Diagnostic of insulated building walls of old restored constructions using active infrared thermography


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Abstract

In this study, an experimental protocol for the diagnostic of insulating building walls of old restored constructions is developed. Active infrared thermography in step heating mode is used to estimate thermal resistance of different commercial multi-layered panels. The influence of the heating measurement duration is investigated. Finally the combination of heat transfer modeling based on thermal quadrupoles and asymptotic approach with identification procedure leads to quite satisfactory estimated thermal resistance in most of the investigated cases.

1. Introduction

This work follows up the results of "PROTOMERES PARIS" project which was led by this consortium within the framework of PREBAT 2005 program. This project led to the establishment of a protocol of measurement of the total thermal resistance of insulated interior wall. The feasibility of this application in laboratory then in real site was proven on a particular case [1]. The present work aims to widen the methodology and the metrology for the diagnostic of old restored constructions. This work was carried out during the NADIIAH project with a financial support allowed by the ADEME (French Agency for Environment and Energy Saving). The restored old buildings whose energy performances remain poor are concerned with this research. This type of buildings accounts for 60% of the park of residences in France. This shows the importance to have a method of diagnosis considering the considerable number of concerned buildings. Infrared thermography is well-suited to this type of inspection because of its non destructive character.

2. Experimental set-up and measurement protocol

A test bench was set up in order to measure front and back sides temperatures of standard panels made up of 1cm of plaster and various thicknesses of insulating materials (expanded polystyrene, polyurethane foam, rock wool). In the present work, the panels are fixed on walls with an air gap of thickness equal to 1 cm. This allows performing laboratory experiments as close as possible to real situations. The front side of the panel is painted with standardized black coating (Nextel Velvet coating 811-21) of known emissivity (0.97). The panels considered in this study are presented in table 1 along with their properties (thermal conductivity $k$, thermal diffusivity $a$). The thermal resistance $R_M$ values reported in table 1 correspond to the computed theoretical values considering the thermal resistance of the first plaster layer ($R_1 = 0.01/0.25 = 0.04 \text{ m}^2\cdot\text{K}\cdot\text{W}^{-1}$), of the insulating layer $R_2$, of the air gap ($R_a = 0.15 \text{ m}^2\cdot\text{K}\cdot\text{W}^{-1}$ [2]) and of the concrete wall ($R_3 = 0.2 \text{ m}^2\cdot\text{K}\cdot\text{W}^{-1}$ [2]):

$$R_M = R_1 + R_2 + R_a + R_3$$

*Table 1. List of investigated insulating panels and some of their properties*

<table>
<thead>
<tr>
<th>Insulating material</th>
<th>Denomination</th>
<th>Insulating layer thickness (mm)</th>
<th>Number of experiments</th>
<th>$k$ (W.m$^{-1}$K$^{-1}$)</th>
<th>$a$ ($\times10^{-7}$ m$^2$.s$^{-1}$)</th>
<th>$R_M$ (m$^2$.K.W$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expanded Polystyrene</td>
<td>10+20</td>
<td>20</td>
<td>5</td>
<td>0.038</td>
<td>13.1</td>
<td>0.92</td>
</tr>
<tr>
<td></td>
<td>10+40</td>
<td>40</td>
<td>3</td>
<td>0.038</td>
<td>13.1</td>
<td>1.44</td>
</tr>
<tr>
<td></td>
<td>10+60</td>
<td>60</td>
<td>3</td>
<td>0.038</td>
<td>13.1</td>
<td>1.97</td>
</tr>
<tr>
<td></td>
<td>10+100</td>
<td>100</td>
<td>3</td>
<td>0.038</td>
<td>13.1</td>
<td>3.02</td>
</tr>
<tr>
<td>Rock wool</td>
<td>10+60RW</td>
<td>60</td>
<td>3</td>
<td>0.035</td>
<td>5.7</td>
<td>2.10</td>
</tr>
<tr>
<td>Polyurethane foam</td>
<td>10+60PU</td>
<td>60</td>
<td>3</td>
<td>0.023</td>
<td>5.5</td>
<td>3.00</td>
</tr>
</tbody>
</table>
The panels are heated using 24 DC halogen spots of 20 W each. A step heating excitation of duration equal to 5400 s was used for all experiments. A schematic description and a view of the experimental set-up are presented in figures 1 and 2. The experimental setup is controlled by a Labview program. A long wave infrared camera (FLIR A320G model) and thermocouples are used to carry out temperature measurements during the exposure phase and subsequent cooling. Particularly air temperature at front side of insulated wall is recorded.

