Thermal characterisation and 3D virtual modelling of a modern timber-frame small scale house

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Abstract: This paper relates to a concrete sustainable development project. A small scale timber frame house (1/10 scale) has been designed, directly inspired by "Napevomo" house presented in solar decathlon challenge 2009. The building itself was already described in a previous paper. It has been manufactured according to the real strict and recent new French standard RT2012 which aims to improve the global thermal and environmental performances of the houses. Infrared imaging and temperature measurements are firstly detailed. Then, an equivalent thermal modelling of the small scale house is build. Global thermal behaviour under various conditions is simulated. Finally, results are compared to experiments thanks to a 3D VRML graphical visualisation, to validate the modelling.

1. Small scale House project state of art

1.1 Generalities

The project of small scale house model started a few years ago, thanks to a collaboration between LTP St Nicolas, Paris (secondary school for vocational training -joinery), ENSEIRB MATMECA electronic engineering school of Bordeaux and Faculty of Electrical Engineering of Craiova.

The aim was to build a original timber frame model of house (1/10 scale) with genuine wood construction materials [2]. It is directly inspired by "Napevomo" house presented in solar decathlon challenge 2009 [1]. The finished model is used as:

    - Research support
    - Educational support for practical lessons and electronic projects,
    - Sensitizing tool to Sustainable Development.

1.2 General framework of the project

1.2.1 Generalities

With the climate change, sustainable development concept introduction and agenda 21 adoption, Kyoto protocol has defined an ambitious goal for France: to divide the French green gasses emission by four. Private houses and buildings represent a significant contribution of the whole emission. Thus, improvement of new buildings design and renovation

of old French flats and buildings have been decided by French government, in order to reduce the power consumption and gasses emission [3].

Our study is a didactical and modest illustration of this major challenge.

1.2.2 Interest of the presented work

From Research point of view, creating an original small scale "tool" helps to experiment a full scale phenomenon in laboratory conditions. Indeed, the small size of the house allows in door comparative studies that might be more difficult to make in true houses (for technical and financial reasons).

From a pedagogical point of view, it is a citizen 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.

1.3 Scaled house design short overview

The small scale house itself is now achieved. Its building (with true materials) required one academic year and was detailed in [2]. The miniature house is manufactured according to "up to date" RT2012 standard [4], [5], [6]. Thus, the small scale house looks like a "perfect replica" of a modern timber frame, high thermal efficiency house. Each part consists of a

sandwich of different layers assembled exactly like in reality according to the true technical architect rules, building trade, carpenter, plumber, painter, roofer, and so on.

The small scale house is directly inspired by "Napevomo" and "Baïtycool" house designed by Nobatek company and ENSAM Bordeaux [7] for the 2009 and 2018 solar decathlon challenge. This is a one floor 25m^2, flat roof, square shape compact small house. In order to reduce the heat losses by the walls, it is obvious that it is necessary to reduce surfaces in contact with outside; for a given volume, the compactness is thus very important. At 1/10 scale, the overall dimensions are L=50 cm x l=50 cm x H=29 cm (all included).
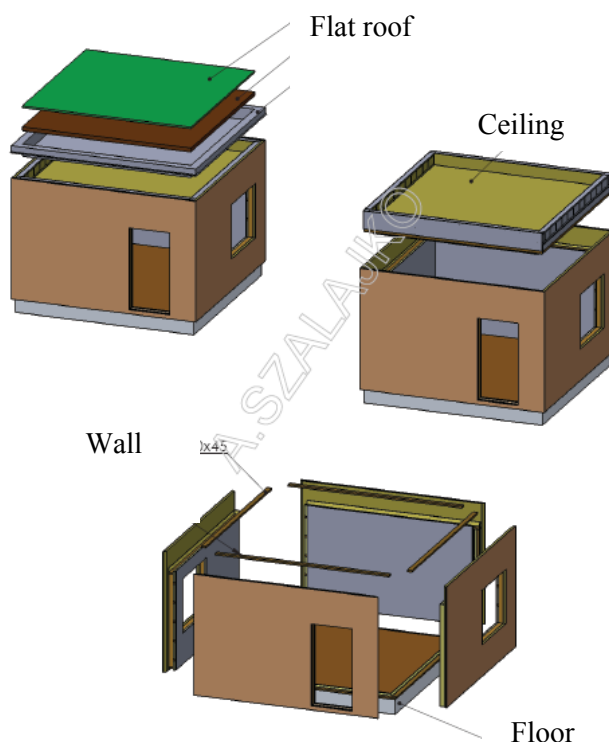

Figure 1: Floor plan of the small scale house

The double and single glazed windows frames have been cut and machined from the same raw material plate (PVC). Small glasses have been cut from a unique glass plate. The space between the two glasses is a simple air gap (no rare gas inside). 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 2mm polyurethane insulation film.

