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INTERNATIONAL JOURNAL OF CURRENT RESEARCH

International Journal of Current Research
Vol. 6, Issue, 12, pp.10507-10515, December, 2014

ISSN: 0975-833X

RESEARCH ARTICLE

EXPERIMENTAL APPROACH FOR CHARACTERIZING A THICK BUILDING WALL: ESTIMATION OF RESPONSE TIME

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ARTICLE INFO

Article History:
Received 24th September, 2014
Received in revised form
26th October, 2014
Accepted 09th November, 2014
Published online 27th December, 2014

Key words:
Solar Solicitation,
Analysis of Thick Material,
Characteristic Response Time,
Thermal Insulation,
Thermal comfort,
Energy Efficiency

ABSTRACT

Losses are difficult to control because of the lack of characterization method thick materials engineering. The work presented here is an experimental approach to characterize a thick material. We used the power of the sun as a source of excitation of the material. We set up a simple sensor consisting of a Peltier element and a thermocouple for measuring surface. With the help of a chain of acquisition, we recorded in steps of 10 s data flow and temperature in real time on the outside and inside of a building wall. Analysis and appropriate treatments based on the method of quadrupole were then allowed us to estimate the characteristic response time of the wall. Campaign measurement data is done in five days. So we could calculate the characteristic response time of each day, which obviously depends on the weather conditions and the thickness of strained layers in the wall. We determined an average characteristic time of 2h 21 min or 8460 s, which corresponds to a homogeneous material diffusivity ($a = 10^{-6}\, m^2/s$) at a depth of about 12 cm polled. We believe that the implementation of an infrared camera, it would be possible to make Non-Destructive Testing (NDT) such materials.

INTRODUCTION

To meet the requirements of European Regulations thermal (RT), many software were created. They propose using data of thermo physical properties of materials available in the literature, building walls composed of several layers of homogeneous materials, in order to meet these requirements. The walls are thus expected to play two roles. They must have transmission inertia to protect the habitat enclosure against external temperature changes. They must also have inertia absorption to store any surplus heating and power it back in a timely manner. But there is no way to confirm or deny in-situ, the results of theoretical calculations from software. The question is: is it yes or no buildings on the basis of these calculations meet the predicted results? The building Napevomo installed on the Esplanade Arts and Crafts in Talence (Bordeaux), was built according to these calculations. He has also won numerous awards in the first Solar Decathon in Madrid for its Technological innovations. To resolve this issue, we developed a method to evaluate in-situ dynamic storage capacity of the wall, which is expected to be ($31kWh.m^{-2}.K^{-1}$) we got ($29kWh.m^{-2}.K^{-1}$) Prodjinonto, (2011), (Prodjinonto, 2013).

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The present paper is an extension of the results already obtained. A further analysis of the data led us to propose an alternative to the problems encountered in the laboratory, in the characterization of thick materials. Indeed, the characterization of heterogeneous thick materials in general and those used in civil engineering in particular, infrared thermograph is a difficult problem. Attempts to implement this method have focused on the detection of insulation faults or water stains (Sakagami and Kubo, 2002), (Wu and Busse, 1998), Wiggenhauser, (2002). Despite the attraction that provide images of pseudo-temperature, stationary information considered by the passive methods, include personal issue of the target surface and the reflection of the surrounding environment. Those informations are difficult to use, because of the ignorance of the emissivity and environment disturbances.

Active thermography of thermally excited surface referred transient eliminates the effects of the environment (assumed stationary). These methods (Wu and Busse, 1998), Wiggenhauser (2002), (Hay *et al*., 2004), (Parker *et al.,* 1961), are widely used in the field of NDT of composite thin materials in the aerospace industry. In the building sector, the main difficulties of the transitional methods are related to the facts that the characteristic time of diffusion through thick walls are very long Wiggenhauser (2002), the power required to start is too large (Bjegovic *et al*., 2001), and that the heating engineer does not know how to maintain this energy constant for a short time. Contact methods, in turn, gave quite interesting laboratory results for relatively small thickness samples. By these methods, the thermo physical properties of the samples of materials used in civil engineering are fairly well known to constitute a database for users. However, no observation of these results compared to *in-situ* reality is not available.

To circumvent these difficulties, we propose in this work, a method that uses the power of the sun as energy source excitation. We used to estimate the characteristic response time of the west wall of a building (Napevomo) located on the Esplanade Arts and Crafts in Talence (Bordeaux). The approach is very informative and good prospects in the *in-situ* analysis of buildings. It is inexpensive and simple implementation.

