Experimental works with new prototype for measuring thermal resistance of building walls.

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Abstract - This paper presents experimental works on thermal resistance estimation with real walls under controlled environment conditions. A new approach of measurement setup based on an active method was developed to improve the quality of measured data and to eliminate sensitive factors of estimation. Three different estimation models were applied in order to find out the thermal resistance of the studied wall (Internal Wall Insulation or IWI). According to final results, thermal resistance can be estimated around theoretical value with error less than 10%.

Keywords: Thermal resistance; inverse problem; building; active method; measurement.

Nomenclature

T	temperature, °C
Fab	absorbed flux, $\mathrm{W/m^2}$
b	thermal effusivity, $\mathrm{J.K^{-1}.m^{-2}.s^{-1/2}}$
h	internal heat transfer coefficient, $\mathrm{W/m^2.K}$
e	thickness, m
Greek symbols	
λ	thermal conductivity, $\mathrm{W/m.K}$
ρC_p	volumetric heat capacity, $\mathrm{J/K.m^3}$
τ	time constant, s
Index and exponent	
I	internal
E	external
a	air
S	surface of the wall
IWI	Internal Wall Insulation
GHB	Guarded Hot Box

1. Introduction

The thermal resistance is one of the physical parameters which allows qualifying building thermal insulation level. By considering the global objective about energy consumption, the thermal regulation requires a limit of this value for the construction of new buildings and the renovation of older ones. According to the French thermal regulation [1], the objective to be achieved is to have an energy consumption below 50kWh/m^2/year depending of the building localisation. Therefore, the need for a robust measurement method of the thermal resistance becomes more necessary. In this context, several methods and measurement techniques which can estimate this kind of parameter were developed [2, 3, 4, 5]. However, to avoid unwilling error during measurement, various conditions which may not be available all the time must be required. For this reason, some studies were started to examine these weaknesses in order to obtain a more robust measurement method for the thermal resistance. Being one of them, the RESBATI project (RESistance thermique de paroi des BATIments), which is granted by French

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National Research Agency (ANR), was launched. The project objective consists in developing an in-situ device based on an active method which works with any kind of walls at any moment of the year (winter or summer) and which requires short measurement duration in order to estimate the thermal resistance of the wall.

After validating estimation methods via numerical studies [6], several experimental tests were performed to validate the capability of the measurement device. Internal Wall Insulation (noted IWI) was chosen during this study because of its popularity in France and of its medium resistance and weak lateral effect of thermal diffusion. Different constant and varied environment conditions were tried by using climatic chambers at LNE and CEREMA. The proposed prototype in this study is based on active method which is carried on under different conditions¡ Then the thermal resistance will be calculated by solving inverse problem.

2. Presentation of estimation process

2.1. Estimation algorithms

During this study, three different estimation methods proposed by CSTB, IFSTTAR and CERTES were used. Each of them is based on different approach of heat transfer modelling. The details of all methods were presented in [6]. A representation of a wall by using RC circuit is used in model of CSTB (based on the ISABELE method [7]). This approach can be considered as a gray box method. The resistances and capacities are adjusted in order to maximize the likelihood function. The complete estimation process is done by using CTSM-R package [8]. In the IFSTTAR approach, one-dimensional heat transfer differential equation and finite element method are considered as direct model. The descent gradient and Tikhonov regularization [9] are used as main algorithm of parameter estimation. Instead of directly solving heat transfer equation in time space, CERTES proposed to apply the Laplace transform on the differential equation in order to obtain a linear quadrupoles relation. The Bayesian inference [10] is used in CERTES model to identify the thermal resistance.

2.2. Thermal resistance estimation procedure

Three measurement data are collected: the internal surface temperature T_{SI}, the external surface temperature T_{SE} and the net absorbed flux on the internal surface Fab_{SI}. Following numerical results in [6], it has been shown that the wall parameters are better estimated with IWI if we focus on T_{SI} instead of the two other measurement data.

Therefore, in this study, we consider T_{SE} and Fab_{SI} as inputs of the direct model then minimize the least-squares functional $S(\beta)$ of T_{SI} computed by the direct model with parameter vector β and measured (see equation 1) in order to obtain the estimated parameters:

$$S(\beta) = \sum_t \left(T_{SI}^{model}(t, \beta) - T_{SI}^{meas.}(t) \right)^2 \qquad (1)$$

Because each partner used different representations for heat transfer modelling in the wall, the estimated parameters are not the same. The Table 1 presents the parameters which are estimated by each partner.