3. Thermal modeling

One dimensional modeling based on thermal quadrupoles and Laplace transforms as well as an asymptotic simplified model were developed under Matlab environment. These models simulate a three-layered wall with an air gap between insulating layer and concrete.

3.1. Heat transfer modeling using quadrupole method

Figure 3 presents a schematic description of the wall structure considered in the thermal model. The heat power density $P_0$ absorbed by the heated face is considered as constant during the experiments. We also consider the global heat exchange coefficient $h_0$ on the front face of the wall as a constant. The heat exchange coefficient $h_e$ on the rear face of the wall is fixed to 10 W.m$^{-2}$.K$^{-1}$. We denote as $e_i$, $b_i$ ($b_i = k_i / \sqrt{\rho \alpha_i}$) and $\tau_i$ respectively the thickness, the thermal effusivity and the time constant of layer $i$, with $i = 1$ for plaster, $i = 2$ for insulating layer, $i = 3$ for concrete wall. The time constant $\tau_i$ of one layer is defined as: $\tau_i = e_i^2 / b_i$. The thermal resistance $R_i$ of one layer can be calculated using the thermal effusivity and time constant of the considered layer as follows:

$$R_i = \frac{\sqrt{\tau_i}}{b_i} \quad (2)$$

The thermal quadrupole method based on integral transforms is used to solve the heat transfer problem inside the multi-layered wall [3]. We assume that at initial time the system is in thermal balance ($T(t=0)=0$). A Laplace transform is applied to heat equation to link the temperature-heat flux density spectra $\theta_i$ and $\phi_i$ behind the concrete wall:

$$\begin{bmatrix} \theta_1 \\ \phi_1 \\ \theta_2 \\ \phi_2 \\ \theta_3 \\ \phi_3 \end{bmatrix} = \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \\ A_2 & B_2 \\ C_2 & D_2 \\ A_3 & B_3 \\ C_3 & D_3 \end{bmatrix} \begin{bmatrix} 1 & R_w \\ 0 & 1 \\ 1 & 1/h_e \end{bmatrix} \begin{bmatrix} \theta_1 \\ \phi_1 \\ \theta_2 \\ \phi_2 \\ \theta_3 \\ \phi_3 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} \theta_1 \\ \phi_1 \end{bmatrix} \quad (3)$$

where the matrix transfer coefficients $A_i$, $B_i$, $C_i$ and $D_i$ ($i=1, 2, 3$) are associated to a wall layer $i$ of thickness $e_i$ (see figure 3) and equal to (where $p$ is the Laplace variable):
Finally an inverse Laplace transform is performed numerically to return to the time domain by using the de Hoog algorithm [4].

\[ A_i = D_i = \cosh(\sqrt{\tau_i p}) \quad B_i = \frac{\sinh(\sqrt{\tau_i p})}{b\sqrt{\tau_i p}} \quad C_i = b\sqrt{\tau_i p} \sinh(\sqrt{\tau_i p}) \]  (4)

3.2. Air temperature variation

The variation of the air temperature at the front face of the insulated wall was measured using three thermocouples placed inside the air gap between the heating reflector and the front surface of the wall. As these temperature measurements are very noisy, and in order to take into account the variation of the air temperature into the thermal model, it is necessary to adjust thermocouple measurements using an empirical relationship. We chose to use the following expression:

\[ T(t) = A \left[ 1 - \exp(Bt) \operatorname{erfc}(\sqrt{Bt}) \right] \]  (5)

The Laplace transform of the preceding relationship is expressed as:

\[ \tilde{\theta}(p) = \frac{A\sqrt{B}}{p(\sqrt{B} + \sqrt{p})} \]  (6)

3.3. Simplified models – asymptotic approach

The use of simplified thermal model allows obtaining values of some \textit{a priori} unknown parameters of the quadrupole thermal model. The parameter values obtained can then be used either to fix some parameters as known parameters in the quadrupole thermal model or either to obtain initial values for parameters to be identified. In this study, we chose to use an asymptotic approach to obtain simplified thermal models.

