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Replication Studies paper

A comparative assessment of the standardized methods for the in–situ measurement of the thermal resistance of building walls

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ABSTRACT

The in-situ thermal resistance (R-value) measurement of building walls is essential for the accurate assessment of the thermal performance of an envelope and is lately a subject of increasing attention. The present study examines the four available standardized methods: for the R-value measurement as described in two international standards: ISO 9869 and ASTM C1155. The required measuring period and the variability of the results of each method are examined by measuring the thermal resistance of three representative walls (drywall, rubble and brick) at different measuring conditions in terms of surface temperature difference and direction of heat flow (stable or alternating during the day). It is concluded that the two most commonly used methods, the Average and the Summation method, require high temperature difference between the indoor and outdoor surfaces of the tested wall in order to provide R-values in short measuring period with low variability. On the contrary, the required measuring period for the other two methods, the Dynamic and the Sum of Least Square method, appears to be independent of the measuring conditions. The resulting values have low variability as long as the direction of heat flow is stable during the measurements.

1. Introduction

Energy performance of buildings depends on a variety of factors such as the thermal performance of the envelope, the climatic conditions, the efficiency of heating/cooling systems and electrical appliances and the user behavior. Among them, the performance of the building envelope, partly quantified by means of the thermal resistance value (R-value) of the walls, affects in a critical way the total energy performance of the building since space heating/cooling demands representing a large percentage (35–70%) of the total energy demand [1]. Therefore, limiting the R-value of the walls is one of the most common measures in order to reduce the energy consumption for space heating/cooling [2].

The theoretical calculation of design R-values is essential during the design stage of a building but may vary and deteriorate in practice due to construction irregularities, the quality of workmanship, multi-dimensional heat and moisture flow and material degradation effects [3]. Therefore, in-situ measurement of R-value may be required for post-evaluation of the thermal performance of a building envelope especially in cases of renovation but also for providing real values to BIM platforms and energy efficiency evaluation software.

Since the 1980s, in-situ R-value measurement has been the topic of many research works proposing methods that involve measurements of heat flux and temperature at the inner and outer surface of the wall for a period of time [4–12]. The collected time series data can then be analyzed in different ways for the calculation of the R-value. According to the literature there are two main approaches for the analysis: a) modeling of the envelope with R-C networks and use of system identification tools [13–17] and b) the use of standardized methods [18,19] (often with minor modifications). The system identification methods can conditionally provide more accurate results as long as the tools developed are adequately validated and the users are highly experienced [20]. On the other hand, the standardized methods are more likely to produce reliable results when used by non-experienced users and thus, are the most widely used.

In any case it is well known that R-value measurements of the same wall using different methods are not always in agreement. Cesaratto et al. [21] employed different analysis tools (both R-C network tools and standardized methods) for the in-situ estimation of thermal resistance for a large number of walls and they found that the results for each wall could deviate significantly (up to 30%) depending on the analysis tool. Ghazi Wakili et al. [22] showed that

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the estimations of R-value for a wall using a R-C network model and a standardized method may deviate up to 10%. Androutsopoulos et al. [20] compared the spread of the results using different system identification tools for the estimation of the thermal resistance of specific walls. They concluded that the measurements should be analyzed by a person with experience in order to obtain reliable results.

Regarding the standardized methods, two international standards are currently available for the estimation of the thermal resistance of building envelope components using in-situ measurement data – ISO 9869 and ASTM C 1155 [18,19]. The ISO 9869 standard introduces the Average and the Dynamic Method, while ASTM C 1155 standard introduces the Summation and the Sum of Least Square Method. All methods require the measurement of the internal and external surface temperature and the internal heat flux for at least three days.

The Average and the Summation methods are similar to each other with their main advantages being the simplicity in use and the rapid export of results, making them the most widely used methods. However, their precision strongly depends on the measuring conditions [18,19,23]. On the other hand, the Sum of Least Square and the Dynamic method, are more likely to provide reliable results regardless of the measuring conditions [18,19], but require the development of complex algorithms and computational tools for the analysis of the time series data due to their sophisticated methodology. For this reason, these methods are less commonly used.