Figure 2 shows a picture of the finished small scale house model.

Figure 2: Finished small scale house.

2. Thermal behaviour characterisation

2.1 General interest of thermal measurements

Since a few years, the use of thermal camera has been democratized: infrared thermometers or cameras can be found in supermarket. In particular, "low cost" cameras are now currently used in building trade for energy performance and thermal losses of flats diagnosis [8], [9]. Indeed, diagnosis and display of the performances are required before the sale of a flat in France (official decree in September 2006).

Moreover, Bordeaux was one of the leading cities in France to ask for a full thermal assessment of thermal losses in living building [10]. A thermal cartography of the Bordeaux and suburb [11] has been done flying over and scanning the city with an infrared camera. The collected data's allowed the authorities to suggest improvements of roof insulation efficiency and renovation in faulty houses.

2.2 Operating conditions

Small scale house model is located in-door, in a underground fresh and dark workroom to avoid parasitic infrared rays as well as possible. Real conditions (outdoor measurements) can obviously not reproduced. However, small house can be heated more than the room temperature to produce a temperature gradient between inside and outside. For each measurement, the values of the temperature given by the IR camera will be correlated to those indicated by a multi channels temperature recorder. The heating source is a 20W halogen lamp. It can be considered as a punctual source located in the middle of the house.

2.3 Test equipment short description

The infrared camera used for this study is a FLIR B335 with a "target preset-able emissivity". Main characteristics are:

- IR analysis range: 7-13μm,
- IR sensor matrix: 320 x 240 pixels
- Lens: 25°, manual or autofocus
- IR image superposed or merged with a normal digital image
- Thermal resolution: 0.05°C (at 30°C)

Temperature recorder is a portable GL220 Graphtec, 10 channels mini logger. All the channels are used and connected to thermocouples PTFTE type K. Due to the limited memory size, the total possible recording time depends on sample interval and number of used channels. For the present experimentation, recording time is largely enough (around 24h), compared to thermal time constant of the small scale house.

2.4 Test bench preparation

2.4.1 Thermocouple location
Choosing a correct placement of thermocouple is very important. Indeed, static measurements will help to determine equivalent thermal resistance of each thermal "way" while transient measurements will enable to obtain their thermal time constant for future thermal modelling extraction.
Thus, it requires first to identify the significant and different thermal paths. Here, six kinds of thermal ways are identified as indicated on figure 3.
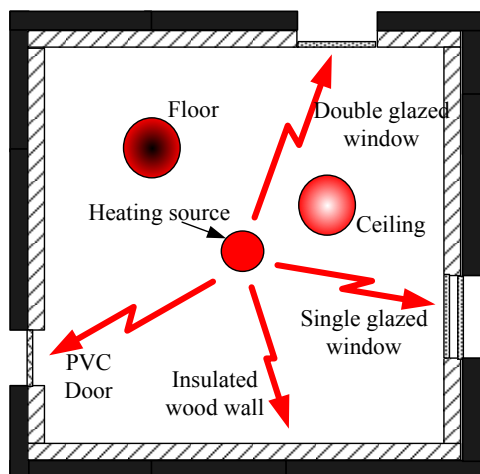

Figure 3: Identified thermal paths (top view)

- One for the vertical walls
- One for the double glazed window,
- One for the single glazed window,
- One for the door,
- One through the ceiling,
- One through the floor.

Thermocouples will be stuck on each representative internal and external surfaces of the house to get the more realistic surface temperature measurement.
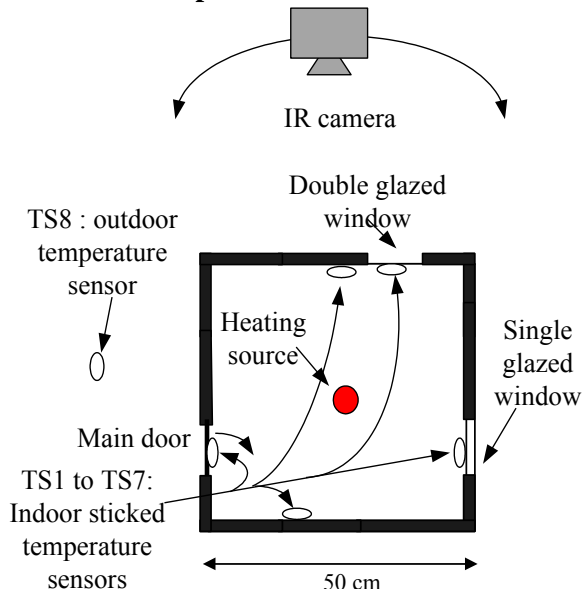
2.4.2 Test bench implementation

Figure 4: Test bench

Thermocouples measure internal and external surface temperatures while Infrared camera observes only the outside surfaces of the house.