MATERIALS AND METHODS

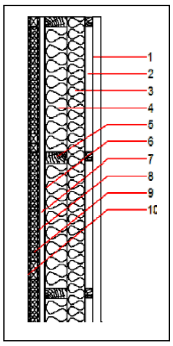
Materials

The wall that served as a basis for experimentation is the west wall Napevomo. It is a building that has participated in the first Solar Decathlon Europe in Madrid, where he won numerous awards for its technological innovations along the lines of sustainable development, while ensuring comfort conditions copies.

Said wall is structured as follows Table1.

Table 1. Composition of the west wall of Napevomo

N°	Description Material	Thickness[mm]	ρ [kg/m^3]	k [W /(m.K)]	C_P[J/(kg.K)]	μ
1	Maritime Pine Cladding	22	500	0.14	1500	35
2	Highlyventilated air space	40	-	-	-	1
3	Wood fiberboard	100	170	0.042	2100	5
4	IWoodfiberinsulation	120	55	0.038	2100	5
5	Pine frame maritime45/120 [between 600mm axis]	120	500	0.14	1500	35
6	Wood fiberboard	8	800	0.1	2100	60
7	Air blade unventilated [Blank Technology]	40	-	0.155	-	1
8	Gypsum panel cellulose	12.5	1125	0.36	1100	13
9	Raw land panel	40	1950	0.87	850	8
10	Gypsum panel cellulose	12.5	1125	0.36	1100	13



Methods

Experimental background

Among other difficulties encountered in the analysis of heavy materials in the laboratory or in situ, there is the substantial energy, necessary for the implementation of the methods. As part of this work, we take the energy output of the sun, used as the excitation source with the above device (Fig. 2).
The characteristics of the experimental context:

- the environment: the external and the internal environment
- the flow of excitation from the sun
- the measuring instrument is subject to variations in meteorological parameters (wind, sun, humidity, pressure, rain etc.).

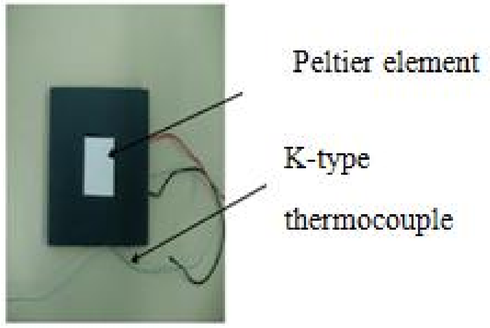


Figure 1. The components of the sensor measurements of temperature and flow

The process of our strategy is to measure the flow $\phi(t)$ and temperatures $T(t)$ at the inlet and outlet of the system over time.

Manipulations

We disposed outside and inside the wall, a sensor composed of a thermocouple and a Peltier element. The thermocouples are connected to the stabilized power supply (24.2 V LASCAR; adjustable) that converts the voltage signals with the aid of two amplifiers in temperature.

The Peltier elements are themselves connected to the stabilized power supply. All this set is connected to the datalogger which in turn is connected to the PC for recording data in real time (see Fig. 3) below.

1-The transmitter converter, 2-Device reset, 3-Element Peltier, 4-K-type thermocouple, 5-Stabilized power supply: 24.2 V Lascar, 6-PC, 7-Data acquisition: NATIONAL INSTRUMENTS NI USB INPUTS 8-6009 14-bit Multifunction I / O, 8-Resistance.

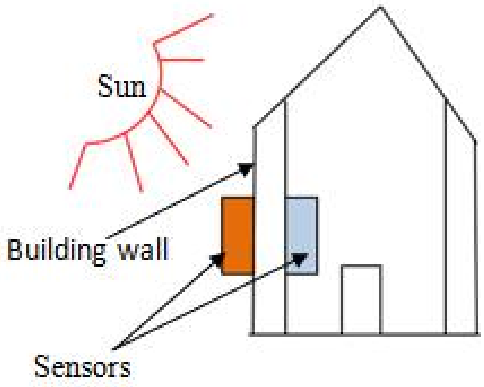


Figure 2. Measurement of temperature and flow on the west wall of the building Napevomo

Data Processing

A measurement campaign was conducted over five days. Data recording is done in steps of 10 s. In total, approximately fifty thousand (50,000) data is stored in a table with four columns including: changes in external and internal flows and changes in external and internal temperatures. After removal of some outliers, a Matlab program allowed to make average amplitude of 360 to obtain hourly data. Then, a cutting length section 24 was used to extract the daily values. Information on the thermal behaviour of the wall, for five days, is grouped in matrices of size 24x4 designated by $J_i (1 \leq i \leq 5)$.