If we consider only short measurement times or heating durations (<60s), we can consider that the wall behaves like a semi-infinite body. If we also neglect for the heat exchanges at the front face of the wall, we obtain the short-time simplified (asymptotic) model:

\[ T(t) = T(0) + \frac{2}{\sqrt{\pi}} \frac{P_0}{b_i} \sqrt{t} \]  (7)

Now, if we consider only long-time measurements (>1800s), we can state that the temperature evolution behaves according to the following relationship:

\[ T_\infty - T(t) = K \exp(-\lambda t) \Leftrightarrow \ln(T_\infty - T(t)) = \ln K - \lambda t \]  (8)
This relationship includes an interesting parameter, namely $T_\infty$, that describes the temperature which would be reached onto the heated surface after an infinite heating duration, that is to say in steady-state regime. A schematic description of heat exchanges in steady state conditions is presented in figure 4. The absorbed power density $P_0$ is divided into two non equal parts:

- a fraction of the heat absorbed is transferred by conduction inside the wall that can be now modeled by using only a global thermal resistance $R_M$;
- the other fraction is exchanged with the ambiance: this transfer can be modeled using a thermal resistance equal to $1/h_0$.

This simplified approach allows obtaining an estimation of the thermal resistance of the wall if both $P_0$ end $h_0$ parameters are known, according to the following relationship:

$$R_M = \frac{1}{h_0} \frac{T_\infty}{T_m - T_\infty} \text{ with } T_m = \frac{P_0}{R_0}$$ (9)

### 3.4. Identification procedure

As described before, the model contains several unknown parameters:

- the thermal effusivity and time constant of the two layers of the insulating panel (plaster, insulating material);
- the absorbed power density;
- the front face heat exchange coefficient.

The other parameters (properties of the concrete wall, thermal resistance of the air gap between the wall and the insulating panel, rear face heat exchange coefficient) were considered to be known and constant and their respective values were given in the preceding sections.

A sensitivity study has shown that all these parameters cannot be identified simultaneously due to some correlation existing between these parameters. Thus, it was necessary to fix the value of some of these parameters. First of all, the thermal effusivity of the insulating material ($b_2$) was fixed to the normalized value given by the manufacturer (see table 1). Indeed, in the final application of this work, the nature of the insulating material will be known. Besides, as presented in section 3.3, the short time asymptotic approach allows obtaining the value of the thermal effusivity ($b_1$) of the first layer (made of plaster). An estimation of this parameter using the short-time simplified heat transfer model was performed for each measurement and then the value obtained was fixed inside the identification procedure. Therefore, we obtain only four unknown parameters, namely $P_0$, $h_0$, $\tau_1$ and $\tau_2$.

The inverse problem is formulated in the least-squares sense and consists in finding the optimal solution that minimizes the functional:

$$S = \sum_{j=1}^{J} [T_{\text{meas},j} - T_{\text{estim},j}(\beta)]^2$$ (10)

where $T_{\text{meas}}$ are the measured temperatures, $T_{\text{estim}}$ are the estimated temperatures computed thanks to the heat transfer modeling presented in 3.1 by using $\beta$ vector constituted by the parameters to estimate, $J$ is the number of experimental data. $\beta$ vector is given by $\beta = [P_0 ; h_0 ; \tau_1 ; \tau_2]$. Minimization of $S$ is realized by using Levenberg-Marquardt algorithm [5] in order to estimate the components of $\beta$.

Reduced sensitivity coefficients corresponding to the four parameters to estimate are presented in figure 5. These parameters are not correlated but we observe that the sensitivity to the $\tau_2$ parameter is very small compared to the other parameters. The problem is that this parameter is the most important to obtain an accurate estimation of the thermal resistance of the insulating layer and consequently of the entire wall. Moreover, the low sensitivity of the thermal model to $\tau_2$ combined to the presence of measurement noise makes the estimation of this parameter strongly dependent to the initial value fixed in the identification algorithm. To overcome this problem, the initial value of $\tau_2$ was chosen equal to the value computed from long-time asymptotic thermal model.

