (cf. figure 8 and 9) is interlocked and a new set of measurements is performed.

Figure 8: Interlocking double internal insulation.

A last, experiment has been done after filling the attic with additional mineral wool. (Cf. figure 10).

All these measurements have been performed several times to check the reproducibility of the results. Some of them were run two hours, to check transient and also steady state responses.

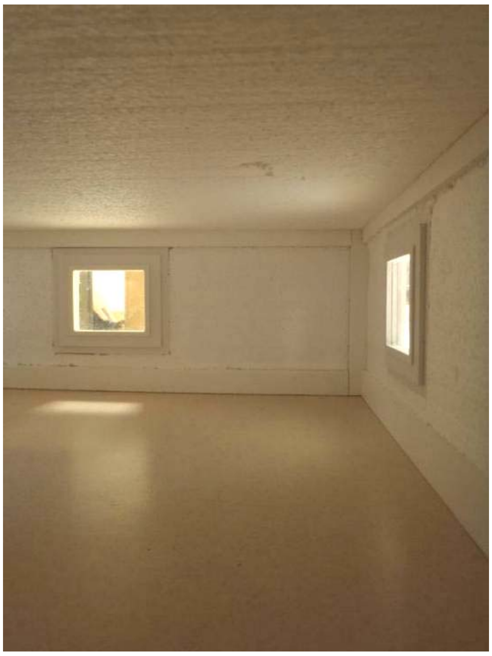

Figure 9: Polystyrene wall and ceiling viewed from inside.

In addition, Infrared camera FLIR B335 was taking picture of the house during each transient test, to check the temperature evolution of external walls and roof. (Cf. I.R. capture in figures 12 to 19).

Experimental results are given in §5 and then discussed in §6.

Figure 10: Attic filled with 1 cm mineral wool.

5. Experimental results

Figure 11 shows the four transient responses of the house inside temperature, reported according to the conditions given in § 4.1 and 4.3. Vert. scale: average inside temperature (°C), H. scale: time (minutes).

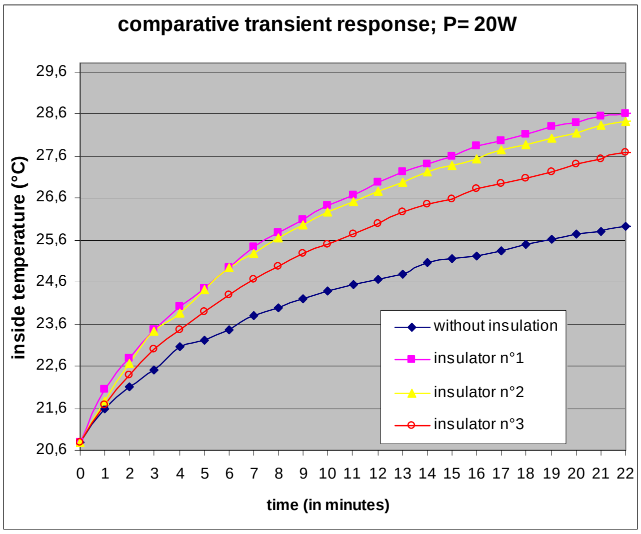

Figure 11: Comparison between the different types of insulators (transient response)

Sixth order polynomial approximation gives the following equations:

-for insulator 1
y = -3E-10x6 + 2E-07x5 - 3E-05x4 + 0,0017x3 - 0,0518x2 + 0,9189x + 21,031 (1)
-for insulator 2
y = -4E-10x6 + 2E-07x5 - 3E-05x4 + 0,002x3 - 0,0583x2 + 0,9535x + 20,891 (2)
-for insulator 3:
y = -4E-10x6 + 2E-07x5 - 3E-05x4 + 0,0016x3 - 0,047x2 + 0,7993x + 20,897 (3)
-without insulation:
y = -4E-10x6 + 2E-07x5 - 2E-05x4 + 0,0015x3 - 0,0408x2 + 0,6301x + 20,914 (4)

where x in minutes, and y in Celsius degrees.