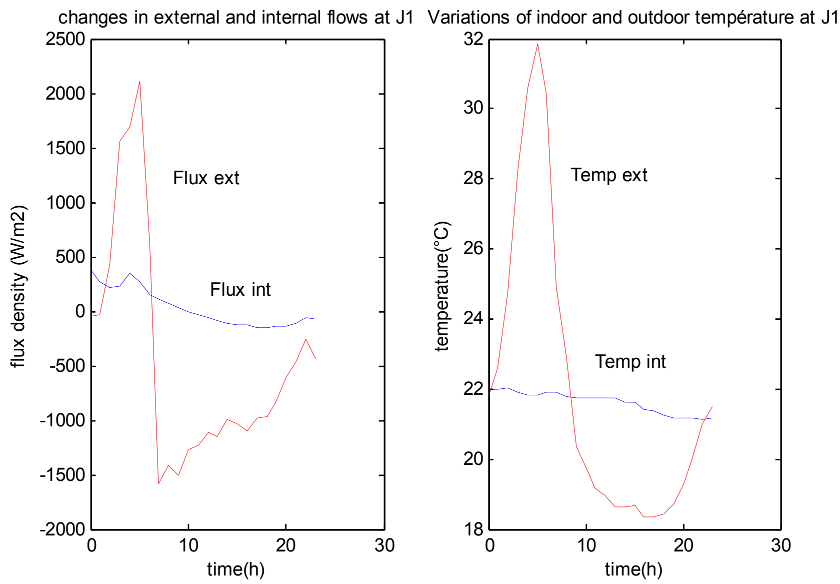


Figure 4a. The curves of variations: left flow; right temperature at J_1

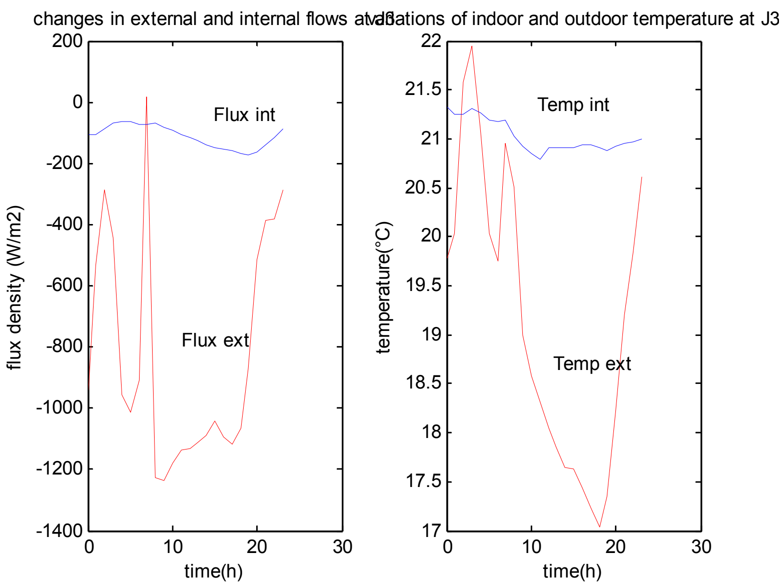


Figure 4b. The curves of variations: left flow; right temperature at J_3

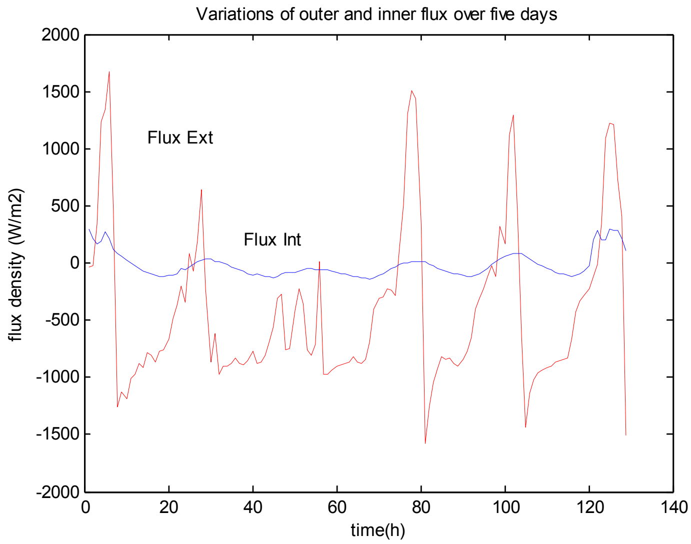


Figure 4c. Compilation of changes in external and internal flows

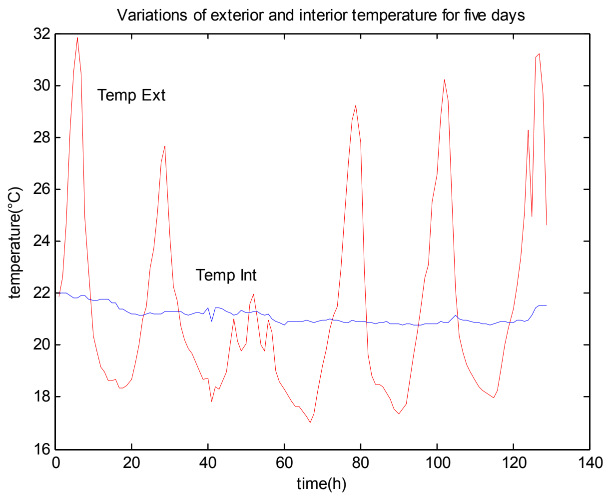


Figure 4d. Compilation of changes in outdoor and indoor temperature

Some curves from data formatting

We present here the curves for (J_1) and (J_3) and a compilation of five days (see Figs 4 a, b, c, d). On the third day(J_3), the curves are atypical because it was rain until late afternoon. This testifies to the loyalty of our equipment even sensitive to variations of the environment. For other days curves are similar to those of (J_1). External data are red. Changes in external data in red trace quite well the frequency of the alternating day / night for 24 hours. As for curves for internal observations (blue), they have not undergone major changes. The inner wall temperature was constant around 21°C while the flow oscillates around zero. We must remember that the measurements were made doors, windows and other issues solar closed and no internal energy source. In view of the large variations in the exterior, the interior light temperature fluctuations observed cannot be attributed to heat conduction through the wall. It is therefore logical to say no disturbance occurred outside had no effect inside the building. Moreover, it is relevant to say that the wall is ell insulated since amplitude of 32°C outside has not disturbed inside.

