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Introduction to an In-situ Method for Rapid Measurement of the Walls' Thermal Resistance in Existing Buildings

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Abstract

Large deviations observed between the actual and theoretical gas consumption in Dutch dwellings, cast a shadow of doubt on the accuracy of the energy labeling method. In this sense, the accuracy of the calculation methods as well as the inputs being fed, fall under the question. According to several studies, the significance of wall's thermal resistance as one of the most sensitive inputs has become clear. From the lack of sufficient information regarding the exact construction of the existing walls, arises a necessity for in-situ measurements. However, such measurements are generally not being performed because the existing methods demand very long monitoring periods. In this research, a rapid transient in-situ thermal resistance measurement technique, Excitation Pulse Method (EPM), has been introduced, experimentally applied to a case study, and compared to the existing international standard method ISO 9869, showing a very good agreement. EPM is based on the theory of thermal response factors. It allows in-situ determination of the walls' thermal resistance and the average volumetric heating capacity in a couple of hours. The method is therefore believed to aid in better and much quicker estimation of the thermal resistance Rc-value of the walls, leading to more accurate energy labels.

Keywords – transient heat conduction; thermal resistance; response factors; energy labeling; in-situ measurement method

1. Introduction

Accounting for nearly 40% of total energy consumption in Europe, buildings can play a key role in its reduction [1]. As a consequence, the definition of building energy labels has become an obligation as a part of EPBD (Energy Performance of Building Directive). In the Netherlands,

ISSO publications [2, 3], developed as a part of EPBD, prescribe calculation methods leading to a theoretical value, predicting the gas and electricity consumptions. However, these values, defining the energy labels, have shown to be strongly deviating from the actual consumption [1, 4]. A deviation which is much larger in the buildings with poorer labels, where the energy consumption is highly overestimated (up to 50%). Majcen et al. [5], performing a sensitivity analysis, showed that the U-value of the walls is an extremely sensitive parameter in prediction of the heating demand. While the U-value in new buildings with generally known construction is a matter of calculation, in older buildings, it is an issue due to the lack of information regarding the construction type and the materials involved. The U-value of the walls in old buildings can therefore not be calculated, but is to be measured. However, because of the time and effort involved, such measurements generally do not take place. Instead, the Rc-values and therefore the U-values are suggested based on construction period [6]. Consequently, different walls built within the same period of time are assumed to have the same Rc-value, conveying a strong possibility of a very poor estimation taking place in such cases.

Today, according to the emphasis being laid on renovating existing buildings on an economically viable way, it seems important to estimate accurately enough the heat resistance of walls. New methods are demanded to aid in quicker and easier measurement of the Rc-value in unknown constructions, comprising an acceptable level of accuracy. The aim of this study is to introduce a fully transient in-situ method to be used in energy labeling, energy auditing, and building monitoring processes.

2. State-of-the-Art

As an alternative to implementation of numerical methods to solve the partial differential equations for the transient heat conduction, the Response Factors (RFs) method, developed by Mitalas and Stephenson [7] has been widely used since 1967. Practical applications came later and the principles of the RF method were first applied in 2008 in Spain in a lab by Sala et al. [8] and later by Martin et al. [9] using a hot box similar to [10]. Generally, the Rc-value measurement methods fall into two categories: in-situ and in-lab. For studies concerning existing buildings, in-lab methods are of no interest. The most well-known in-situ method for determination of the Rc-value is the heat flow meter method introduced in the international standard ISO 9869 [11] and the American standard ASTM 1145 and 1046 [12, 13]. This method demands a very long measurement period [14] (up to more than 2 weeks), an obstacle for applying it during energy labeling inspections. Even though in terms of time, the standard method is dramatically inefficient, its merit as being applicable on site, has been illustrated in many studies. The advantage of such measurements to calculation methods based

on thermal properties is shown by the differences found between actual and theoretical Rc-values [14-18]. To solve the problem of the long time demand, other methods are proposed such as IR thermography [19] which involves a variety of limitations.

3. Methodology

When employing the ISO9869 or ASTM standards for Rc-value measurement [11-13], in case of insufficient information regarding thermo-physical properties of the wall, the application becomes problematic. This is because, the corrections, as well as termination criteria strongly depend on properties such as specific heat capacity. Therefore, these methods suggest sampling of the materials [20], which is generally not allowed by the occupants during the energy labeling inspections. Moreover, depending on weather circumstances, extremely long monitoring periods may become necessary. The current paper presents a fully transient method, Excitation Pulse Method, EPM, by which the Rc-value of a wall can be measured in a few hours. Accordingly, the concept of this method can be appropriate for energy labeling procedures.