Partner	Estimated parameters
CSTB	Equivalent thermal resistance R and heat capacity C for each layer (3 layers)
IFSTTAR	Thermal conductivity λ and volumetric heat capacity ρC_p for each layer (4 layers, the thickness e of each layer is fixed during the estimation)
CERTES	Thermal effusivity b and the time constant τ ($= e^2\rho C_p/\lambda$) for each layer (4 layers)

Table 1 : *Parameters of the wall estimated by each partner (more details in [6]) for all tests by minimization of equation (1).*

3. Presentation of experimental setup

3.1. Wall configuration

The investigated wall is an IWI wall of section 2x2 m^2 made by CSTB (see Figure 1). The Table 2 presents the characteristics of each layer. The thermal conductivity of second layer (Expanded Polystyrene Insulation or EPS) was measured by the Guarded Hot Plate (noted GHP) [11] at the average temperature of 10 °C at LNE. According to these values, the theoretical thermal resistance of the wall is 4.09 K.m^{2}W^{-1}. Several thermal sensors (thermocouples and heat flux meters) were installed inside each layer to observe internal variation of temperature and heat flux.

	Material	Thickness	Thermal conductivity	Thermal resistance
Unit		mm	mW.m^{-1}.K^{-1}	K.m^2.W^{-1}
Layer 1 (internal)	Plasterboard	13	250	0.05
Layer 2	EPS	118.7	30.8	3.85
Layer 3	Concrete	150	850	0.18
Layer 4 (external)	External coating	15	1300	0.01

Table 2 : *Physical characteristics of investigated IWI wall .*

3.2. Thermal excitation source

We used a lamp box for the thermal excitation of the wall. It was developed during a preceding project in CERTES [12] and modified in this new project. This box is made of wood and its inner faces are covered by a reflective film to homogenize heat flux leaving its open front face (see figure 2). This IWI wall was tested in different testing devices (Guarded Hot Box at CSTB, energy room called REBECCA at LNE and climatic chamber at CEREMA). This wall was trucked between different sites.

During sensitivity tests before running experiments, we found out that the heat transfer coefficient h_I has a very high sensitivity compared to others (see Figure 3). To highlight this effect, three estimations of the thermal resistance were ran with numerical data simulated by

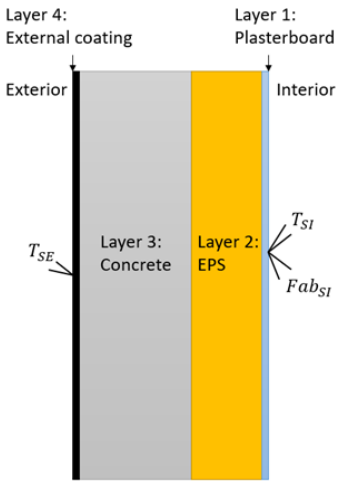

Figure 1 : *Presentation of tested IWI wall .*

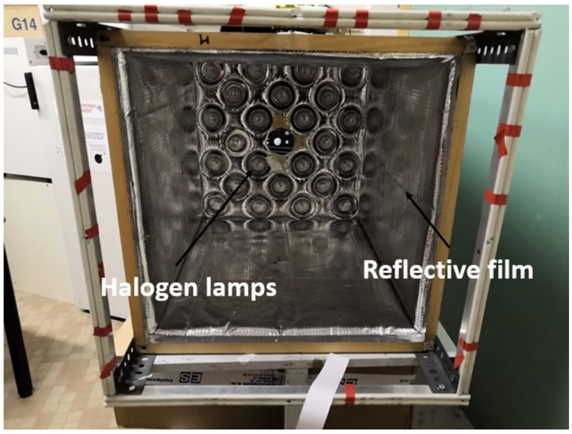

Figure 2 : *Lamp box used as heat excitation source .*

varying 1% of the h_I value. Shown in Figure 4, three results totally different were obtained with the CERTES estimation method. Therefore, to avoid the influence of this parameter, an aluminum plate was installed in front of the lamp box and allows us to measure directly the net absorbed heat flux Fab_{SI} which comes through the wall (see Figure 5). Hence, the coefficient h_I is removed in this configuration. This plate has to be in contact with the wall surface as much as possible [1]. Several thermocouples and heat flux meters are fixed on this plate by using a high conductive glue made of iron in order to verify its lateral homogeneity of thermal state. An insulation guard made of extruded polystyrene around the plate is required to avoid heat exchanges on its edges. The lamps heat the plate coated with a black paint and the heat flux passes through it to reach the wall surface. The complete configuration of the experimental setup is represented in figures 6 and 7. Several advantages can be listed by using this plate: simple and fast installation (5-10 minutes), high signal-to-noise ratio for measurement data, the internal heat transfer coefficient not included and better homogeneity for the thermal state applied on the heating zone.