Thermal analysis of the wall is very complicated. It must take account of its thermal history when the analysis is done. But it also depends on the ebb and flow of control during the day. A gust of wind, a passing cloud or a sudden increase in solar activity can reverse for a time the flow direction. Before going further into the investigation, we will, in view of the data obtained, formulate hypotheses and the problem to solve.

Hypothesis and problematic

The observation of different previous curves suggest to the following points and assumptions (see Fig.5).

Assumptions

We measure

- an outside temperature $\left(T_{ext}(t)\right)$ on the wall, which oscillates between a minimum and maximum to a depth (d) within the thickness (e) of the wall. The oscillation occurs around a mean value $\left(T_{moy}\right)$. This measured temperature is therefore composed of a fluctuating part and a middle part, around which it oscillates

- one stream $(\phi_{ext}(t))$ entering through the outer wall of the west Napevomo building from solar activity and having the same structures as the temperature
- a substantially constant temperature of the inner wall $(T_{int}(t) = cst)$ and a virtually zero flow inside $(\phi_{int}(t) \cong 0)$.

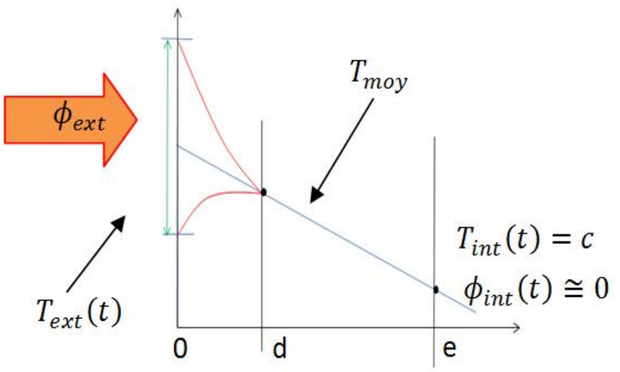


Figure 5. The components of the measured data

The sampling is $(\Delta t = 1h)$.The measurements are made on an interval $(t_{max} = 24h)$. We also assume that the fluctuating part is zero mean. The ebb and flow during a day, eventually canceled, so that any incident flux reaches a certain depth in relation to its frequency content without being disturbed.

Problematic

Can we analyze $(\phi_{ext}(t))$ and $(T_{ext}(t))$ together to extract the characteristic response time of the wall or other thermophysical parameters? To answer this question, it seems necessary to go further in the investigation by other specific data processing. Previous curves do not provide sufficient information on the contents of the thermal data recorded.