In the EPM, one side of the wall is exposed to a triangular surface temperature pulse. RFs are defined based on the heat flux profiles formed on two surfaces of a wall, as a response to this triangular pulse and are measured. According to the RF theory, the RFs are also calculable as a function of walls' thermo-physical properties and sample time interval. Once the RFs are calculated, the transient heat flux can always be calculated at each moment, as a function of the temperature history, using the following set of equations:

$$\begin{cases} \dot{q}_1 = \begin{bmatrix} T_1^t & \dots & T_1^{t-n} \end{bmatrix} \begin{bmatrix} X_0 \\ \vdots \\ X_n \end{bmatrix} - \begin{bmatrix} T_2^t & \dots & T_2^{t-n} \end{bmatrix} \begin{bmatrix} Y_0 \\ \vdots \\ Y_n \end{bmatrix} = \sum_{i=0}^{\infty} X_i T_1^{t-i} - \sum_{i=0}^{\infty} Y_i T_2^{t-i} \\ \dot{q}_2 = \begin{bmatrix} T_1^t & \dots & T_1^{t-n} \end{bmatrix} \begin{bmatrix} Y_0 \\ \vdots \\ Y_n \end{bmatrix} - \begin{bmatrix} T_2^t & \dots & T_2^{t-n} \end{bmatrix} \begin{bmatrix} X_0 \\ \vdots \\ X_n \end{bmatrix} = \sum_{i=0}^{\infty} Y_i T_1^{t-i} - \sum_{i=0}^{\infty} X_i T_2^{t-i} \end{cases} \quad (1)$$

Where \dot{q}_1 and \dot{q}_2 are the heat fluxes, and X and Y are the RFs for interior and exterior sides of the wall respectively. Indices t and i are time and RF number respectively.

In simulation methods, the heat flux is calculated from the RFs that are calculated from the thermo-physical properties of the wall (Equation 1). In

the EPM, the order is reversed and the heat flux resulting from the temperature excitation are measured, leading to the RFs, in turn leading to the thermo-physical properties.

On one hand, in principle, the RFs are originally defined for a pulse with a magnitude of 1 K. On one hand, when it comes to practice, the noise level and the fluctuations on a wall's surface are far beyond this value. On the other hand, the RF method is based on Laplace transform [21], allowing superposition principle [7]. Therefore, in EPM, the triangle is generated with an amplitude much greater than 1K. This feature is beneficial in terms of allowing omission of temperature/heat flux noise, sufficient heat penetration, and ease of application and control. The magnitude of the triangle should be such that it would not cause any damage to the finishing of the wall. According to the superposition principle, the heat flux responses are translated to RFs, dividing them by the magnitude of the triangle, as following:

$$\begin{cases} X_i = \dot{q}_1 / \delta \\ Y_i = \dot{q}_2 / \delta \end{cases} \quad (2)$$

Where X and Y are the RFs and δ is the magnitude of the excitation pulse. An experimental set up is designed to test the method in practice on a building's wall. In Fig. 1, the apparatus and the application process of the method is depicted. As seen in this figure, a triangular surface temperature pulse is formed on the wall by exposing the wall to a certain profile of heat flux, leading to the wall's RFs.

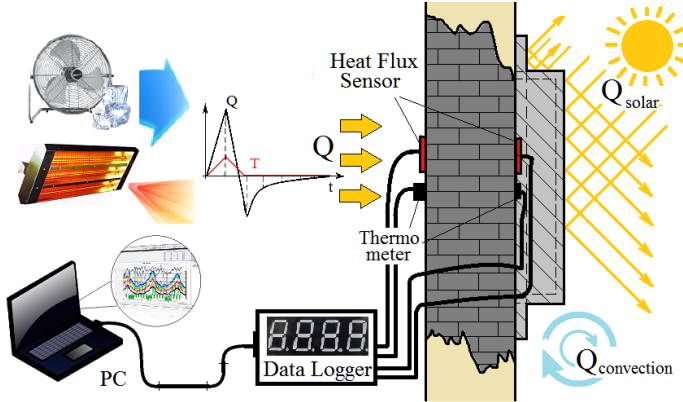


Fig. 1 EPM experimental set up: linear heating and cooling by radiation and convection respectively, making a triangular surface temperature pulse on the wall. Meanwhile, the data gathered from the measurements are stored in the data logger