3.3. Tests in climatic chambers

For controlling environment temperature effectively, two climatic chambers were used, one at LNE (REBECCA cell [13]) and another at CEREMA. For each chamber, several internal and external air temperature scenarios during 24 hours were programmed.

On one hand, due to the variation of thermal conductivity of materials as a function of operating temperature, three levels of constant temperature were used to verify the measurement capability of the prototype under different conditions (cases 1 to 8). On the other hand, four variable tests at CEREMA used true temperature records in France for external air (cases 9 to 12). For each case, we applied two different heating powers to study the influence of this parameter on estimation results. The complete schedule for the two chambers is shown in Table 3 and plotted in Figure 8.

[1] In fact, a thin air gap, which is not ventilated thanks to the insulation guard, located in the middle of the aluminium plate and wall surface should be taken into account because it is hardly to ensure a perfect physical contact between them. According to RT2012 [1], our non ventilated air gap (thickness<1 mm) has a thermal resistance of 0.04 $K.m^2/W$. In order to analyse correctly the thermal resistance of tested wall, this additional amount was removed from the estimated results presented in this study.

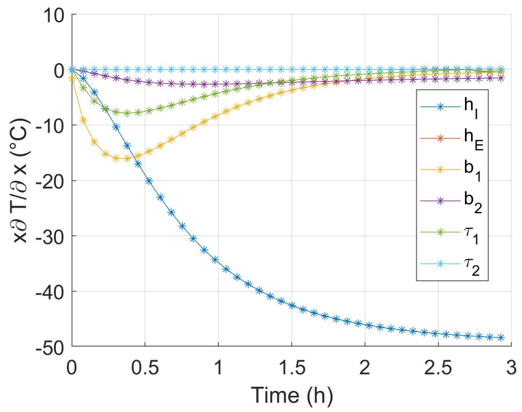

Figure 3 : *Reduced sensitivity coefficients of parameters: internal and external heat transfer coefficient h_I and h_E, thermal effusivity and time constant of first layer b_1,τ_1 and second layer b_2,τ_2, for T_{SI} computed by CERTES model.*

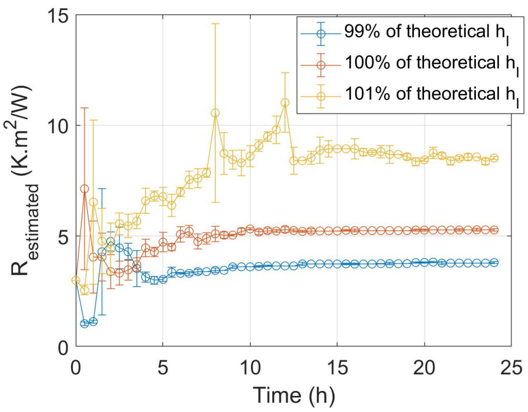

Figure 4 : *Different evolution of estimated thermal resistance by varying the internal heat transfer coefficient with the CERTES estimation method .*

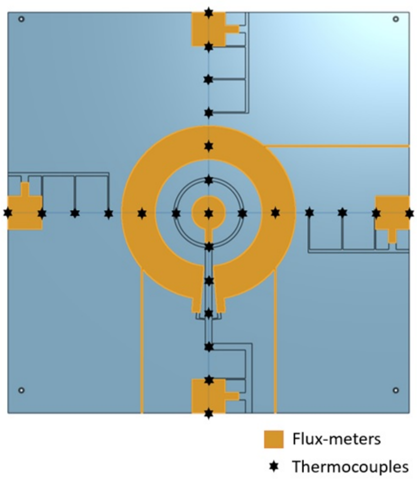

Figure 5 : *Aluminum plate face which is in contact with the building wall with integrated thermal sensors .*

