Energy and Buildings 119 (2016) 51–61

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

A response factor-based method for the rapid *in-situ* determination of wall's thermal resistance in existing buildings

Arash Rasooli [a,*], Laure Itard [a], Carlos Infante Ferreira [b]

[a] OTB, Delft University of Technology, Julianalaan 134, 2628 BL Delft, The Netherlands
[b] P&E, Delft University of Technology, Leeghwaterstraat 39, 2628 CB Delft, The Netherlands

ARTICLE INFO

Article history:
Received 22 October 2015
Received in revised form 3 March 2016
Accepted 4 March 2016
Available online 7 March 2016

Keywords:
In-situ measurement
Thermal resistance Rc-value
Thermal transmittance *U*-value
Response factors
Transient method
Energy labeling

ABSTRACT

The *in-situ* estimation of the thermal resistance (Rc-value) of walls in buildings is of major significance to determine their energy performance. The exact construction of walls is generally unknown, especially in older buildings, making the estimation of the Rc-value inaccurate. *In-situ* measurement is generally not being performed because, for the current standard method (ISO 9869), generally a measurement period of more than ten days is required. In the present paper, a new transient *in-situ* measurement method (Excitation Pulse Method, EPM) based on the theory of response factors is derived, applied experimentally on three walls, showing that it is possible to measure the Rc-value within less than 2 h. The results are compared to the ones obtained by ISO 9869 method, showing a good agreement. Additionnally, EPM measurement technique can provide the average Volumetric Heat Capacity and thermal conductivity. It is also shown that the ISO 9869 method can be easily improved by using an additional heat flux meter. EPM is believed to make a significant contribution to the quick and accurate estimation of the thermal resistance in unknown constructions and therefore to the accuracy of the prediction of energy consumption in buildings.

1. Introduction

The building stock in the European Union accounts for nearly 40% of total EU energy consumption [1]. In accordance with the EPBD (Energy Performance of Building Directive), it is mandatory for all European countries to define Energy Labels for buildings. In The Netherlands, such energy labels are based on calculation methods described in ISSO 82.3 [2], developed as a part of EPBD, leading to a theoretical value of gas and electricity consumption. Referring to studies by Majcen et al. [1], and Ioannou and Itard [3], it turns out that the actual energy consumption for heating, strongly deviates from the predicted values. The poorer the energy label, the worse is the prediction. Generally, poorer energy labels are given to the older buildings with poor insulation in which the heating energy consumption is shown to be strongly overestimated (up to 50%). In a sensitivity analysis carried out by Majcen et al. [4], it was illustrated that one of the very sensitive parameters in predicting energy consumption is the *U*-value of the walls. Even slight changes in the *U*-value result in considerable changes in heating demand [1].

It is much more difficult to estimate the *U*-values in old buildings than in new ones. In the newer buildings, the wall construction is generally known whereas in old ones, it is often impossible to know even if an insulation layer is present or not.

In The Netherlands, the *U*-value and the Rc-value of the walls are seldom measured but rather estimated following the descriptions available in [2], based on calculations and procedures in [5] which suggests thermal resistances for different types of construction materials. However, in old buildings, the construction and the material of the walls are often unknown. Hence, the procedure will lead the inspector to use Rc-values based on the year of the construction, tabulated in [6]. Accordingly, it is very well possible that this method currently used for several years leads to a very poor estimation of the thermal transmittance in old buildings with unknown construction. The valid measurement techniques available today for *in-situ* Rc-value measurement include the international standard ISO 9869 [7] and the American standard ASTM [8,9]. These methods require long periods of measurement (up to 2 or more weeks) which is obviously an obstacle to making measurements. Hence, new methods are required to measure the Rc-value of unknown constructions on-site with a good level of accuracy in a short time. The topic of this research has become so far crucial that the International Energy Agency's program Energy in Buildings and Communities (EBC) has dedicated the ongoing (2011–2015) project

* Corresponding author.
E-mail addresses: A.Rasooli@tudelft.nl (A. Rasooli), L.C.M.Itard@tudelft.nl (L. Itard), C.A.InfanteFerreira@tudelft.nl (C.I. Ferreira).

http://dx.doi.org/10.1016/j.enbuild.2016.03.009
0378-7788/

Nomenclature

Symbols

k	Thermal conductivity ($Wm^{-1}K^{-1}$)
l	Wall thickness (m)
$\dot{q}$	Heat flux (Wm^{-2})
Rc	Conductive thermal resistance (m^2KW^{-1})
T	Temperature (K)
t	Time (s)
X	Response factor at excitation side ($Wm^{-2}K^{-1}$)
Y	Response factor at the other side of excitation pulse ($Wm^{-2}K^{-1}$)

Greek letters

Δ	Difference
δ	Magnitude of the triangular excitation signal

Indices

i	Response factor number
n	n^{th} response factor
ss	Steady state
w	Wall

Abbreviations

EPM	Excitation Pulse Method
RF	Response Factor ($Wm^{-2}K^{-1}$)
VHC	Volumetric Heat Capacity ($Jm^{-3}K^{-1}$)

"Annex 58" to "Reliable building energy performance characterization based on full scale dynamic measurements" [10].