Figure 12, 13, 14 and 15 correspond to the first series of test (i.e. without internal insulation).
Figure 12 shows the Infrared image of the house at initial time t=0 (before applying the power pulse).
Figure 13 shows the outside wall temperature after 20 minutes of heating. The average initial wall temperature in cursor Ar1 is 20.4°C.

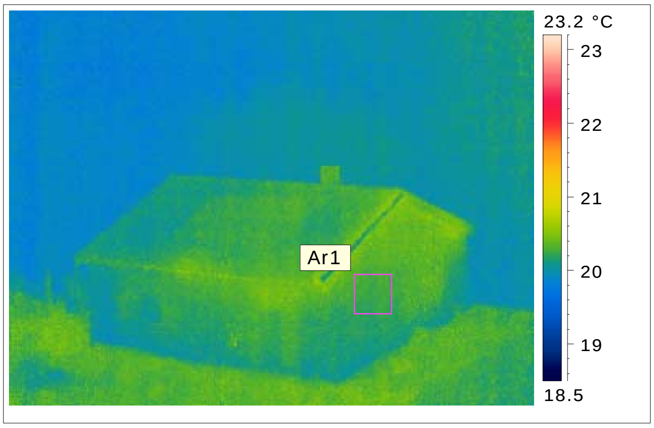

Figure 12: Infrared imaging (initial condition)

The final average wall temperature in the same area increases up to 21°C.

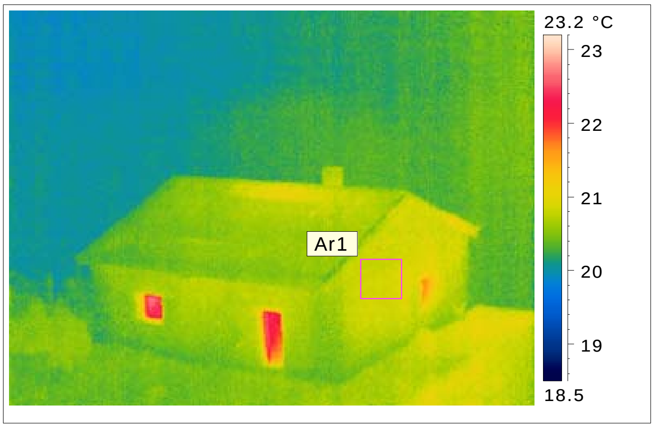

Figure 13: House outside temperature after 20 minutes and without insulation.

Figure 14 shows the final roof temperature after 20 minutes and Figure 15 the corresponding temperature profile along the roof (cursor line Li1). Temperature variation along the line, is between 20.5°C (roof border) and 21.5°C (on the top).

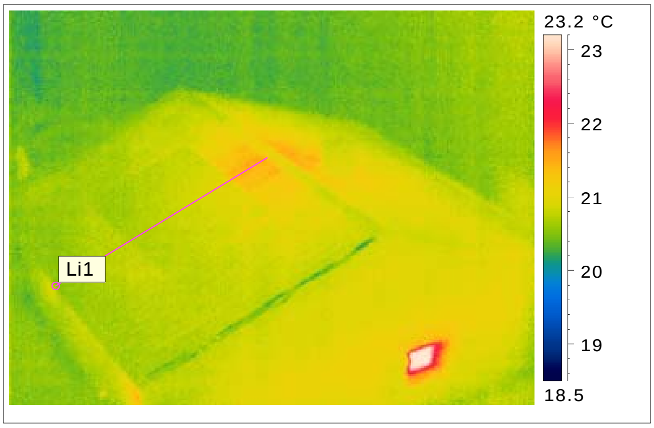

Figure 14: Roof infrared imaging (after 20min without double internal insulation)