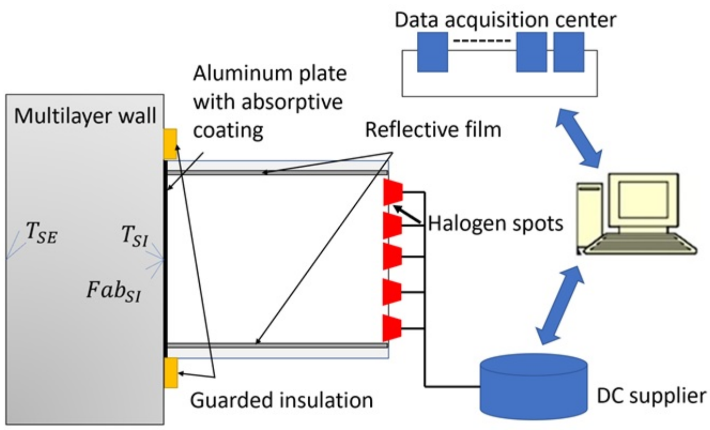

Figure 6 : *Schematic view of experimental setup*

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4. Results

4.1. Guarded Hot Box measurement at CSTB

The normalized method ISO 8990:1994 [5] was first tested to obtain a reference normative value of thermal resistance for the tested wall. We used the Guarded Hot Box (GHB) at CSTB for this measurement. Three levels of average temperature were applied: 10 °C, 20 °C and 30 °C. The result of this measurement will be used as a reference value for estimation comparison. However, the tests under ”Varied type 1” condition in climatic chamber have an average temperature around 15 °C. Then, to obtain a reference value for this case, we considered an average value between 10 °C and 20 °C GHB results. Table 4 presents the thermal resistances obtained at various operating temperatures and these results are used as reference values R_{ref}

Case no.	Test	Internal temperature T_{aI}	External temperature T_{aE}	Heat power	Regime
1/2	LNE 1/2	20°C	0°C	50% / 100%	c.
3/4	CEREMA 1/2	20°C	0°C	50% / 100%	c.
5/6	CEREMA 3/4	30°C	10°C	50% / 100%	c.
7/8	CEREMA 5/6	25°C	35°C	50% / 100%	c.
9/10	CEREMA 7/8	20°C	Varied type 1	50% / 100%	v.
11/12	CEREMA 9/10	20°C	Varied type 2	50% / 100%	v.

Table 3 : *Test schedules at the LNE and CEREMA with IWI wall under constant (c.) and variable (v.) environmental conditions (note that odd case numbers refer to half heating power whereas even case numbers refer to full heating power).*

for estimation. Note that the GHB provides the U-value of the wall and the measured superficial thermal resistances have been remove to obtain the thermal resistance of the wall.

Average temperature (°C)	Thermal resistance (K.m^2.W^{-1})	Uncertainty (K.m^2.W^{-1})
10	3.8	0.6
20	3.5	0.8
30	3.3	0.5
15*	3.65	–

Table 4 : *Guarded Hot Box measurement results (*: computed by averaging) with their uncertainties [5] .*

4.2. Estimation results for constant environmental conditions

The Figures 9 and 10 present the estimation results estimated by CSTB, IFSTTAR and CERTES, respectively after 6 hours and 12 hours of measurement. Here, the results are normalized by the reference value corresponding to each average temperature case.

The first eight cases were launched under constant conditions, we observe that we can estimate a quite good thermal resistance which stays within 5% and 10% zones of relative error between estimated and reference values after 6 hours of measurement in most of cases. Moreover, if we focus on the cases with odd numbers which use only 50% of maximal heat power, the results do not change much from 6 hours to 12 hours, except for case 7. We see the same tendency with the full power cases (even number cases). Only the case 2 shows a high variation between 6 and 12 hours but its estimated value stays in the same acceptable zone.

We must note that for cases 7 and 8, the constant heat flow is in opposite direction of the heating excitation because outdoor temperature (35 °C) is higher than indoor temperature (25 °C). The use of half power (case 7) seems not to be sufficient in this particular situation to obtain