2.5 Preliminary calibration

2.5.1 Thermocouple calibration
The most important is not absolute accuracy but more surely the matching between thermocouples to perform reliable measurements. Calibration process is as follows: The 10 thermocouples are submitted to the same temperature from 0° to 50°C in a test temperature controlled and programmable chamber.

Figure 5: Thermocouple matching test

Average value is computed as well as difference between each sensor and average value. A correction table is extracted and will be applied on experimental results.

2.5.2 Infrared emissivity set up

Target emissivity must be known or corrected to performed reliable measurements: it can be done in three ways:

- Application on the target surface of a thin special high emissivity black painting (ε very close to 1),
- Automatic « pixel by pixel » correction by digital and software processing on top level camera. In this case target is considered as grey body: emissivity is assumed constant whatever the chosen wavelength for the analysis,
- Extraction from materials emissivity reference table.

Here, the first method is obviously not applicable for esthetical reasons. The second one's requires an expensive camera with its emissivity correction software.

Thus, average emissivity value of the "target" is chosen and set up into the camera, after the following test: a part of the house wall material is submitted to two reference temperatures. Average surface temperature is checked with two stick thermocouples and observed at the same time, with the camera. Emissivity is set up for the best matching between values read by thermocouples and IR camera over our temperature range.

2.6 Thermal measurements

Measurements were performed several times to check reproducibility and fidelity. The full recording time for each experiment (one heating/cooling cycle) was voluntary over estimated at 2 hours, in order to be sure that transient and steady state were correctly recorded. Sample time interval is 1 minute. Infrared images are saved each 3 minutes during the heating period.

2.6.1 Transient measurements

Thermal transient behaviour is obtained by submitting the small house to a heating power pulse of 20W (two halogen spotlights of 10W each).

Thermocouple values and IR images are recorded simultaneously during the experiment. IR images are saved only during the heating phase (T_{final}=60 minutes) and thermocouple values are registered both during heating and relaxing phase. Among the numerous IR images recorded, a set of 4 IR images are presented in

figure 6. Corresponding to t=0s (top left), $T_{final}/3$, $2/3*T_{final}$ and T_{final} (bottom right).

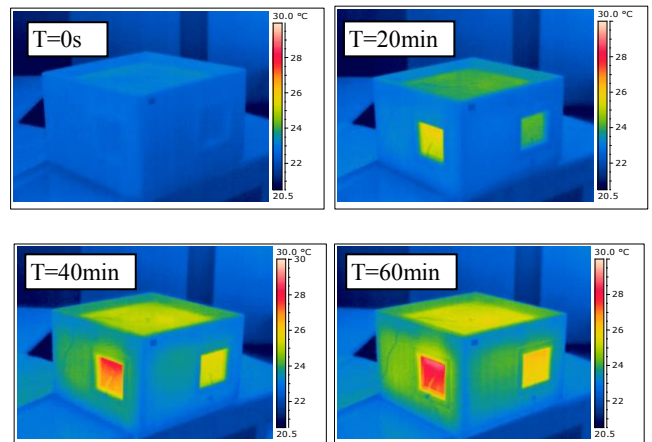Colored Vertical scale "Rainbow palette": T(°C) 20.5 to 30°C.