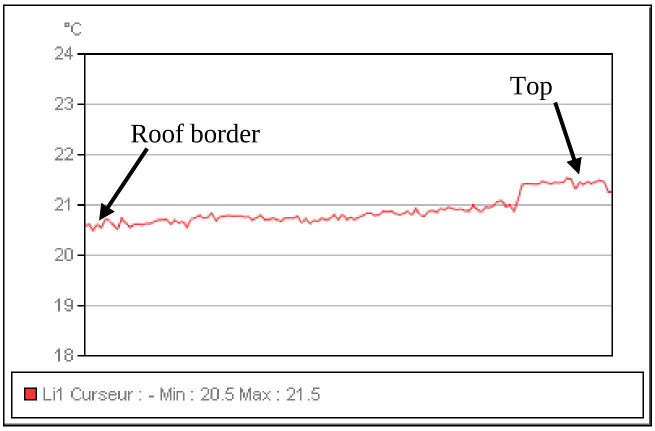

Figure 15: Temperature profile along the roof without double internal insulation

Figure 16 and 17 correspond to the second series of measurements (i.e. with insulator n°1). Figure 16 shows the temperature of the roof reached after 20 minutes and Figure 17 the corresponding temperature profile along the roof (cursor line Li1). Temperature variation along the line, is between 20.1°C (roof border) and 21°C (on the top).

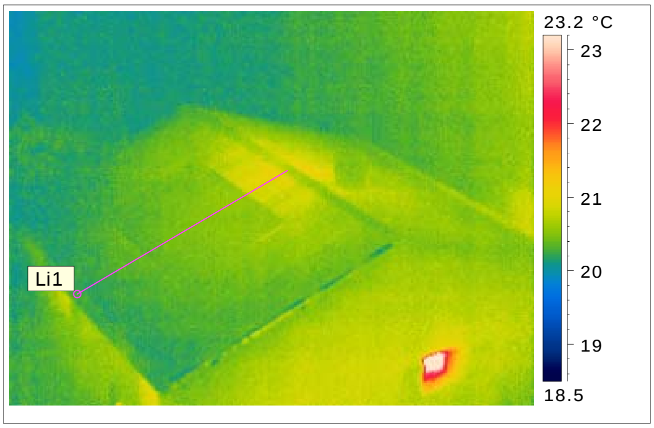

Figure 16: Roof infrared imaging (after 20min with insulator 1)

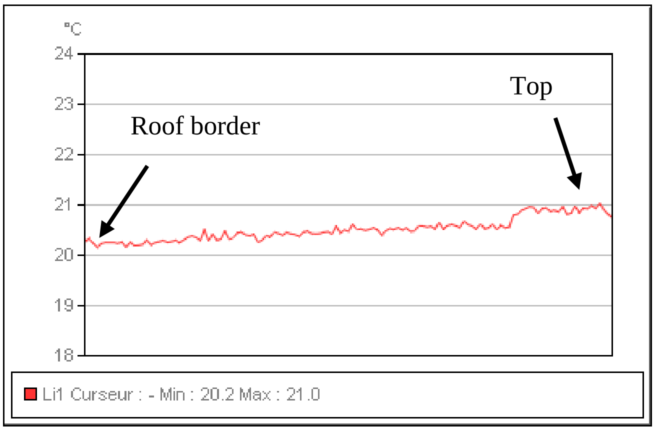

Figure 17: Temperature profile along the roof (with insulator n°1)

Figure 18 and 19 shows the effect of single and double glazed windows when steady state is reached. Average outside surface temperature is given by cursors Ar1.