It is already worth noting that the wall consists of several layers and therefore the solutions to be made to his questions will necessarily on a uniform wall thickness equivalent to our multilayer wall. This development made, we will analyze the frequency content of the recorded data. For this, the time data flow and temperature are converted to frequency data by applying the Fast Fourier Transform (FFT).

In (Figs 6a and 6b) which follow, are presented, external modules, flux density and temperature, in relation to the harmonic rank to J_1. The curves being essentially symmetrical, they have been represented, without loss of information on a half-space.

Representations of modules of FFT data according to the rank of harmonics on a half-space

The curves of temperature and flow have the same shape. This indicates a certain stability of the wall, which seems to respond proportionately to any request, giving the ability to predict its response to a given stress. The temperature decrease is much more pronounced than that of the flow and seems to vanish from the sixth harmonic, showing an asymptote at zero. Wall tends to behave like a low-pass filter.

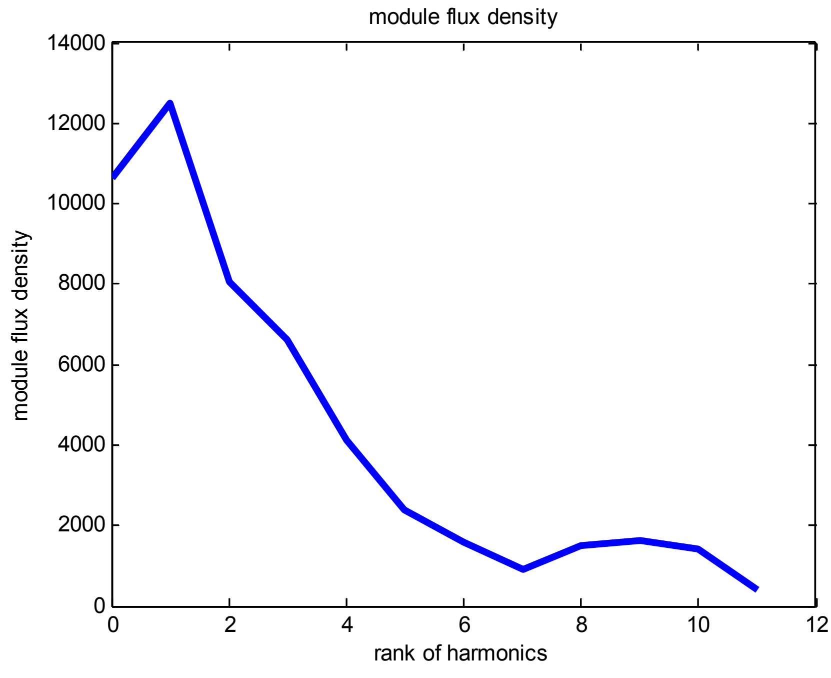


Figure 6a. Curve module flux density depending on the rank of harmonics at

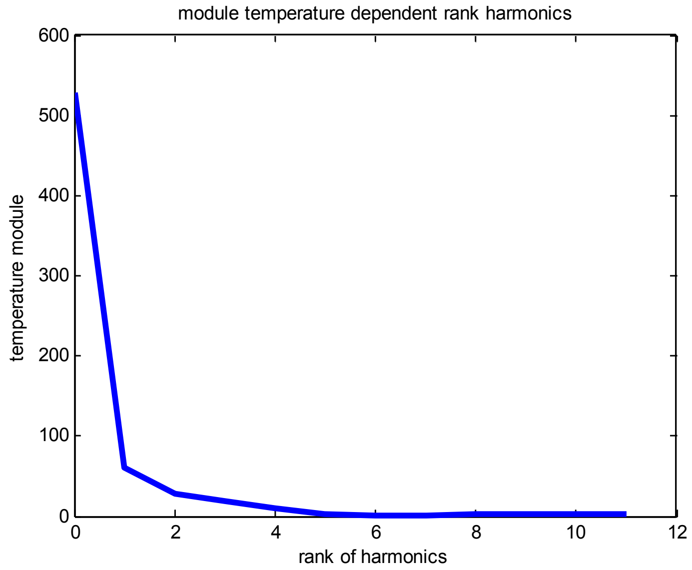


Figure 6b. Curve of the Temperature module depending on the rank of the harmonics at J_1