Figure 6: sequence of sample IR images

After data processing, calibration correction, and conversion to Excel file, surface temperatures registered by thermocouples are displayed. Some resulting curves are shown in Figures 7a to 7c.
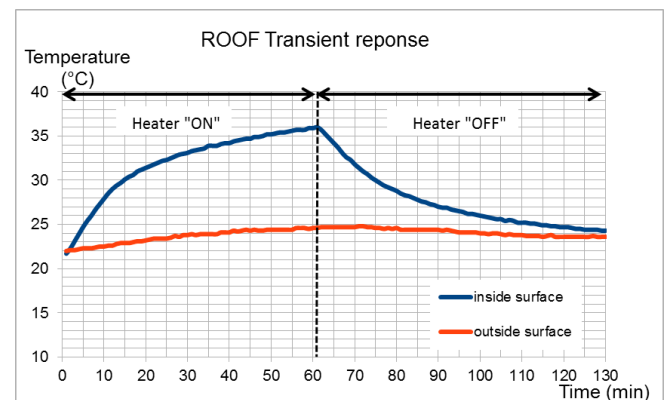
Figure 7a: Evolution of inside and outer surface of the roof during heating and relaxing phases.
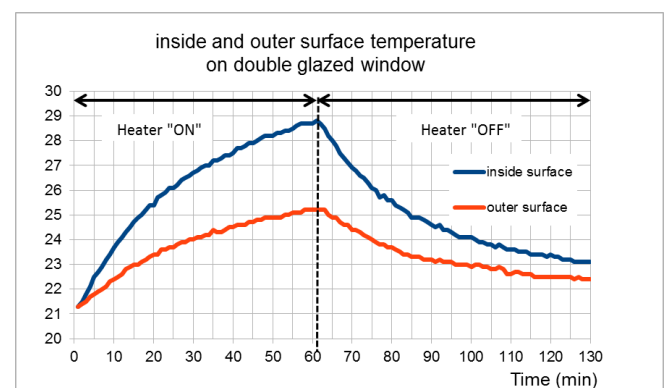
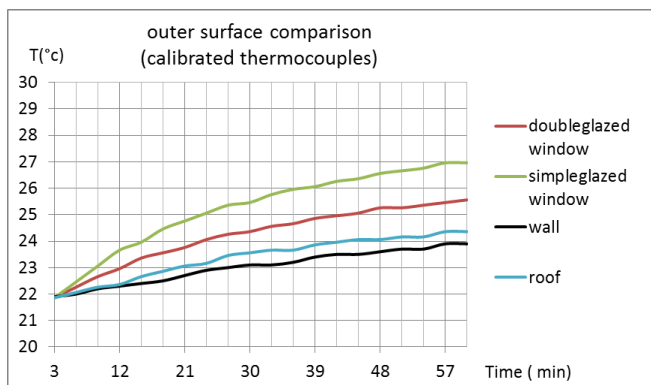Figure 7b: Double glazed window surface temperature transient response

Figure 7c: Evolution of main outer surfaces during the heating phase.

In order to check the matching between IR and thermocouples measurements, a comparative analysis has been done for each main outer surface. For example, the last figure compares the temperature value extracted from IR images to the ones recorded by thermocouple on roof surface.
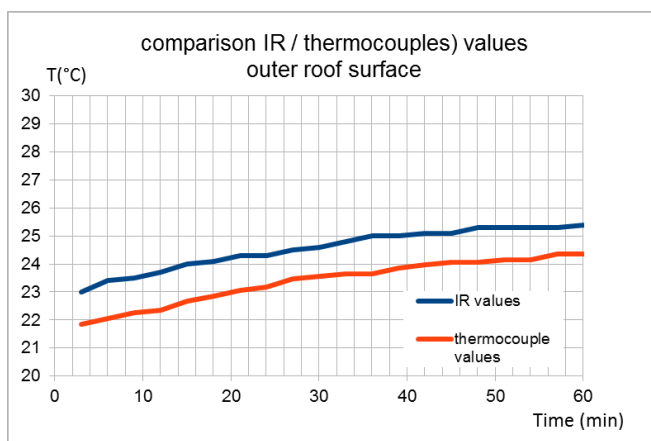

Figure 7 d: Comparison of thermocouple and IR temperatures readings.

The IR temperature value is always higher than the thermocouple value with a constant and permanent gap of 1°C, whatever the outer surface and whatever the temperature; Thus, we can consider it as a permanent non disturbing error which can be easily corrected.

2.6.2 Static measurements
To complete the experiment some static measurement are performed. An example of steady state observation of the door is given in figure 8. The top of the door is obviously slightly hotter than the bottom.
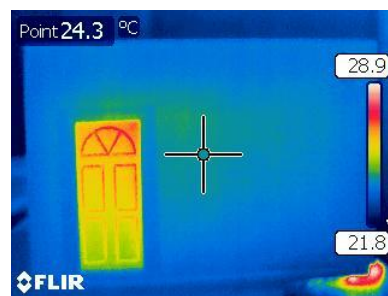

Figure 8: closed door

2.6.3 Comparison double/single glazed window
Comparing single and double glazed window effect requires a strict experimental process to ensure the reliability and reproducibility of results:
- Heating source is located at the same distance from the two windows.
- We perform only relative and comparative measurement to eliminate absolute accuracy problems.
- Outer surfaces temperatures are measured for two different heating powers (10W and 20W) with thermocouple and IR camera in the three following situations:
- The two windows are first mounted identically with a single glass. No significant temperature difference is observed.
- The rear window is mounted with double glazed while the other is single glazed; Outer double glazed surface temperature is lower than the other.
- The left window is double glazed and the rear one's single glazed. Outer double glazed surface temperature is lower also than the other.