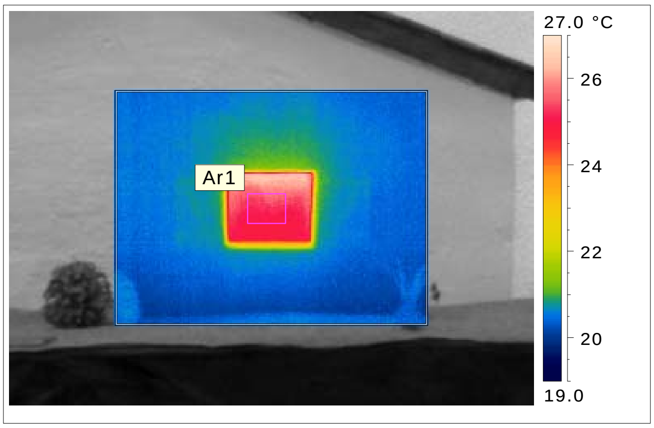

Figure 18: Single glazed window

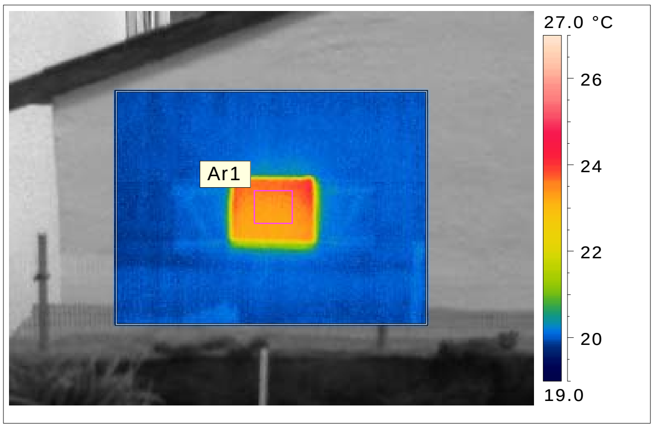

Figure 19: Double glazed window

6. Results discussion and analysis

Results in Figure 10 can be analysed as follows:

a) Without any insulation, inside temperature increases slowly and final temperature is obviously lower than the others.

b) With insulator n°2 (wall and ceiling 5mm polystyrene), the temperature obviously increases more quickly. An improvement of 2.5°C (as compared to the previous situation) is obtained after 22 minutes. Major part of improvement comes from the ceiling insulation.

c) Insulator n°1 (6mm mineral wool) gives almost the same result than insulator n°2 (thermal conductivities are quite identical).

d) Insulator n°3 (thin 3mm cork layer on the wall) is not so good as the others: gain compared to a) is around 1.76°C. From b), contribution of polystyrene ceiling represent around 1.31°C, contribution of cork layer wall insulation is thus around ΔT_{cork}= 0.35°C.

Relative efficiency of cork and polystyrene can be checked approximately:
Since thickness of cork layer is 3mm (against 6mm for mineral wool) and its thermal conductivity is around 0.05 W/m.K (against 0.03 W/m.K for mineral wool) insulation, correct proportions are retrieved between the two materials.

From infrared imaging outside surface temperature, some checking and cross validation can be made:
a) From figure 13, 14, 15 (“without insulation” test) final surface wall temperature (21°C) and roof temperature (20.5°C to 21.5°C) after 22 minutes of heating.
b) From figure 16 and 17, (insulator n°1 test), the final outside surface temperature are a little bit lower: 20.8°C for the wall and 20.2°C to 21°C for the roof.
c) From figure 18 and 19, an outer surface temperature difference of 1.8°C between single and double glazed window is observed; double glazed surface temperature is obviously lower.

Thermal effect of insulation is thus confirmed. Main tendencies, relative measurement and order of magnitude are enough coherent and significant to use the small scale house as didactical tool and/or demonstrator.

At last, no significant improvement was observed when filling attic with mineral wool: the impact is obviously small since ceiling is already well insulated by a polystyrene layer. Corresponding curve was not reported on figure 11 to avoid useless curves superposition.

7. Simple 1D thermal modelling identification and extraction

7.1 Modelling aims

Thermal modelling is a complex domain which requires high knowledge level and specialists.
Firstly, as the major competencies field of ENSEIRB institute is Electronic, the aim of this simplified approach is to obtain a simple and global “image” of the small house thermal behaviour. Thus, it must be understandable in a quite short time for non thermal specialists.
Lastly, modelling must be just fine enough to easily understand mains tendencies, effect of double internal or external insulation, thermal inertia and to run simple day/night scenario.

7.2 Modelling identification

Due to the equivalence and analogies between electrical and thermal quantities, each thermal way can be classically modelled [11] 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. 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.