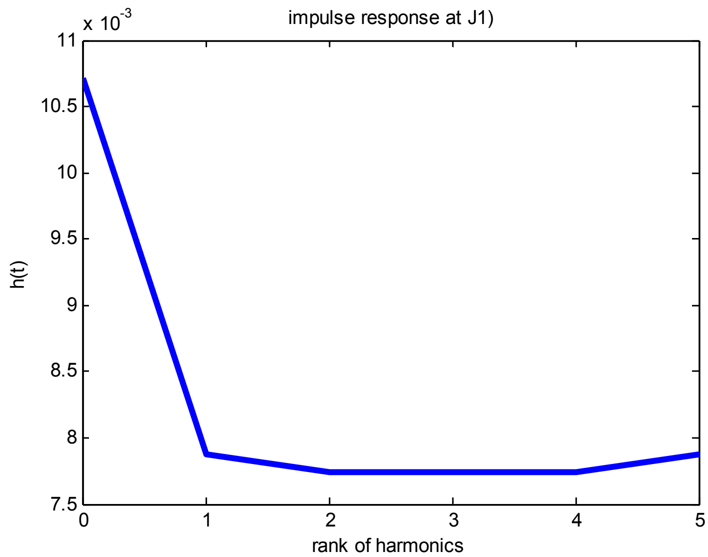


Figure 7a. Impulse of raw

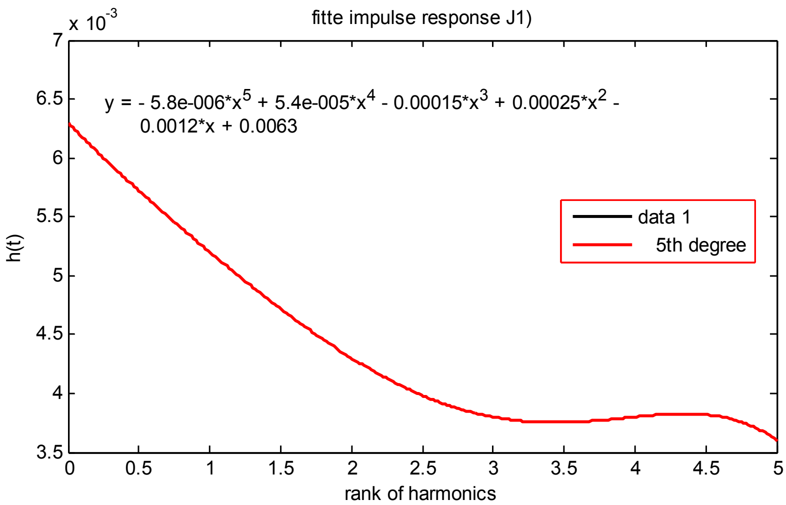


Figure 7b. Impulse response of fitting data

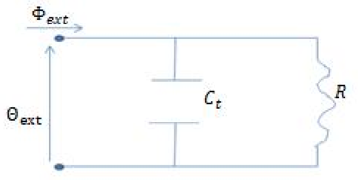


Figure 8. Schematic of the quadrupol wall

Study of the relationship between the Laplace transforms of temperature and flux density

To better understand the behavior of the wall, we examine in this section the report:

$\Theta_{\text{ext}}/\Phi_{ext} = A/C = Z$ .... (1)

The ratio (1) wherein (Θ_{ext}) and (Φ_{ext}) represents the Laplace transform of the temperature and the flux density respectively, is the impedance of the system formed by the layers of the wall. (See Equ: 3.37 page 73 of (Maillet *et al.*, 2000). The inverse Laplace transform of equation (1):

$\mathcal{L}^{-1}(\Theta_{\text{ext}}/\Phi_{ext}) = h(t)$ .... (2)

is the impulse response of the system. We examine below, the curve of the impulse response to understand the characteristics. The curve (Fig. 7a), is obtained from the raw data. The curve (Fig.7b) is derived from a light filtering (interpolation of the first raw data) we subsequently fitting (red curve).

It is remarkable in (Fig. 7a), more preferably in (fig. 7b), the curves decrease sharply. Furthermore, a fit of the equation is obtained and is in the form:

$y = -5.8.10^{-6}x^5 + 5.4.10^{-5}.x^4 - 0.00015.x^3 + 0.00025.x^2 - 0.0012.x + 0.0063$ .... (3)

which shows that the decay is exponential (approximately five degree (5)).We acknowledge (p. 14) (Maillet *et al.*, 2000) response characteristics front, solicitation front.