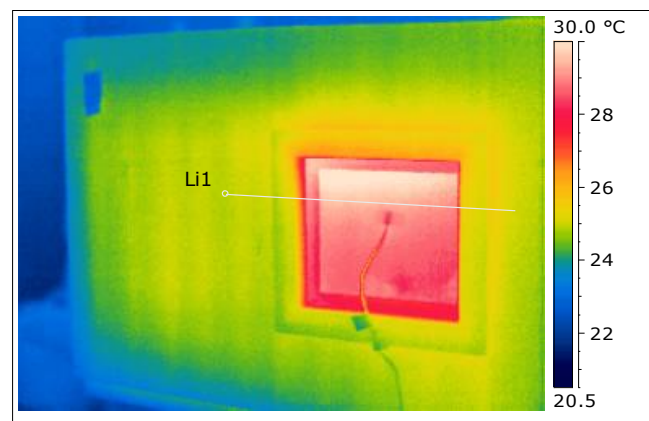Corresponding experimental results are displayed (for 20W heating) in Figures 9, 10, 11.

Figure 9: Single glazed window and thermocouple

Figure 9 shows Infrared image of single glazed window. Figure 10 shows the infrared image of the double glazed window. On each view, a cross section

along the horizontal line passing through the middle of windows is performed. (With FLIR reporter 8.5 software). (Thermocouples stuck on the middle of windows can be seen).
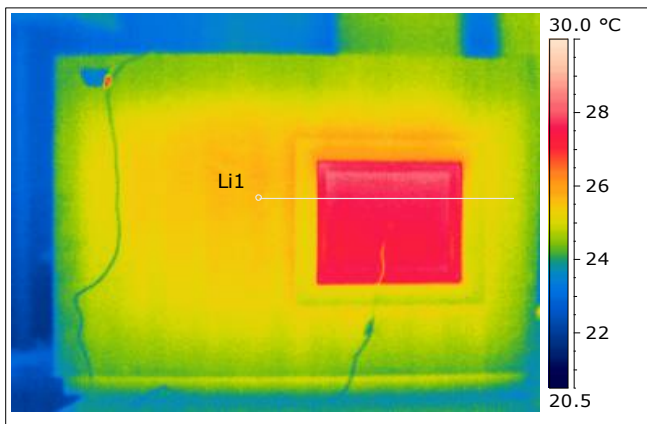

Figure 10: Double glazed window

Thus, Figure 11 displays the comparative outer surface temperature profile of the two windows along the horizontal line cursor "Li1".
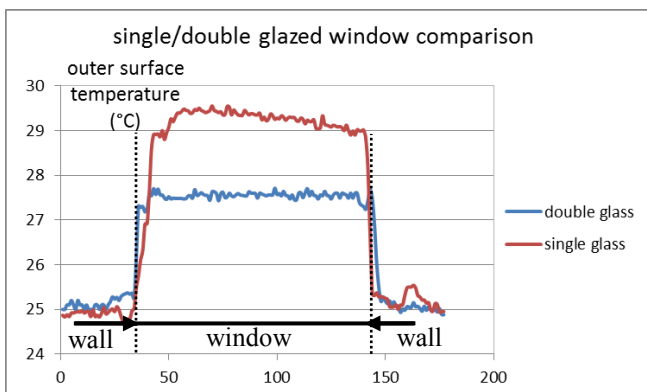

Figure 11: Outer surface temperature cross section

Temperature surface of the double glazed window is logically and significantly lower than the one of single glazed. An average surface temperature difference of 2°C between the two windows is observed.

2.7 Comments on experimental results
Coherence between thermocouple values and IR images are checked: a small and permanent gap "error" between absolute values, but correct relative matching is observed. Temperature variation and evolution observed with IR and thermocouple are similar (same delta value and same time constant). looking at outer relative surface temperature on figure 7c, we can classify the losses from the greatest to lowest : simple glazed, double glazed, roof and wall.

The figure 7a demonstrates a very good insulation of roof, because there is big delta (around 10°C) between inside and outside temperature. Lastly, Figure 11 shows a temperature difference of around 2°C between windows outer surfaces. Thus, a significant effect of double glazed windows can be confirmed.

3. Three dimensions virtual modelling
From experimental characterization, we can extract a 3D virtual and didactical modelling representing the thermal behavior of the small scale house as indicated below.

3.1 VRML short overview
The free "Virtual Reality Modelling Language"(VRML) was born in 1995. Initially, it was used to make three dimensions drawings and virtual animation for didactical and/or scientific purposes [14], [15]. VRML can be considered like one of the "fathers" of the most popular and modern software's tools (BLENDER or the graphical interface modules of MATLAB/SIMULINK). Lastly, VRML can be interfaced with well-known SPICE simulator.
Graphical animation can be programmed in two ways:
- by including in a *.wrl description file, a set of « *interpolator* » instructions. Movements are then described in a table where the position of the moving object is given as a series x, y, z coordinates vs discrete time,
- or by including some JavaScript and mathematical equations describing the trajectory.

Colours of objects can also be animated in a similar way.