### 4. Results

#### 4.1. Raw experimental data

An example of raw experimental data obtained for three different insulating panels is presented in figure 6 for three insulating panels containing 20, 40 and 100mm of expanded polystyrene. The surface temperature increases rapidly at the beginning of the experiment and tends to reach an asymptotic value at the end of the excitation period (5400s). During the
first 2000s of heating all curves are superimposed. It is necessary to use a heating duration of at least one hour to distinguish different insulation levels. The maximum increase of the temperature depends on the insulating layer thickness. Nevertheless, the difference of maximum temperature between two consecutive two panels is small: 2°C between 10+20 and 10+40 panels and only 1°C between 10+40 and 10+100 panels for a mean temperature variation of about 30°C. Thus, the key point to achieve an accurate estimation of the thermal resistance of a wall using this method is to be able to perform reproducible measurements. This can be achieved by using a stable heating source and a camera with very low temporal drift.

Figure 7 presents an example of air temperature evolution $\Delta T_{TC}$ near the heated wall surface. A comparison between thermocouple measurements and the model corresponding to equation (5) shows that this model can described adequately the air temperature evolution. Moreover, the maximum air temperature variation is about 5°C. So, this variation is significant enough to be considered in the thermal model.

4.2. Asymptotic analysis

The value of $P_0$ for short heating durations was obtained by a calibration procedure. This procedure consisted in replacing the panel by a material of known thermophysical properties and of the same emissivity. The plot of the temperature variation upon square root of time allows obtaining the value of $P_0/b_1$ and consequently, the $P_0$ value if $b_1$ is known. In this study, the short-time calibration was performed using a PVC plate of thermal effusivity $b_1 = 408$ W.s$^{1/2}$·m$^{-2}$·K$^{-1}$. The obtained $P_0$ value is equal to 207 W·m$^{-2}$. After this calibration step, it is now possible to obtain the value of the thermal effusivity of the first layer of each insulating panel by considering short-time temperature variations only. The obtained values for the different
panels used are varying between 374 and 486 W.m\(^{1/2}\).m\(^{-2}\).K\(^{-1}\) which is quite in agreement with the theoretical value of 435 W.m\(^{1/2}\).m\(^{-2}\).K\(^{-1}\).

Again, \(P_0\) and \(h_0\) for long time experiments were determined by using a calibration procedure. This procedure consisted in performing two independent measurements using two insulating panels: the first one with a small insulation layer thickness and the second one with a large insulation layer thickness. The obtained values of \(T_*\) parameter for these two measurements allowed computing values of \(P_0 = 189\) W.m\(^{-2}\) and \(h_0 = 6.28\) m\(^2\).K.W\(^{-1}\) for a measurement duration of 5400s and of \(P_0 = 184\) W.m\(^{-2}\) and \(h_0 = 6.15\) m\(^2\).K.W\(^{-1}\) for a measurement duration of 3600s. The plot of figure 8 shows the dependence of the parameter \(T_*\) as a function of the wall thermal resistance using the computed values of \(P_0\) and \(h_0\). Some experimental values are also presented in the figure as a comparison.

Figure 9 and 10 present the computed values of the wall thermal resistance for all experiments performed. Data obtained considering measurement durations of 3600 and 5400s are compared to theoretical values (see table 1). We can notice that this simplified modeling can give a first quite good approximation of the insulation level, excepted for some experiments (N°6 and 11 in figure 9 and 5 in figure 10). The obtained values considering measurement duration are in most cases closer to the theoretical value. We also recall that these values are used to compute initial values of parameter \(\tau_2\) in the identification procedure.