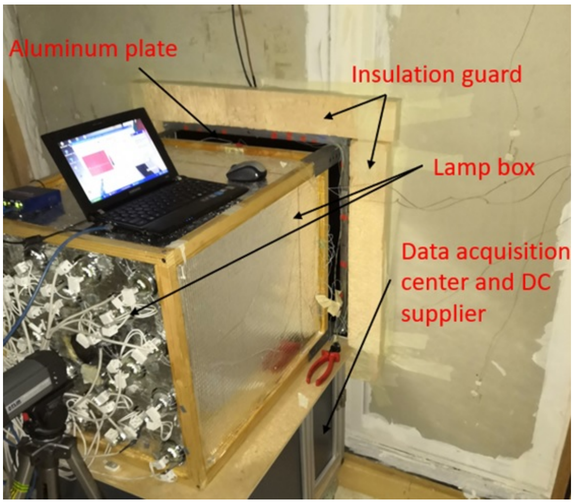

Figure 7 : *Real view of experimental setup in the climatic chamber of CEREMA .*

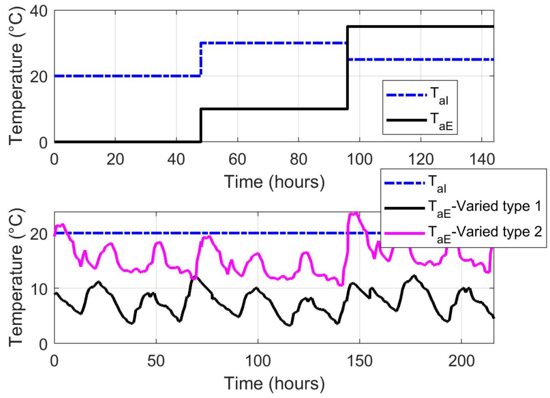

Figure 8 : *Constant and variable environmental conditions tested during measurement campaign.*

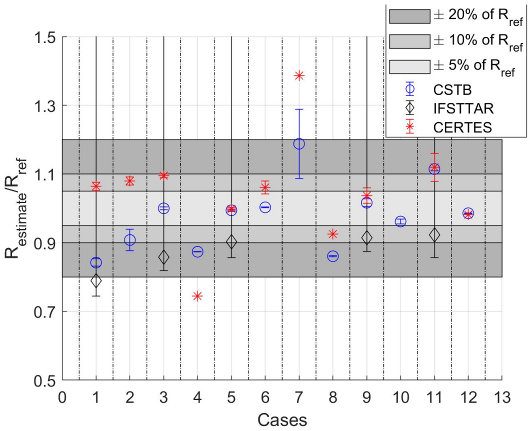

Figure 9 : *Estimated thermal resistance and its uncertainty obtained after 6 hours of measurement .*

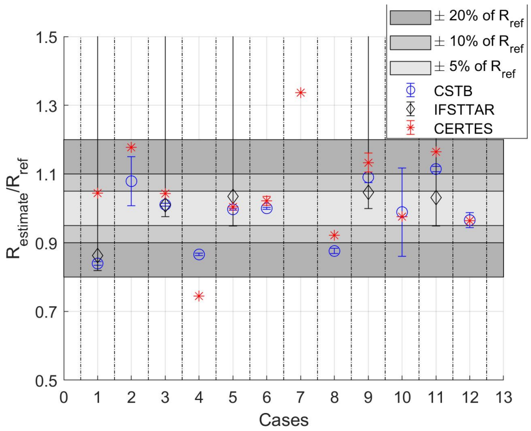

Figure 10 : *Estimated thermal resistance and its uncertainty obtained after 12 hours of measurement .*

a good estimation of the thermal resistance. The use of full power is preferable (case 8) here.

4.3. Estimation results for variable environmental conditions

The variable case results are presented in Figures 9 and 10 with cases 9 to 12. As observations of constant case, we obtain acceptable thermal resistance values with at least 6 hours of measurement. If we compare these cases in terms of applied heat power, the full power cases show better results than the half power ones. The explanation of constant 25 °C/35 °C test results also seems correct for these cases. The higher power supplies a strong enough flow in order to erase effects coming from variable outdoor condition.

To sum up, these results obtained by the three groups (CSTB, IFSTTAR and CERTES) showed that 6 hours of measurement are sufficient to obtain a high efficiency in thermal resistance estimation under real conditions. This is an important advantage in comparison to other existing measurement methods.

5. Conclusion

This experimental work was carried out in order to test the prototype developed in RESBATI project and to validate the estimation methods proposed by the project partners. We worked with a real wall in climatic chambers under constant and variable environmental conditions which were similar to outdoor conditions encountered in reality. According to the obtained results, we need at least 6-hour data measured by the proposed prototype, which is less than existing methods, to obtain a value of the thermal resistance of a real IWI wall very close to the one measured by the normalized method, whatever the environmental conditions. The next measurements concern two other walls (External Wall Insulation and Wood Frame Wall) in climatic chambers and a Single Wall of a building in the Sense-City equipment of IFSTTAR.

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