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Influence of heating systems on thermal transmittance evaluations: Simulations, experimental measurements and data post-processing

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ABSTRACT

Nowadays, understanding the actual performance of building components is one of the key factor to achieve energy savings. For this reason, on-site measurements are essential but the boundary conditions during surveys can affect the final results. This can occur during heat flow meter measurements, when the thermal transmittance value of a wall can be influenced by disturbing factors, such as the heating system power-on and off. Due to this, the aim of this study is to investigate the influence of these disturbing factors, moving away from steady-state conditions. This research is divided in two main steps: a first critical analysis of data obtained by in-situ measurements and an investigation of how the mentioned disturbing factors can affect the final results, employing a FEM code, where stationary conditions are not respected; a second analysis related to the data post-processing procedures, proposing a new supplementary approach able to exclude heat flow distortions and able to obtain measured U-values closer to the calculated ones, according to ISO 6946. Starting from simulations and on-site measurements, the proposed method was preliminary validated, analyzing actual case studies characterized by heating systems with radiators and obtaining preliminary satisfying results. The simulations allowed to assess a reduction in the difference between the measured and the calculated U-value that goes from +22.1% to +0.7%. Post processing of experimental data with the proposed methodology allowed to significantly reduce the difference between measured and calculated U-values (from +36.9% to −7.6% in the best case study). Starting from the preliminary results, the proposed approach seems to be promising with U-value corrections in accordance with the theoretical ones.

1. Introduction

In the last years, the energy diagnosis of existing buildings became very important in order to achieve energy savings in the building sector. More restrictions were also introduced by recent European Directives [1,2] and, in such context, the evaluation of the energy performance of structural elements can be considered essential. In particular, analyzing building components, the thermal transmittance (U-value) evaluation and the cold bridges analysis are fundamental for understanding how and where to intervene [3–5]. These assessments require reliable experimental approaches, such as the heat flow meter method, the infrared thermography, the blower door test and so on.

In literature, several studies have been carried out showing results related to experimental campaign aimed at evaluating the energy performance of buildings [6–10]. In their study, Ficco et al. [11] showed the results of experimental measurements related to the metrological performance of different heat flow meters, assessing the influence of the environmental conditions in seven building walls. The results proved that high temperature variations can significantly influence the obtained thermal transmittance, estimating high uncertainties ranging from 8% (optimal boundary conditions) to about 50%.

Currently, standardized methods are available for obtaining actual U-values and, in their paper, Gaspar et al. [12] compared the progressive average method and the dynamic method described by ISO 9869 [13], in order to highlight which best fits theoretical values. The authors analyzed three buildings in Catalonia, showing that the differences between the calculated and measured U-values can be reduced when the dynamic method is employed.

Infrared thermography can also be applied for assessing the energy performance of vertical opaque building elements. Thermal imaging cameras are commonly used to evaluate thermal bridges or plant failures in buildings [14–16] but they can also be employed to measure the thermal transmittance of walls. According to this, Nardi et al. [17] presented a study aimed at evaluating the

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effectiveness of thermographic methods for obtaining thermal transmittance values. In particular, they made a comparison between the infrared method and the heat flow meter technique, comparing the obtained values with the theoretical ones.

Moreover, investigations on thermal transmittance were conducted taking also into account historical buildings [18]. In her study, Lucchi [19] made a comparison among standard suggestions, calculated and measured U-values. The author showed that traditional building walls are characterized by a better performance than the one expected from the standard calculations. As a matter of fact, the tabulated values provided by standard and the analytical calculation tend to a thermal transmittance overestimation compared with the in-situ measurements. Usually, the standard tabulated values provide conservative data in order to consider safety margins.

It is worthy to notice that the consequences of a thermal transmittance measurement can be several. The aim of the measurement can be the evaluation of the actual energy performance of a wall, comparing the obtained values with those provide by technical data. On the other hand, it is known that U-value measurements can be influenced by different factors, leading to over- or under-estimations. One of these factors is represented by the data processing carried out by users, beyond the adopted methods for the data analysis. U-value over- or under-estimations could be used to support an energy retrofit or boost the building energy class, respectively. These consequences are related to data acquisitions and their critical analyses.