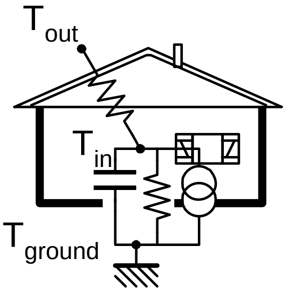

Figure 20: Intuitive ultra-simple modelling

Between this ultra-simple modelling given in figure 20 and a fine 2D or 3D finite element modelling, a medium complex modelling is suggested. It is enough detailed to understand the major thermal aspects.

7.3 Modelling parameters

Six main and parallel kinds of thermal ways are identified (cf. figure 21):

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

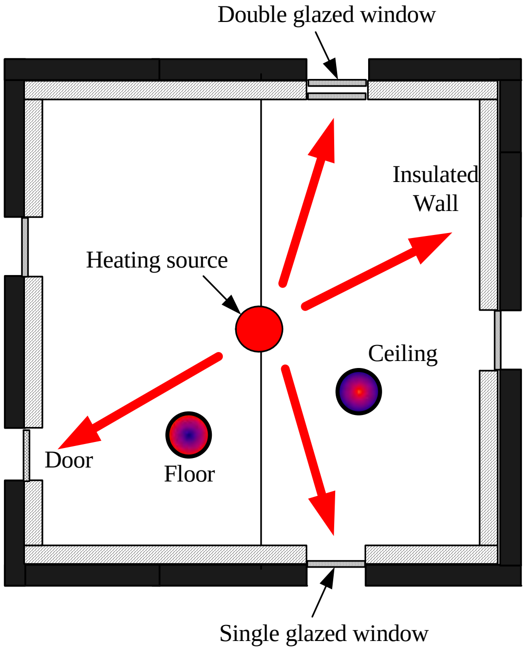

Figure 21: Thermal paths

A typical thermal “equivalent” electrical schematic for one path is given in figure 22.

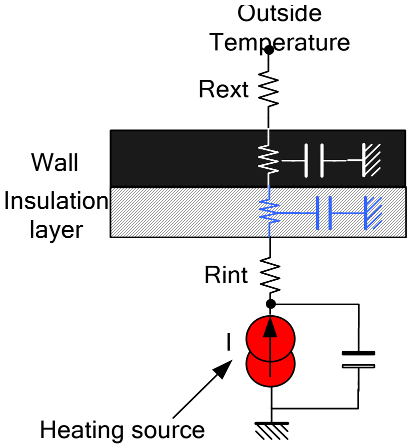

Figure 22: Typical equivalent path

R_{int} and R_{ext} represent the “in” and “out” coefficients of superficial exchange. R_{int} and R_{ext} depends on vertical or horizontal position the walls. Coefficients are obtained from data base [12].

For vertical walls:

$$R_{int} = (0.13m^2.°C/W) /S \quad (5)$$
$$R_{ext} = (0.04m^2.°C/W) /S \quad (6)$$

For horizontal walls with heat flux toward the top:

$$R_{int} = (0.10m^2.°C/W) /S \quad (7)$$
$$R_{ext} = (0.04m^2.°C/W) /S \quad (8)$$

Where S is the wall exchange surface.

And each layer is represented by a R, C network. R (°C/W), C (W.s/°C) values are estimated from materials thermal characteristics given in literature (Louvain catholic university (Belgium) database [12]) and from the geometrical characteristics of the each part of the small house (surface and thickness).

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:

$$S = 4.S1-(4.W+D) = 0.280m^2 \quad (9)$$

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 $W.h/m^3.°C$, the equivalent thermal resistance is obtained by:

$$R= (1/\lambda)e/S \quad = 0.76°C/W \quad (10)$$

And an equivalent thermal capacitance:

$$C = 3386\ W.s/°C$$

Thus, the AAC walls thermal time constant τ is:

$$\tau = R.C = 2537s\ (\#\ 42min) \quad (11)$$

A similar calculus is performed for each thermal path described before.