The Rc-value measurement by EPM takes place in a form of a test. The test is applied in the 10 following main steps:

- 1- A proper test area of the wall is allocated by IR thermography. The area should have a constant, homogeneous temperature profile.
- 2- Two T-type thermocouples and two heat flux meters (EKO MF-180) are mounted on two sides of the wall opposite to each other. Meanwhile, the data from these sensors are gathered, converted, and stored in a data logger unit.
- 3- An insulating box is mounted on the exterior surface of the wall to avoid the fluctuations caused by solar radiation and air flow convection from being included in the heat flux and temperature measurements on the exterior surface of the wall.
- 4- A pre-defined triangular temperature profile as a function of time is prepared for control-feedback process of the exerting heat flux.
- 5- An IR radiative heater is held in front of the wall to exert variable heat flow to the surface. The distance between the heater and the surface of the wall is continuously adapted in such a way that its temperature is raised linearly up according to the pre-defined triangle's amplitude (δ).
- 6- Right after reaching the maximum temperature, the distance is again continuously adapted in such a way that the surface temperature of the wall is linearly decreased according to the pre-defined triangle profile.
- 7- At the moment that the temperature stops decreasing, a cooling fan with variable air flow is used in combination with ice bags to continue reducing the temperature according to the predefined linear profile.
- 8- At the end, when the triangle reaches its initial level (zero of the pulse), cooling is continued to keep the pulse at zero level.
- 9- After a few time intervals (5 to 6 intervals), the test may stop.
- 10- The data being processed, the RFs derived from (2) lead to the equivalent Rc-value of the wall using the following equation:

$$Rc = 2 \times \left(\sum_{i=0}^n (X_i + Y_i) \right)^{-1} \quad (3)$$

Where X and Y are the thermal RFs obtained from the heat flux measurements on two surfaces of the slab. With the thickness of the wall, the average thermal conductivity is obtained. Thereafter, by solving the original RF set of equations [7] for the Volumetric Heat Capacity (VHC), it should be possible to determine the wall's other properties such as thermal mass,

thermal inertia, and thermal diffusivity. Note that all the thermo-physical properties obtained are defined for an equivalent homogeneous wall, exactly as does the ISO [11] and ASTM [12, 13] methods for the Rc-values. Thanks to the large magnitude of the excitation pulse, the heat penetrates much faster than the conventional methods and therefore, the duration of the measurement is reduced to a few hours. The time interval is arbitrary, around 15-30 minutes, depending on the construction.

The Rc-value measurement method EPM is validated based on the “Average Method” by the international standard ISO 9869 [11], in which the cumulative Rc-value is calculated using the following definition:

$$Rc = \sum_{t=1}^n \Delta T_t / \sum_{t=1}^n \dot{q}_t \quad (4)$$

Where ΔT_t is the temperature gradient along the two sides of the wall at time interval t and \dot{q}_t is the heat flux in the direction of temperature gradient. As suggested by the ISO 9869 [11], the insulating box is mounted on the exterior surface in order to protect it from solar radiation.

4. Results

EPM has been applied to a case study wall of 27 cm thickness, located in Delft. The energy label of the house is F, and the construction year is 1680. In Fig.2, the case study and in Fig 3, the results of the EPM measurement are presented.



Fig. 2 Case study - The whole building (left), the inside surface of the wall (middle), and the outside surface and sensors covered by the box (right). Delft, Nov 2014