3.2 VRML description of the house
We need first to build the 3D graphical representation of the house. Since the shape of the timber frame small scale house is very simple and compact, the VRML description is done using only basic parametric boxes representing walls, doors, windows, floor, and ceiling. Three dimensions visualization is done with the free viewer "orbisnap "(figure 12).

3.3 VRML color management
For an efficient use of VRML, it is important to understand the basic management of colours. The colour is an object consists of a mix of the three primary colours: red, green, blue (R, G, B). The

percentage of each primary colour is given by a number comprised between 0 and 1. Table 1 below show some usual colours. The colours is thus defined by a triplet of value R, G, B (comprise between 0 and 1 i.e. 0 to 100%).
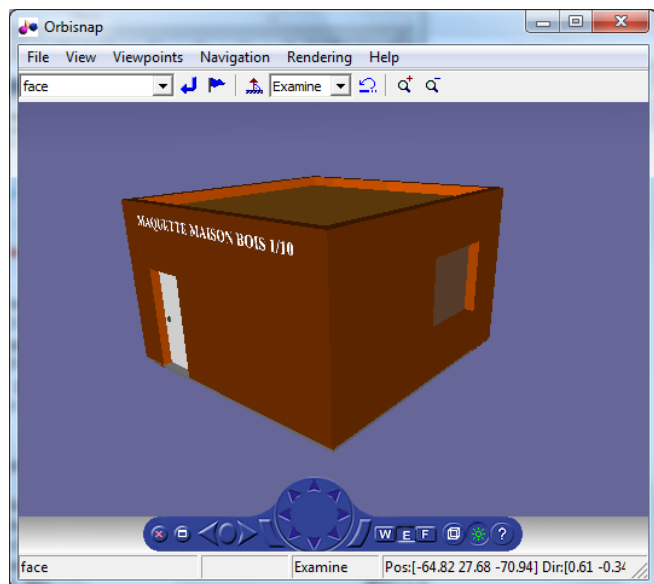

Figure 12: 3D VRML modeling of the scaled house

Color	Red (R)	Green (G)	Blue (B)
silver	0.75	0.75	0.75
white	1	1	1
Dark blue	0	0	0.5
Grey	0.5	0.5	0.5
Yellow	1	1	0
Black	0	0	0
Brown	0.5	0.2	0

Table 1: Basic useful colours in VRML

3.4 Rainbow palette building

To make our 3D colour modelling comparable to the experimental infrared images, we need first to build a VRML colour palette similar to the one used by the infrared B335 camera (Rainbow 900). Minimum or initial temperature T_{min} corresponds to dark blue colour and maximum temperature T_{max} corresponds to white colour.

The normalized temperature T_n is defined as:

$$T_n = (T_{(°C)} - T_{min})/(T_{max} - T_{min})$$
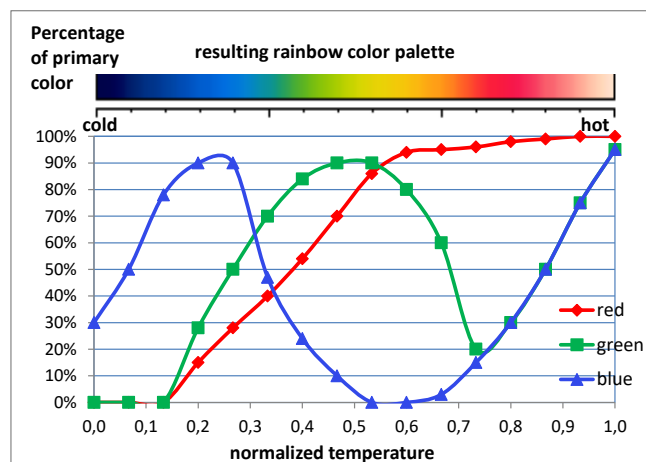
Thus, $0 < T_n < 1$.

Figure 13: Normalized rainbow palette building

As the IR camera palette is mobile and adaptable to the observed temperature range, we need to create a normalized palette which could expendable and adjustable to fit the IR experimental palette.

The proportion of each primary colour to build the desired rainbow scale is shown in figure 13. And percentage of colours effect is checked by filling cells in Excel sheet with the "personalized background colour" and comparing with the rainbow palette.

The 3 curves Red (R), Green (G), Blue (B) are then modeled from figure 13 by polynomial curves (Excel spreadsheet):

$$R = -22.8T_n^6 + 71.659T_n^5 - 77.145T_n^4 + 28.358T_n^3 + 1.1704T_n^2 - 0.2368T_n - 0.0018 \quad (1)$$

$$G = -166.24T_n^6 + 466.92T_n^5 - 452.22T_n^4 + 168.61T_n^3 - 16.779T_n^2 + 0.6746T_n - 0.0086 \quad (2)$$

$$B = 137.71T_n^6 - 424.59T_n^5 + 472.39T_n^4 - 213.88T_n^3 + 25.88T_n^2 + 3.1919T_n + 0.2779 \quad (3)$$

And equations are entered in the VRML description file.