7.4 Final modelling

The equivalent schematic (figure 23) is then built, considering the 6 paths identified previously. A current source (20A) is added to simulate the power heating source (20W), a reference DC voltage source to simulate the ground temperature, and a second variable voltage source to simulate outside air temperature.

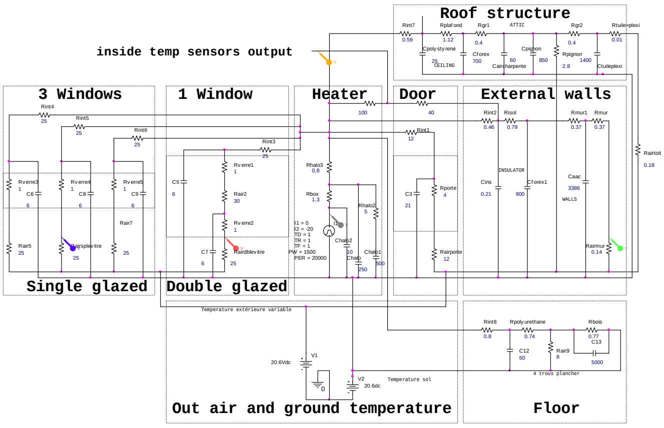

Figure 23: Equivalent electrical schematic

7.5 Simulations

7.5.1 Modelling fitting

A few ORCAD-SPICE simulations were first performed to refine the model (due to uncertainty on some values (attic behaviour, thermal conductivity of the floor…). Adjustment was done with data extracted from “insulator 1” experiment run.
Once fitted, various scenarios are simulated, in order to compare the tendencies observed before.

7.5.2 Simulation results

SPICE data are converted in Excel file for easy comparison with experimental curve given in §6.1. Scales on figure 24 to 27 are as follow: Horizontal scale time (in second), total simulation time 1320 seconds, i.e 22 minutes); Vertical scale: node voltage in V (value directly equivalent inside temperature in °C).

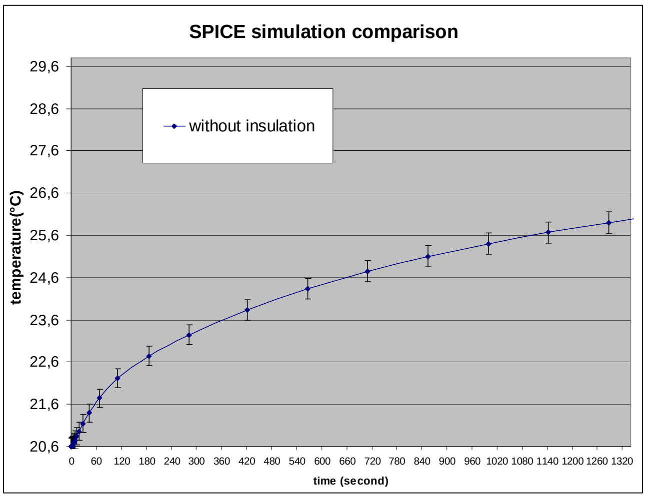

Figure 24: Simulated transient response (without insulation)

Figure 24 shows the transient response of the equivalent circuit corresponding to the “without insulation” situation. Inside temperature curve has to be compared with figure 11, “without insulation” curve.

Figure 25 shows the transient response of the equivalent circuit corresponding to the wall cork insulation situation. Inside temperature curve has to be compared with figure 11, “insulator 3” cork panel curve.