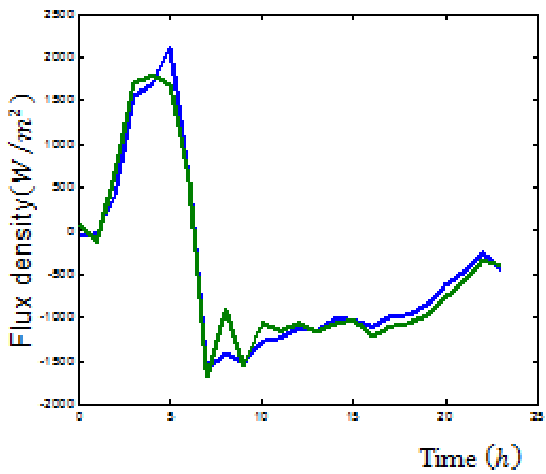


Figure 9a. Comparison of the flux density (blue) with the reconstituted flux density (green) for J1

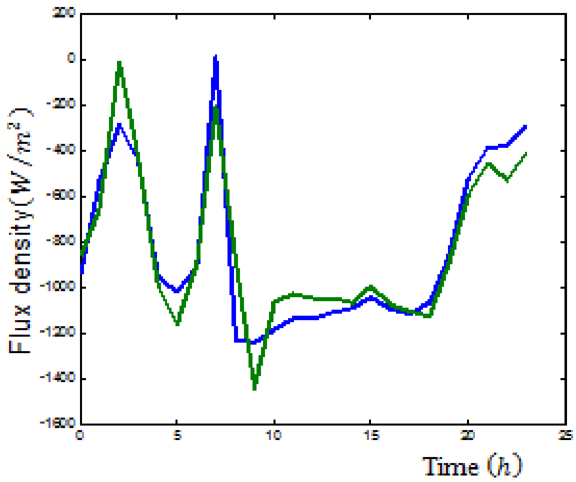


Figure 9b. Comparison of the flux density (blue) with the reconstituted flux density (green) for J3

Modeling and estimation of the wall characteristic response time

In view of the shape of the impulse response of the wall, together with the exponential decay of the temperature (fig. 7a), and by analogy to electrical circuits RC_t, we can model the impulse response in the time domain by:

$T_{ext}(t) = T_0 + Q/\rho cd\,.\exp(-t/RC_t)$ .... (4)

where in $Q(J/m^2)$ represents the density of the pulse energy; $R(m^2.K/W)$ the thermal resistance of the wall; $C_t(J/(m^2.K))$ its thermal capacity and $T_0(K)$ the minimum temperature.
Assimilating the wall to a homogeneous wall, we can write: $C_t = \rho cd$; $R = d/k$ where $\rho(kg/m^3)$ is the density; $c(J/kg.K)$ is the specific heat; $k(W/m.K)$ is the equivalent thermal conductivity and $d(m)$ the thickness reached.

Table 2. Estimated parameters of the vector component

Days	Dynamicstoragecapacity $\boldsymbol{C(Wh/m^2.K)}$	Reverse resistance $\boldsymbol{1/R\ (m^2.K/W)}$	Response Time $\boldsymbol{\tau = RC(h)}$
J1	27.75	13.67	2.03
J2	22.5	9.75	2.31
J3	32	8.25	3.88
J4	28.58	17.25	1.66
J5	25.83	13.75	1.88

Under these conditions, the quantity $\tau = RC_t$ is homogeneous with time, and called the time constant of the wall. Quadrupole representation of said wall being understood that the characteristic times are in the order of hours, is given (see pp. 78 -80) (Maillet *et al.*, 2000). The quadrupole pattern (Fig.8) can be translated by the relation:

$\Phi_{ext}(0,\omega) = j\omega.(\rho cd).\Theta_{ext}(0,\omega) + \Theta_{ext}(0,\omega)/R$ .... (5)

wherein (Φ_{ext}) and (Θ_{ext}) are the Laplace transforms of the flow and temperature.

The inverse Laplace transform of (5) is written:

$\phi_{ext}(t) = (\rho cd).dT_{ext}(t)/dt + T_{ext}(t)/R + cst$ .... (6)

For (N) observations of the couple (ϕ_{ext}, T_{ext}), we obtain the following system of equations:

$$\begin{bmatrix}\phi_{ext}(t_1)\\ \phi_{ext}(t_2)\\ \vdots \\ \phi_{ext}(t_N)\end{bmatrix} = \begin{bmatrix}\frac{dT_{ext}}{dt}(t_1) & T_{ext}(t_1) & 1\\ \frac{dT_{ext}}{dt}(t_2) & T_{ext}(t_2) & 1\\ \vdots & \vdots & \vdots\\ \frac{dT_{ext}}{dt}(t_N) & T_{ext}(t_N) & 1\end{bmatrix}\begin{bmatrix}\rho cd\\ \frac{1}{R}\\ Cst\end{bmatrix} \quad \text{..........} (7)$$

which can be put in a condensed form as:

$\boldsymbol{\phi = X\beta}$ .... (8)

where $(\boldsymbol{\phi})$ denotes the vector of observations of flux density; $(\boldsymbol{\beta})$ the vector of parameters to be estimated, and $(\boldsymbol{X})$ the sensitivity matrix to the vector $(\boldsymbol{\beta})$.