6. 5 Graphical animation

Transient responses (cf. figures in § 2.6.1), to a heating power pulse) are first modeled.

The mathematical equations of each surface temperature (vertical walls ($T_{outwall}$), double glazed window ($T_{outdblewin}$), single glazed window ($T_{outdsglewin}$), roof ($T_{outroof}$), door ($T_{outdoor}$) of the house are extracted and normalized (polynomial approximation). So we get the normalized temperature T_n vs. normalized time t_n (cf. figure 14).
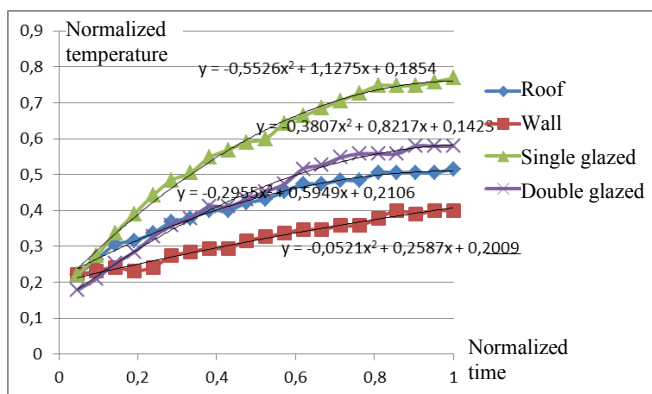
Figure 14: Normalized polynomial approximation

Once time and temperatures normalized (cf. figure 14), the followings normalized equations are entered in JavaScript programs.

$Tn_{outwall} = -2E-08t_n^6 + 2E-06t_n^5 - 6E-05t_n^4 + 0,0013t_n^3 - 0,0199t_n^2 + 0,1999t_n + 6E-06$ (4)

$Tn_{outdblewin} = 2E-08t_n^6 + 2E-06t_n^5 - 6E-05t_n^4 + 0,0013t_n^3 - 0,0199t_n^2 + 0,1999t_n + 6E-06$ (5)

$Tn_{outdsglewin} = 2E-08t_n^6 + 2E-06t_n^5 - 6E-05t_n^4 + 0,0013t_n^3 - 0,0199t_n^2 + 0,1999t_n + 6E-06$ (6)

$Tn_{outroof} = 2E-08t_n^6 + 2E-06t_n^5 - 6E-05t_n^4 + 0,0013t_n^3 - 0,0199t_n^2 + 0,1999t_n + 6E-06$ (7)

$Tn_{outdoor} = 2E-08t_n^6 + 2E-06t_n^5 - 6E-05t_n^4 + 0,0013t_n^3 - 0,0199t_n^2 + 0,1999t_n + 6E-06$ (8)

Thus, for each simulation time t_i interval, (cf. Table 2) the instantaneous surface temperature T_i is calculated and associated to a triplet R_i, G_i, B_i, thanks to the rainbow VRML color palette and equations (1), (2), (3) (cf. §3.4).

time	Reduced time	Surface temperature	Normalized Temperature	VRML colors		
t	$t_n = t/tm$	T	$T_n = \dfrac{T - T_{min}}{T_{max} - T_{min}}$	Red/Green/Blue		
(s)		(°C)		R	G	B
0	0	T_{min}	0	0	0	0
.	…	.	…	.	.	.
t_i	t_n	T_i	T_n	R_i	G_i	B_i
.	.	.	…	.	.	.
t_m	1	T_{max}	…	1	1	1

Table 2: Generic table of values

Animation is played in real time with the 3D viewer and some images are captured at regular time interval. An easy visual comparison (Figure 23) can be done between VRML simulation and the sequence of experimental infrared images.

Top image: to=0,second image: t= 20min, third image: t=40min, bottom image: t= 60 min.