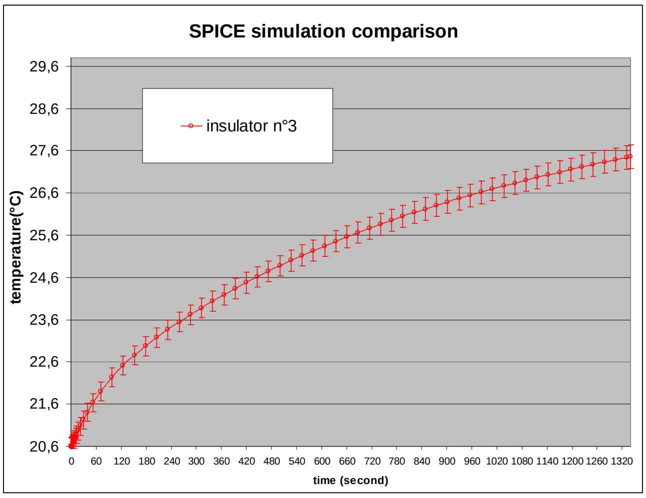

Figure 25: Simulated transient response (insulator n°3)

Figure 26 shows the transient response of the equivalent circuit corresponding to insulator 2 double insulation. Inside temperature curve has to be compared with figure 11, “insulator 2” curve.

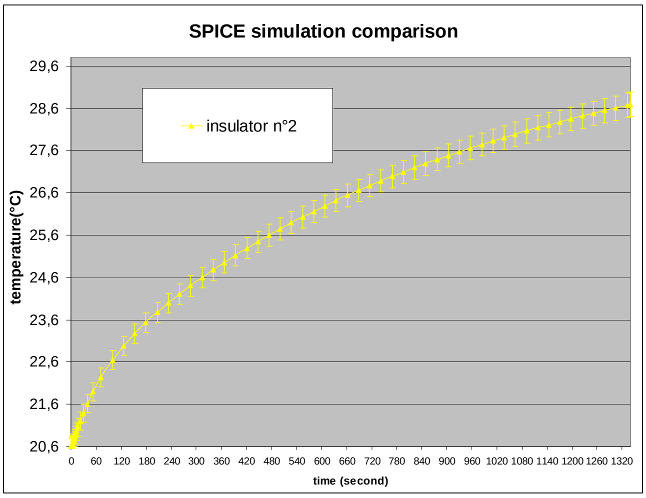

Figure 26: Simulated transient response (insulator 2)

Figure 27 shows the outside surface temperature on single glazed and double glazed windows. Simulation gives surface temperature difference of 1.9°C after 22 minutes elapsed time.

These comparative simulations show a correct matching with experimental results previously obtained in §7.1. This can be seen as an illustration of what is called "cold wall" effect.

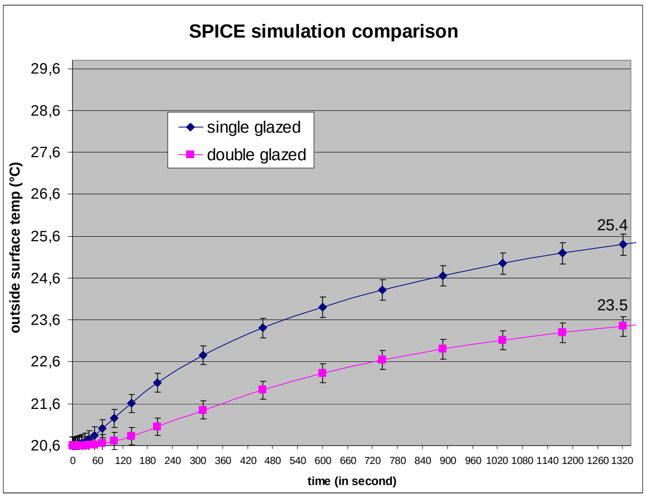

Figure 27: Comparison of single/double glazed window

7.5.3 Other simulation results

Since thermal flux (W) is equivalent to current (A), the respective flux through the different surfaces can be estimated, for example for insulator 1 situation, as follows:

surfaces	Heat Flux	percentage
Total house	20 W	100%
Insulated wall	7 W	35%
Insulated roof	5.3 W	26.5%
Windows and door	1.7 W	8.5%
Floor	6 W	30%

Table 1: Simulated heat flux through the different surfaces

Since heat flux per surface unit (W/m^2) is equivalent to current density (A/m^2); the flux density is obtained by dividing the heat flux by the surface of each part. Table 2 shows the results and of each material of the house sorted from smallest to highest flux density.

surfaces	Flux density
Insulated ceiling and roof	22W/m^2
Insulated wall	23W/m^2
Double glazed window	57W/m^2
Single glazed window	98W/m^2
Door	100W/m^2

Table 2: Simulated heat flux density

7.6 Simulation results discussion and comments

The small scale house can obviously not strictly compared to a real house [13], [14], [15], because thermal phenomenon at full scale and small scale are different (convection, volume and border effects) but order of magnitude and proportions are similar to the one's found in common data base [16].