In this paper, a transient method is presented for *in-situ* measurement of the thermo-physical properties of the walls including thermal resistance. The method is based on the principles of the thermal response factors (RFs) method by Mitalas and Stephenson [11].

In Section 2, a state-of-the-art about relevant measurement techniques is presented. Section 3 describes the theoretical part of the method, the experimental set up is introduced in Section 4, and in Section 5 the results of the measurements are analyzed. Conclusions and recommendations are drawn in Section 6.

2. State-of-the-art

In principle, the Rc-value of an existing building component can be obtained by applying the standard method of measuring the heat flow rate on one side and the temperatures on both sides of the element under steady state conditions. However, since static conditions are never achieved on site in practice, other approaches are necessary to overcome this issue.

2.1. Lab methods

The use of steady state methods such as application of hot-box apparatus [12] in labs and transient methods are common approaches for measurement of the Rc-value. For example, large scale devices such as ORNL hotbox apparatus [13] have been used for large building components reliably [14]. In the large scale, other specific kinds of hot boxes can be used as well to assess the dynamic performance of walls by simulating outdoor conditions in the lab. These experiments include the static and dynamic tests by Sala et al. [15] and later on by Martin et al. [16] which were done *via* an air chambered hot box in the lab. Along the same line, outdoor test cells are developed to measure the thermal characteristics of building components [17]. Jiménez et al. [18] used such a large scale cell to characterize a wall exposed to actual weather conditions.

2.2. In-situ *methods*

Regardless of the benefit of aforementioned lab methods in including the actual weather conditions, they cannot be applied in existing residential buildings. Therefore, in the recent past, *in-situ* measurements have become more popular and numerous in-depth studies have been conducted regarding *in-situ* evaluation of thermal characteristics such as thermal resistance, effective thermal mass [19], and specific thermal conductance [20] .*In-situ* measurements are performed by measuring the heat flow rate at the surface of the wall and surface temperatures over a long enough period. By application of a dynamic theory [19,21] in the analysis of recorded data the fluctuations of the heat flow rate and temperatures can be taken into account. In accordance with the literature and relevant technical reports, although various *in-situ* measurement methods [21] have been proposed till today, the challenge remains for handling the fluctuations of the temperatures and heat fluxes on both sides of the building walls, in addition to the time delay in thermal response of the ones with higher thermal mass due to which static conditions are never achieved.

2.2.1. Methods based on ISO 9869 and ASTM standards

ISO 9869 [7] and ASTM [8,9], using the same principles, prescribe the standard measurement method for *in-situ* measurement of Rc-value and *U*-value of building components. The analysis of the measured data is done *via* Average method (Summation method in ASTM) and *via* Dynamic method (or by Least Squares method in ASTM), which does not shorten the minimum measurement period in heavy elements (walls). Especially in heavy walls, when using the Dynamic method, the measurement time required for obtaining the *U*-value is the same as in the Average method [22]. Including the dynamic effect of thermal mass of unknown constructions in ISO 9869 [7] requires sampling and endoscopic inspection by drilling which is generally not allowed by the dwellings' occupants. A desirable on-site measurement method should not only be reliable, but also non-destructive to be applicable during the building inspections [23].

After at least 72 h of monitoring, if the termination criteria has been met [7], the measurements may stop [24]. Ahmad et al. [25] studied hollow reinforced precast concrete walls based on standards ASTM C1155 [8], ASTM C 1046–95 [9], and ISO 9869 [7] in Saudi Arabia finding 6 days enough for satisfaction of the convergence criteria. However, such short period is generally insufficient for obtaining results, especially, in countries with less stable climate [26]. Smaller temperature gradients along two sides [23] and heavy construction of walls are other shortcomings [8] of such measurements. In Scotland, with a monitoring period of 17 days, Baker [27] compared the *in-situ* measurement results based on ISO 9869 [7] with the ones obtained in the lab, resulting in a good agreement. The study was further developed [28] by studying a greater number of case studies where he showed the necessity of longer periods of *in-situ* measurements for achieving satisfactory results. It turned out that in some cases, even 36 days of monitoring had not been enough to measure the *U*-value of the walls. The walls with heavier construction demand more time to stabilize the average heat flux and the average temperature gradient. Note that by long periods of measurement, more climatic fluctuations are included in the results, highly increasing the error probability.

2.2.2. Comparison between calculated and measured values

In the United Kingdom, Doran [29] conducted a research to improve the building simulations by making comparisons between the measured and the standard calculated *U*-values [30]. It was