Due to this, the aim of this study is to investigate the influence of the heating system power-on during heat flow meter measurements, moving away from steady-state conditions. The paper is divided in two parts: a first investigation of the mentioned disturbing factor by means of a FEM code, where stationary conditions are not respected, and a succeeding analysis of in-situ U-value measurements, conducted in three different buildings, where a simple supplementary approach related to the data processing is presented.

2. Thermal transmittance evaluation

2.1. ISO 6946

Heat transfers across multilayer walls can be modeled by using an electro-thermal similarity. It involves the heat flux as an electrical current and each layer of a wall can be described by a resistor. The total thermal resistance of a wall (R_{tot}) can be calculated as follows [20]:

$$R_{tot} = \frac{1}{U} = R_{si} + \sum_i R_i + R_{se} = \frac{1}{h_i} + \sum_i \frac{s_i}{\lambda_i} + \frac{1}{h_e} \tag{1}$$

where U is the thermal transmittance of the wall, R_{si} and R_{se} are the internal and external surface resistances, R_i is the thermal resistance of the ith layer, h_i and h_e are the internal and external total heat transfer coefficients, s is the ith layer thickness and λ_i is its thermal conductivity. Total heat transfer coefficients can be defined as the sum of the convective and radiative heat transfer coefficients: the first one is wind speed dependent and the second one can be calculated using the surface emissivity and the average thermodynamic temperature of the surface and the surrounding surfaces. This well-known methodology is reported in ISO 6946 [21], which can be employed when the wall stratigraphy is known or when it is possible to do destructive tests for determining the materials properties.

2.2. ISO 9869

Several studies in literature and the Standard ISO 9869 provide information about the state of the art of thermal transmittance or conductance measurements [22–25]. In particular, the standard provides information about the technical features of the instrumentation, measurement errors, how to install the instrumentation, data acquisition and data processing. U-value measurements are possible employing a heat flow sensor able to measure the heat flux density across the wall, two air temperature probes (or surface temperature probes) and a data-logger. Heat flow sensor are made of a thin layer characterized by a known thermal resistance. The temperature difference across this thin layer is measured by a series of thermocouple that have the task of amplifying the small electrical signal produced by the single thermocouple. All these elements are enclosed in a moisture-proof protective housing with good mechanical properties. In this way, by detecting the temperature on both sides of the sensor (which is a function of the heat flow through the plate), taking into account an appropriate calibration curve, an assessment of the heat flow density can be obtained. Heat flow meter plates for in situ measurements generally have a few millimeters thicknesses and they are made of rigid or flexible plastic material. These sensors have to be properly coupled, from a thermal point of view, to the wall in order to avoid contact resistances.

The measurement uncertainty is mainly related to the heat flow meter plate that adds a thermal resistance to the investigated wall. Therefore, the thermal resistance of the plate should be very small in order to not affect the heat flux. On the other hand, it is necessary to ensure a minimum resistance so that the plate thermocouples can measure a significant temperature difference.

The Standard suggests a measurement time as a function of the wall "heaviness" (expressed in terms of heat capacity) and appropriate conditions: steady-state conditions of the indoor and outdoor environment before and during the measurement and no disturbing factors (convective movements on sensors or irradiation caused by sources not consistent with the environment).

2.2.1. Measurement errors and uncertainties

As mentioned before, the measurement uncertainty is mainly related to the heat flow meter plate. During field surveys, events able to modify the appropriate measurements conditions can occur and they have to be taken into account to properly post-process data, such as:

- localized increase of radiative and convective thermal energy from the indoor environment (heating by the air conditioning system or by solar irradiation through transparent surfaces, Fig. 1(a));
- localized reduction of radiative and convective thermal energy of the indoor environment (air-conditioning system shutdown, Fig. 1(b)).

These events generate the variation of the surface temperature (facing the indoor environment) of the heat flow meter plate, causing changes during the heat flow measurement.

When the air conditioning system is switched on (or solar irradiation through transparent surfaces enters in the environment), the heat flux sensor installed on the wall is hit by a significant amount of thermal energy transmitted by convection and irradiation. As a consequence, the measured heat flow increases (not equally if compared to the wall) and the result is a higher instantaneous thermal transmittance measurement (Fig. 1(a)). During this phase, there is an increase of the thermal transmittance not related to what is happening to the wall.

When the air conditioning system is switched off, the environment and surface air temperatures are reduced. The surface