At this stage, when certain conditions are met (the exact value of the stream with a known error with mean zero and standard deviation constant i.e. there is no correlation between the (N) measures and $(\boldsymbol{X})$ without measurement noise), the Gauss-Markov (Beck and al. 1977) ensures an optimal estimator $(\boldsymbol{\beta})$ is provided by:

$\boldsymbol{\hat{\beta} = (X^T X)^{-1} X^T \phi}$ .... (9)

In our approach, our measurements are made by contact and independent of each other with a relatively long time $(10\ s)$, which allows us to implement equation (9). Parameter vector $(\boldsymbol{\hat{\beta}})$ is calculated for each of the five days of the measurement campaign, from the data of temperature and flux density measured. The results are shown in Table 2.

Commentary Table 2

On the first column of the table, we arranged the dynamic storage capacity of the wall, on the second reverse resistance relative to the number of layers of the wall requested by the incident flux and in the third, the time response characteristic of the incident flux, the most powerful of the day. We thus obtain an average time characteristic response $(2h\ 21\ mn)$or$(8460\ s)$. The method is interesting in the sense that, if applied to a relatively thick material which we know the thickness (e), it could allow estimating the diffusivity (a) (p. 2) (Hay and al., 2004) by the formula:

$\tau_c = e^2/a\sqrt{\pi}$ .... (10)

In the case of a heterogeneous material of known thickness, we could get the diffusivity of a homogeneous material equivalent, when it exists, of previous. For example, if we assume that the diffusivity of the wall is $(a = 10^{-6}\ m^2/s)$, this will mean that the thickness involved is approximately $(12\ cm)$. The method is still capable of other interpretations. Indeed, the third day of the measurement campaign (J_3) it rained all day until late afternoon. The sun has not appeared in the sky that day. The wall has had time to dump all the energy he had stored outward. However, an incident flux entering or leaving encounter the same resistance. Thus, the result of (J_3) can be interpreted as the flux passing through a certain thickness (d) in the wall which we have felt the effects that about four hours $(4h)$ after. Thus, compared to the previous example, our experience has allowed us to probe the wall to a depth of $(16\ cm)$.

Table 3. Sum of squares of standardized residues

	J1	J2	J3	J4	J5
$r\ \Vert\phi_e - \phi_{rec}\Vert_2/\Vert\phi_e\Vert_2$	0.033	0.048	0.027	0.027	0.033

For the validity of the method, it is necessary to prove its stability. We proved in Prodjinonto (211) (see p 146 -148) by comparing the flux reconstructed from the parameter $(\hat{\boldsymbol{\beta}})$ calculated and measured fluxes. We give the plots (figs 9a and 9b) of the first and third day of the measurement campaign organized. One can notice the margin of error due to the measurement sensors does not exceed 5%.

RESULTS AND DISCUSSION

We developed a simple method to estimate the response time of a thick material under the excitation power of the sun. From measurements of flux density and temperature on the wall of a building using a sensor composed of a Peltier element and a thermocouple, we estimated an average response time of the wall about $(2h\ 21\ mn)$ or $(8460\ s)$. With the knowledge of its thickness, it is possible to estimate its thermophysical properties. It remains to specify the conditions for a good estimate of the characteristic time.

Conclusions

We developed a simple method for characterization of thick materials. The excitation source is the sun. We had already obtained by this method, the dynamic storage capacity of the wall (Prodjinonto, 2013). We push a little further method by estimating here, its characteristic time response $(2h\ 21\ mn)$. Prospects are numerous, including the estimation of thermophysical properties (conductivity, diffusivity, effusivity) thick homogeneous materials. It remains to complete taking into account the weather conditions (wind, sun, rain etc.) in estimating these parameters. We believe that multiple regressions can be implemented to model the characteristic time depending on weather data. The model from the local weather conditions can be exploited in any corner of our planet as we now know a little more about the solar cycle (Balageas *et al*., 1991). Our future research will focus on this goal. With the implementation of an infrared camera, it is possible to do (NDT).

Indeed, the visualization of thermal contrast could help locate faults in a homogeneous material (Balageas and al. 1991), Gaussorgue (1999) or if the thermal properties are known a healthy part in comparison with those of a defective part (Mourand *et al*., 1997).

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