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In-situ characterization of walls' thermal resistance: An extension to the ISO 9869 standard method

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A B S T R A C T

Accurate and reliable in-situ characterization of buildings' thermal envelope is of high significance to determine actual energy use and thermal comfort. In this context, walls' thermal resistance is one of the most critical properties to be identified. Regardless the numerous studies being carried out to accurately measure the actual thermal resistance of walls on site, the heat flow meter method suggested by the ISO 9869 standard is the one being applied the most. The method requires one heat flux sensor and two thermocouples to measure and estimate the average thermal resistance over a sufficiently long period. Despite the advantages of this method, two problems have been seen in practice: long duration and precision problem. The present article describes and demonstrates how modifications to this standard method can improve the results of the in-situ measurements in terms of duration and precision. Simulations and experiments have been applied to show the effect of using an additional heat flux sensor, opposite to the first one. The modified method aids in obtaining the thermal resistance with a higher precision in a shorter period of time.

1. Introduction

Buildings are known to be responsible for a considerable share of worldwide energy consumption [1]. Apart from the occupant behavior, a building's individual energy consumption is highly dependent on the thermo-physical characteristics of its envelope [2,3]. One of the most critical characteristics is the walls' thermal resistance R_c-value, whose accuracy of determination can significantly influence the accuracy of buildings' total energy consumption prediction [4,5]. The accuracy of these predictions is critical in the sense that they are generally used as the basis for the majority of decisions and policies [6]. Therefore, accurate estimation of the actual R_c-value of the wall sections is known to be of high importance. Numerous experimental and computational studies [7,8] have aimed at accurate determination of this parameter using in-lab/in-situ and static (steady state)/dynamic (transient) approaches. On one hand, calculation of the R_c-value can be quite simply done according to ISO 6946 [9], in which the computation methods for thermal resistance estimation based on the construction of the samples are provided. The exact construction of the existing walls is generally unknown and thus, in such cases, this calculation method is not appropriate. On the other hand, many studies have shown the difference between the thermo-physical characteristics calculated or claimed as the design values and the ones measured experimentally during measurement campaigns [10–15], implying the necessity of performing measurements and the investigation of these measurements for being accurate enough. Regardless the numerous studies being carried out to accurately measure the actual thermal resistance of walls on site, the heat flow meter method suggested by the ISO 9869 [16] and ASTM 1046 and 1155 [17,18] standards, which are very similar, are the ones being applied the most. Despite the advantages of these methods, two problems have been seen in practice: long duration and precision problem. The present article describes and demonstrates how modifications to ISO 9869 can improve the results of the in-situ measurements in terms of duration and precision.

2. State-of-the-art

Various measurement techniques have been developed including steady state and transient methods applied in-situ [19,20] and in-lab [21–27] to estimate the accurate thermal resistance, with and without relying on steady state (and quasi-steady state) as-

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Nomenclature

Symbols

C	Specific heat capacity (J kg^{-1} K^{-1})
k	Thermal conductivity (W m^{-1} K^{-1})
l	Wall thickness (m)
m	Minimum required measurement period (h)
$\dot{q}$	Heat flux (W m^{-2})
R_c	Conductive thermal resistance (m^2 K W^{-1})
T	Temperature (K)

Superscripts

∞	Fluid medium (air)
t	Time (h)
th	Theoretical value

Greek letters

α	Convective heat transfer coefficient (W m^{-2} K^{-1})
Δ	Difference
ρ	Density (kg m^{-3})

Indices

acc	Accumulation of heat
ave	Average
in	Associated with the interior surface
out	Associated with the exterior surface
1	Associated with the interior surface
2	Associated with the exterior surface

Abbreviation

HFS	Heat flux sensor

sumption. The steady state and the quasi-steady state assumptions, which are the basis of R_c-value measurements, tend to become problematic when the temperature and heat flux fluctuations are extreme (e.g. unsteady climatic conditions). Therefore, in case of static-based methods, usually additional modifications such as on-site data corrections for large temperature drifts [28] and including the wind velocity effects [29] are addressed to improve the measurement accuracy. Other advanced transient data analysis methods such as regression modelling and ARX-modelling have been used to improve the reliability and robustness of the results [30]. In the recent past, applying the measurement data to mathematical models has become more popular. This type of methodology includes stochastic grey box modelling and inverse modelling [31,32]. For instance, lumped thermal mass models and Bayesian statistical analysis of temperature and heat flux measurements, have been applied to estimate reliable thermo-physical properties of walls [33].