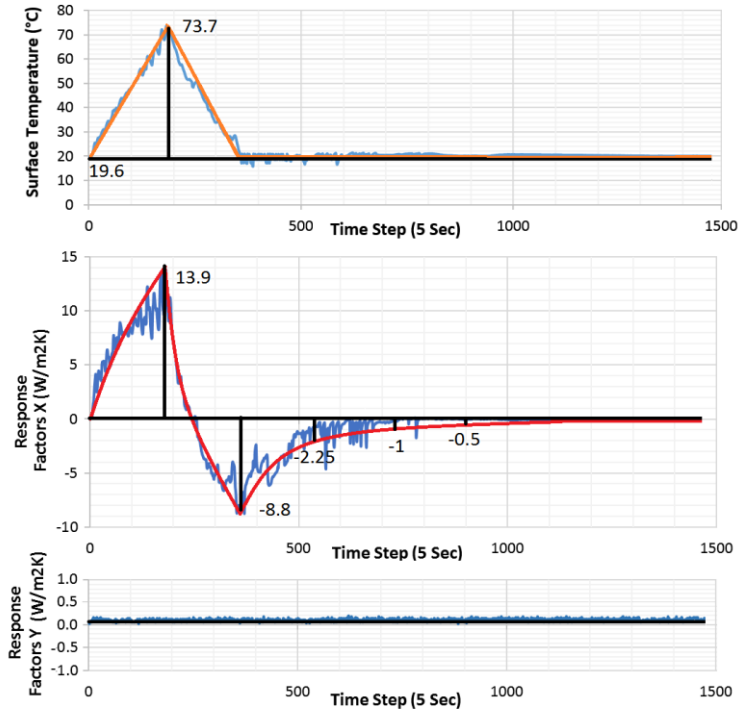


Fig. 3 The RFs and the excitation pulse obtained from the in-situ measurements

The magnitude of the pulse is 54 K and the heat fluxes from both sides are divided by this value. The results of the RF measurements are summarized in table 1:

Table 1 Measured RFs by performing EPM

RF/RF#	0	1	2	3	4	5
X	13.9	-8.8	-2.25	-1	-0.5	-0.1
Y	0	0	0	0	0	0

Note that the Y factors are stated zero here because they are extremely small in the order of magnitude in which the sum of the RFs are affected. The Rc-value based on RFs obtained by EPM measurements is calculated as follows:

$$Rc = 2 \times \left(\sum_{i=0}^n (X_i + Y_i) \right)^{-1} = \frac{2}{1.25} \cong 1.6 \text{ (m}^2\text{KW}^{-1}\text{)} \quad (5)$$

The result of the measurements carried out based on the Average Method according to ISO 9869 is presented in Fig. 3:

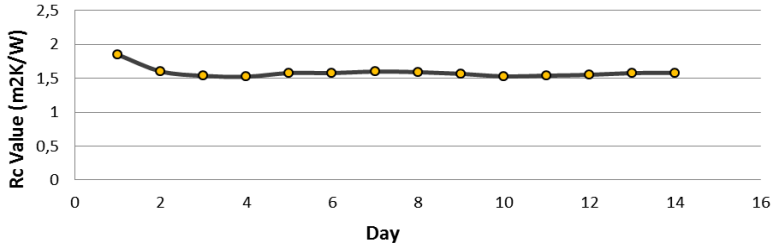


Fig. 4 Results of the cumulative Rc-values by measurement based on ISO 9869

As seen in Fig. 3, comprising the termination criteria of ISO 9869, the cumulative Rc-value obtained by the method based on ISO 9869 converges to $1.57 \text{ m}^2\text{KW}^{-1}$.

$$Rc \cong 1.57 \text{ (m}^2\text{KW}^{-1}\text{)} \quad (6)$$

The results of the validation are presented in Table 2:

Table 2 Results of the validation of EPM by the method based on ISO 9869

Method	Duration	Rc-value	Difference
EPM	2 hours	$1.60 \text{ m}^2\text{KW}^{-1}$	+2.0%
ISO 9869	14 Days	$1.57 \text{ m}^2\text{KW}^{-1}$	-

As seen in Table 2, the results of the Rc-value obtained by EPM show a good agreement in validation based on ISO 9869. In Table3, the Rc value obtained by EPM is compared to the standard value used in the energy labeling method(ISO publications). In the energy labeling method, the standard Rc-value of the studied wall is assumed to be $0.19 \text{ m}^2\text{KW}^{-1}$. The U-value overestimation as a consequence of not measuring the Rc, but taking a standard value is shown in Table 3, showing an overestimation of almost

400%. This is due to the fact that the actual construction may be far different than what is assumed.

Table 3 Comparison between Rc-values and U-values by two methods EPM, and ISSO (energy labeling)

Method	Rc-value	Difference	U-value	Difference
Measured (EPM)	1.60 m^2KW^{-1}	-	0.56 $\text{Wm}^{-2}\text{K}^{-1}$	-
Standard (ISSO)	0.19 m^2KW^{-1}	-88%	2.76 $\text{Wm}^{-2}\text{K}^{-1}$	+393%

5. Conclusion

An in-situ measurement method was developed and studied on a case study to investigate its feasibility in building energy labelling and energy auditing practices. While there is a definite need for improvements, the concept shows to be working well enough to be further studied. Since the first case study, two additional test on different walls were performed, showing similar results. A potential is seen in this method to be further validated both in terms of accuracy and precision. Both in-lab and in-situ validations are to take place. Development of a more elaborated prototype is recommended for further investigations in numerous samples with a range of different properties.

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