The main limitation of all the standardized methods is that the precision of the R-value measurement depends on the measuring conditions and the duration of the measuring period. Generally, the optimum measuring conditions are the high temperature difference with low temperature variations. Flanders et al. [24] analyzed the estimations of R-value using the two ASTM methods (Summation and Sum of Least Square method) and concluded that the agreement between the two methods was within 1–13% for cases with high internal and external surface temperature difference. Deconinch and Roels [23] and Gaspar et al. [25] compared the two ISO methods (Average and Dynamic method) in terms of different measuring conditions and they concluded that the Average method performs equally well to the Dynamic method when the measuring conditions are optimum. In case of low temperature difference only the Dynamic method leads to reliable results. Roulet et al. [26] compared the same two methods regarding the influence of the indoor/outdoor temperature difference. They concluded that the results of the two ISO methods were stable when the indoor temperature was constant before and during the measuring period. Desogus et al. [27] investigated the results of the Average method for two different measuring conditions. They concluded that the measuring conditions, and particularly the surface temperature difference, greatly influence the results. The smaller the temperature difference the less precise were the results.

The second critical measuring parameter is the required duration of the measurements. It can be defined as the minimum duration required by the method in order to provide reliable results. According to the standards this duration can range from 72 h to more than 7 days, depending on the method, the measuring conditions and the type of the tested wall. In case of the Average and Summation methods, it is referred as convergence time and is determined by different criteria for each method. However, in case of the Dynamic and the SLS methods, it is not clearly defined. Gaspar et al. [25] showed that the accuracy of the Dynamic method was significantly improved by extending the measuring period.

From the above brief literature review it becomes clear that the main weaknesses of the standardized R-value measurement methods, namely the effect of the measuring conditions and the duration of the measuring period, are limiting the usability of the methods and can potentially increase the uncertainty of the results. Gaspar et al. suggested that further investigation regarding the optimum measuring period is needed in order to improve the reliability of the results. Furthermore, Desogus et al. [27] have concluded, that it is difficult to achieve ideal environmental measuring conditions especially in mild climates and the solution to that could be the selection of the appropriate method among the available standardized technique.

The main aim of this paper is to address the above issues by evaluating the standardized methods for the in-situ measurements of the R-value of building walls in terms of the required measuring period, the variability of the results and the effect of the measuring conditions on these two parameters. In particular, the examined measuring conditions are the surface temperature difference and the direction of heat flow (stable or alternating during the day). The current study introduces a criterion for the determination of the required measuring period for the Dynamic and Sum of Least Square method. All methods are employed for the Measurement of the R-value of three different building walls (a lightweight drywall construction, a rubble and a brick wall). The results provide guidelines for the in-situ calculation of the thermal resistance of an existing wall, for the pre-processing of measurements and the selection of the appropriate method.

2. Implementation of the four standardized methods

The four standardized methods investigated in this paper are extensively described in the relevant ISO and ASTM standards. All methods require measurements of the internal and the external surface temperature and the internal heat flux of the tested wall. The temperature and heat flux sensors should be installed in homogenous locations avoiding thermal bridges. The standards describe in detail the methodology for the calculation of the thermal resistance, as well as the criteria that should be met in order to provide acceptable results (convergence criteria). The equations for the calculation of the R-value, the convergence criteria and the expected error (for 95% probability) of each method are summarized in Table 1.

For the scope of this study, FORTRAN codes were developed in order to implement the above mentioned standardized methods. The codes compute the R-value and examine if the convergence criteria are met for a given dataset.

For the determination of the R-value according to the Average and Summation methods the heat transfer through the wall is considered one-dimensional quasi-steady state. The model does not take into consideration the thermal storage of the envelope, these methods are sensitive to gradual increase or decrease of the mean (in terms of time and space) wall temperature, especially for massive constructions [19]. Large fluctuations in the internal and external wall surface temperature during and shortly prior to the test increases the required duration of the measurements [28]. A large mean temperature difference between the internal and external surface of the wall is needed for fast and accurate convergence of the methods [6,19,29]. The precision may also depend on the duration of the measurements and the thermal conditions during the test [27].

The Dynamic method requires the development of a model for the solution of the transient heat transfer equation. The model calculates the heat flux at each time interval as a function of the previous measured temperatures and several parameters, among which is the thermal resistance of the wall. The method calculates the R-value in order to minimize the difference between the measured and calculated heat flux values. The method related accuracy depends on the agreement between the calculated and experimental heat flux values and the duration of the measuring period [25].