In summary, there is a large variety of scientific theoretical and practical methods available to determine the R_c-value of existing walls. However, if such determination is to be carried out in large scale (e.g. nationwide monitoring campaigns), a common trusted procedure is needed to be followed as a reference. For this purpose, standards have been developed and applied widely [11, 12,34] to characterize the walls' thermal resistance via in-situ measurements. The standard practices for in-situ evaluation of wall's thermal resistance include the international standard ISO 9869 [16] and the American standard ASTM 1046 and 1155 [17,18]. Beside small differences in details, the principles of the two standards are the same. In 2017, these two methods have been compared [35] in detailed in different case studies finding out the time requirements, measurement conditions, and constraints to improve the results. In these methods, the thermal resistance of a wall is measured using two thermocouples mounted opposite to each other on two sides of the wall and a heat flux sensor (HFS) mounted next to the thermocouple on one side, preferably the interior side because of higher stability in temperature. For accurate post processing of the data, information about the construction is required to include the effect of heat storage and dynamic heat accumulation. In case of unknown construction, if a non-destructive inspection is to be carried out, such information is not available [36] and therefore, corrections cannot take place. This is known to significantly influence the accuracy, leading to a less reliable result. According to the studies in which the method has been applied, there are two main problems which the method can be associated with: First, the long duration of the measurements due to unstable boundary conditions [11,16] and second, the problem of R_c-value precision. The duration required for the R_c-value to be reported, fulfilling the criteria of ISO 9869 [16], can be very long. This becomes a barrier and therefore, makes it difficult for the method to be applied often in practice. The results of the ISO 9869 [16] Average Method are highly dependent on the temperature and heat flux circumstances. The profile of heat flux and temperature determine the final value and the time required for the convergence to occur. According to ISO 9869 [16], presuming that all conditions are taken into account, in order to report an acceptable R_c-value, the main criteria to fulfill and stop the measurement include the following:

1. The measurement period should take at least 72 h with a specific range of sampling and logging intervals.
2. The R_c-value obtained from the last two measurement day should not differ by more than 5%.
3. The difference between R_c-values obtained from the first and last certain number of days [16] is within 5%.

Other criteria such as heat content and dynamic data processing [37] are generally not applicable in in-situ measurements as the exact construction is unknown. The cumulative R_c-value is reported for each day (including the average of the previous days). As this process continues, the curve of the reported R_c-values converges to a certain value, which is the average of the whole measuring period, fulfilling the aforementioned conditions.

Practical experiments, however, in which a second heat flux was installed [19] on the opposite side of the one recommended by ISO 9869 have shown that the two R_c-values are measured based on two heat fluxes (indoor and outdoor wall surface), could converge to two different final values (not in the same range), both fulfilling the criteria of ISO 9869. As seen also in other studies [11,19], it may happen that if the test continues, the final convergence value starts moving towards another convergence point, or that the two R_c-values do not converge to the same value even after a relatively long period. This poses a question about which of the values to report as the actual R_c-value, and if it would not be better to report the average of the two values.

According to the ISO 9868 [16] Average Method, the R_c-value of a wall, based on measurements of ΔT (the surface temperature gradient), $\dot{q}$ (the heat flux), and t (the time interval), can be derived as follows:

$$R_c = \sum_{t=0}^{m} \Delta T^t / \sum_{t=0}^{m} \dot{q}^t \qquad (1)$$

According to (1), the instantaneous R_c-value at each side is different because the two instantaneous heat fluxes $\dot{q}^t$ at both sides of the wall vary, thanks to the thermal mass (resulting in $\dot{q}_{acc}$ in Fig. 1), and temperature and heat flux fluctuations on two sides of the wall. However, in long term, based on energy conservation, the summation of $(\dot{q}^t)_1$ and $(\dot{q}^t)_2$ are equal. According to ISO 9869 [16], such summation is to be done in a long enough time period (at least 72 h for light elements and more than a week for heavy