Matching between the extracted modelling and experiments is checked by superimposing experimental and simulated response.

For example, figure 28 shows the superposition of transient simulated response (yellow curve) (from fig 24), experimental curve (dark blue) (from fig 11) and polynomial fitting curve (derived from equation (4), without insulation.

Maximum error between experimental and simulated curves is less than 0.2°C.

The same maximum error is observed for all other simulated scenario.

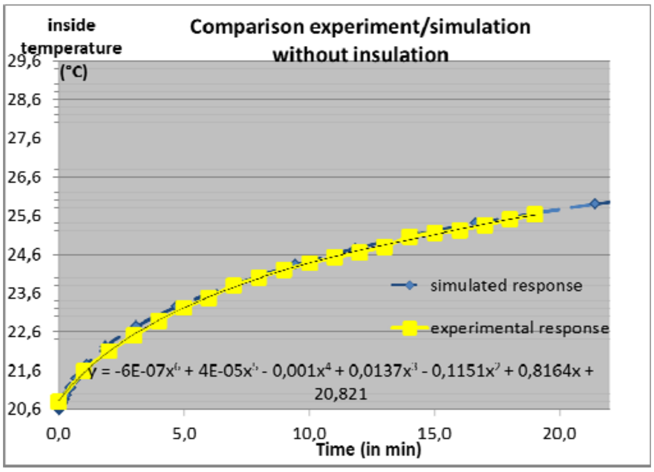

Figure 28: simulation vs. experiment

Thus, results obtained with this 1D modelling are enough coherent and significant to demonstrate main tendencies and impact of thermal insulation.

Static and transient behaviours regarding outdoor temperature changes can also be predicted under various insulation scenarios.

8. Future work

8.1 Theoretical aspects

Previous simple modelling was a first approach. As no local thermo mechanical competencies and tools are available, collaborations to collect more quantitative data [17], to extract a fine modelling, to run thermo dynamical simulations [18], [19] on the small scale house model should be a good future approach to improve and complete the presented study.

In parallel, SPICE modelling will be now included as sub circuit in a higher level simulation modelling to study power consumption of the house, and will also be extended to a multi floor house. Such modelling will allow the prediction of energy saving on each floor when changing insulator materials, replacing single isolation windows by double isolation windows or moving the heating source.

8.2 Practical aspects

In order to confirm energy saving in the small scale house, an electronic circuit to heat the house and regulate the indoor temperature is going to be designed. Some ceramic resistors and heating floor will act as electrical heaters driven by an “on/off” PWM signal. By a real time monitoring of the consumption, it will be possible to know the average energy consumption of the house under various conditions; for example, the impact of heater’s position in the house will be investigated. Comparison between heaters fixed below the window, a common situation in true houses, or elsewhere), will be easily done and thermal measurement correlated to energy consumption monitoring.

8.3 Other future general evolution

Some electronic circuits will be designed and a small scale home automation system (student projects) will be installed in a near future.

9. Conclusion

Three years were necessary for ENSEIRB-MATMECA school and its academic partners, to design a functional realistic small scale house, built in genuine materials. No similar project was done before: It was thus a totally new and innovative sustainable development project. Thermal behaviour of the house model was investigated. Insulation materials efficiency was checked. Relative tendencies were demonstrated by a comparative approach. And an equivalent thermal modelling has been validated.

Studies are now in progress for improving the model, refining the results and for designing some electronic systems like a small scale home automation.

Lastly, this work should be now adapted and converted for educational purpose on thermal measurement techniques at ENSEIRB-MATMECA.

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