Simulated   Experimental IR image
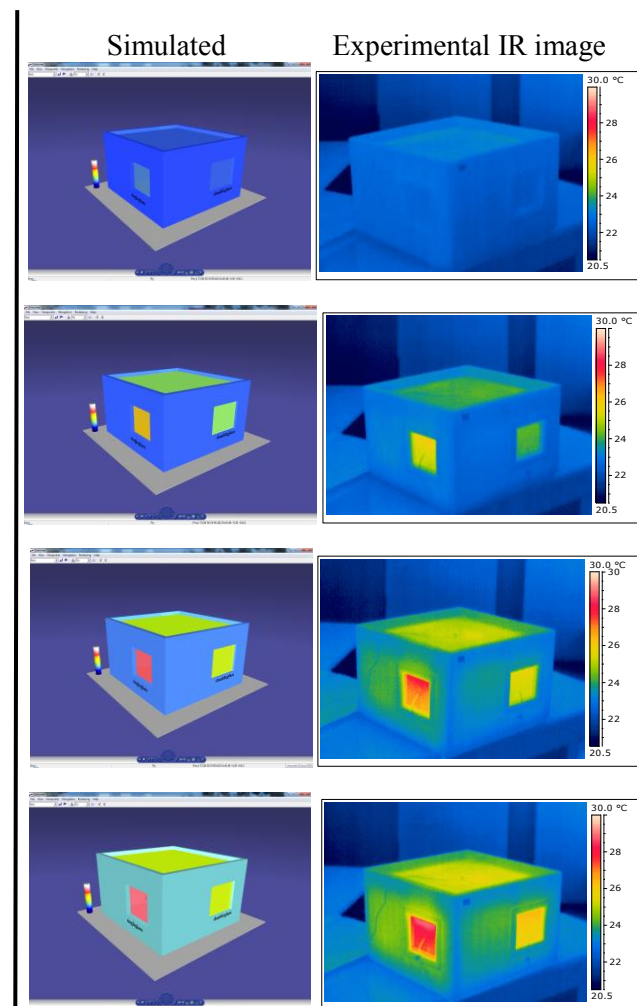
Vertical scale : Time 0 to 60min
(Single glazed window on the left)
Figure 23: Comparaison VRML simulation/ IR images

6. 6 Modelling and simulation comments

VRML gives a simplified and average view of temperature evolution: Colour is uniform along each main surface, (no shaded colour). There is no 3D temperature equation solving, like in finite element software (for example ANSYS /SILVACO).

However, the visual comparison with the experimental IR images shows a correct and enough realistic matching.

Tendencies are well illustrated: the temperature on windows reaches correctly its final value more rapidly than the walls due to its lower thermal time constant.

The single glazed window (on the left side) surface is hotter than the double glazed one's. It confirms that heat losses are more important for the single glazed than for the double glazed.

The walls remain colder due to their high thermal resistance compared to windows.
We can quote a difference in visual aspect of experimental and simulated image. Simulated image looks obviously smoother and homogeneous.

7. Discussion

7.1 Global result analysis
Coherence between experiments and simulations is correctly checked. Relative tendencies and order of magnitude are respected.
Coherence between the small scale house model and a real house is more difficult to do. However, main tendencies (detailed results on Napevomo project are properties of designers and not distributable for public publication) have been checked on the Napevomo ENSAM/Nobatek full scale house [1]. Thus, our "miniature tool "is enough realistic and representative for future pedagogical uses.

7.2 Interest and limits of the modelling

7.2.1 Advantages
The main advantages of the presented approach are:
- Easy understanding of thermal problems for non-thermal specialists,
- No expensive software or sophisticated apparatus required
- Quick and fast VRML simulation (a few minutes). By comparison, simulation by finite element commercial software could take a few hours depending on mesh size and mesh number. In fact, they cannot be really compared because the first one in a graphical tool while the second is a thermal and physical laws solver software tool.
- Possible use for student's initiation during a practical project.

7.2.2 Limits
The main limits are given below:
-The equivalent modelling is a simple 1D linear modelling. It does not take into account surface and volume effect,
- No shaded effect on the wall surface,
- Natural air movement or forced air ventilation are not simulated,
- Not possible to make annual weather conditions or occupation rate scenario [16].

7.2.3 Comparison 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.
The same problem can be obviously solved with different tools. Thus, a very similar study can be performed using MATLAB/SIMULINK [17] in a more "automatic than electronic" approach, depending of the personal sensitivity and preferences of researchers. Graphical interface is a little different with "house", "heater", and conventional feedback block icons. Results and results display interface are very close. Other existing professional and commercial software such as Pleiades (Izuba company) [18] or Design builder [19] are dedicated to architects and house builders. They include a macroscopic building approach with predefined raw materials data base and drawing tools to design real houses. Heating power can be simulated under various scenarios: aspect of the building, 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
Since a house can be seen as a global system, (architectural, technical, economical, and ecological), future studies on life cycle, global energy performance and carbon assessment, will be carried on this timber frame house model with a holistic approach. The house model will also be used for didactical projects merging thermal and electronic aspects.

9. Conclusion
A full academic year was necessary to design a RT 2012 standard compatible timber frame small scale house. It was completed successfully within the framework of collaboration with technical secondary school. Experimental thermal characterisation was performed and an equivalent VRML thermal and graphical modelling was extracted and validated. Main satisfaction is that similar projects are thriving in several secondary schools [20], and universities [21], [22], [23], [24].

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