**Fig. 9.** Computed values of the wall thermal resistance using the asymptotic analysis (experiments corresponding to 10+20, 10+40 and 10+100 panels)

**Fig. 10.** Computed values of the wall thermal resistance using the asymptotic analysis (experiments corresponding to 10+60, 10+60PU and 10+60RW panels)

**Fig. 11.** Example of temperature residuals obtained after parameter identification (10+100 polystyrene panel)

**Fig. 12.** Comparison of measured temperature with estimated temperature (10+100 polystyrene panel)

### 4.3. Parameters estimation

The identification procedure described before was applied to analyse all experimental data. In table 2, an example of results obtained for polystyrene panels is shown. The temperature residuals obtained for 10+100 panel is presented in figure 11. A comparison of the experimental data and thermal model is also presented in figure 12. The amplitude of the
temperature residuals is varying between $\pm 0.2^\circ\text{C}$, which corresponds to the measurement noise level. However, we note that the camera temperature curve presents some temporal fluctuations that locally increase the temperature residuals.

Table 2. Values of identified parameters $P_0$, $h_0$, $\tau_1$ and $\tau_2$ for some polystyrene panels

<table>
<thead>
<tr>
<th>Insulated panel</th>
<th>$P_0$ ($\Delta P_0$) W.m$^{-2}$</th>
<th>$h_0$ ($\Delta h_0$) W.m$^{-2}$.K$^{-1}$</th>
<th>$\tau_1$ ($\Delta \tau_1$) s</th>
<th>$\tau_2$ ($\Delta \tau_2$) s</th>
</tr>
</thead>
<tbody>
<tr>
<td>10+20</td>
<td>296.7 (1.1)</td>
<td>10.1 (0.1)</td>
<td>274.1 (2.7)</td>
<td>414 (23)</td>
</tr>
<tr>
<td>10+40</td>
<td>269.6 (0.9)</td>
<td>9.0 (0.1)</td>
<td>277.7 (2.5)</td>
<td>1009 (34)</td>
</tr>
<tr>
<td>10+100</td>
<td>269.4 (1.0)</td>
<td>9.1 (0.1)</td>
<td>250.6 (2.2)</td>
<td>7498 (287)</td>
</tr>
</tbody>
</table>

4.4. Influence of heating measurement duration

The asymptotic analysis has shown that significant differences of thermal resistance estimations could be observed depending on the measurement duration considered. It is important for the final application of this work to optimize this measurement duration. We present on figures 13 and 14 the estimated values of the identified parameters ($P_0$, $h_0$, $\tau_1$ and $\tau_2$) upon measurement duration considered for the analysis in the case of a 10+100 panel. The relative uncertainties on the identified parameters presented in figure 15 decrease when measurement duration increases. We note that uncertainties on parameters $P_0$, $h_0$ and $\tau_1$ decreases rapidly to reach a minimum value for measurement duration of approximately 2000s. On the contrary, it is necessary to consider measurement duration of 5000s to obtain a relative uncertainty on the $\tau_2$ parameter lower than 10%. We recall here that this parameter is the more important for the computation of the wall thermal resistance. So, a measurement duration of approximately 5000s seems to be the minimum value to obtain an accurate estimation of the insulation level of a wall, in the case of a high insulation level.
4.5. Thermal resistance estimation

On the basis of preceding results, it is now possible to compute the thermal resistance of the insulated wall by combining equations (1) and (2). In figure 16 is presented the estimation of the wall thermal resistance as a function of measurement duration in the case of the use of a 10+100 panel. We can see again that an accurate value is obtained only for measurement duration of about 5000s. This result confirms the conclusions obtained from the temporal variation of relative uncertainties on identified parameters.

A summary of all wall thermal resistance estimations is presented in figure 17. In this figure, the relative error on the thermal resistance estimation is plotted as a function of the insulation level. The relative error on the estimation of the thermal resistance is bounded to ±20% for 90% (18/20) of the experiments performed.

![Fig. 17. Relative error on the thermal resistance estimation as a function of the insulation level](image)

5. Conclusions

This works highlights possibilities of active infrared thermography for the diagnostic of insulating building walls of old restored constructions. The obtain results for several commercial panels clearly demonstrate the accuracy of the method to estimate the thermal resistance of the investigated wall. The study of the influence of the heating measurement duration shows that duration of 5000s is required to obtain accurate estimation and to minimize uncertainties on identified parameters. The perspective of this work is to apply this diagnostic method in real conditions on existing walls.

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