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Research paper
Doi 10.7251/stp202401046P
ISSN 2566-4484

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DETERMINING THE THERMAL TRANSMITTANCE COEFFICIENT OF THE OPAQUE FAÇADE WALL ELEMENT USING NON-INVASIVE METHOD

Abstract

Prior to building retrofitting, thermal performance assessment of the building is essential. An adequate assessment can provide useful insights to heat-losses and envelope anomalies i.e. thermal bridges, mold, air infiltration etc. The most important physical quantity that needs to be defined is the thermal transmittance (U-value) which is the key factor in determining the transmission heat loss coefficient HT, as well as in determining the building's energy efficiency. In the absence of documentation, experimental methods are the only solution to identifying such parameter. This paper makes overview of experimental methods; and presents an example of non-destructive method by using Quantitative Infra-Red Thermography (QIRT) in service of calculating U-value of the opaque façade wall element.

Keywords: U-value, Quantitative Infra-Red Thermography (QIRT), building energy efficiency

ОДРЕЂИВАЊЕ КОЕФИЦИЈЕНТА ПРОЛАЗА ТОПЛОТЕ НЕПРОЗИРНОГ ЕЛЕМЕНТА ФАСАДНОГ ЗИДА НЕИНВАЗИВНОМ МЕТОДОМ

Сажетак

У процесу обнове зграде, од суштинског значаја је процјена топлотних перформанси омотача. Адекватна процјена може пружити увид у топлотне губитке и аномалије омотача нпр. топлотни мостови, појава влаге, инфилтрација ваздуха итд. Најважнији физички параметар који треба одредити је коефицијент пролаза топлоте (U-коефицијент) постојећег зида, који је кључни фактор за одређивање коефицијента трансмисионих губитака топлоте H_T као и енергетске ефикасности зграде. У недостатку документације, експерименталне методе су једино решење за одређивање U-коефицијента. У овом раду је дат преглед експерименталних метода; и приказан примјер примјене недеструктивне методе коришћењем квантитативне инфрацрвене термовизије у циљу одређивања U-коефицијента непрозирног елемента фасадног зида.

Кључне ријечи: U-коефицијент, квантитативна инфрацрвена термовизија, енергетска ефикасност зграде

1. INTRODUCTION

In order to conduct an energy audit and analyse the thermal properties of the envelope, it is necessary to determine the thermal transmittance of the transparent and opaque elements of the building envelope. In practice, the documentation is often not available, or is insufficiently clear to accurately determine the composition of the walls, and therefore their energy characteristics. The thermal transmittance coefficient (U – value, W/m^{2}K) is defined by the ISO 7345:2018 standard as the heat flow rate in the steady state divided by area and by the temperature difference between the surroundings on each side of a system [1]. The U-value of the wall is an important physical quantity that indicates the thermal performance of the building envelope. If it is overestimated, the result will be insufficient thickness of thermal insulation on the wall, and vice versa, if underestimated resulting in inadequate interventions that will not lead to adequate results in building's energy efficiency and can often cause unnecessary financial costs. The U-value represents the starting point for the calculation of the required energy for heating and cooling.

Taking into account all mechanisms of heat transfer, which are conduction, convection, and radiation, the thermal transmittance can be determined as follows:

$$U = \frac{\mathrm{q}}{t_{int} - t_{out}} \tag{1}$$

That is, the U-value can be obtained by measuring the heat flux density (q) and the temperature difference between the indoor (t_{int}) and outdoor (t_{out}) air during stationary heat transfer.

In order to determine the U-coefficient of the existing wall, several methods have been defined, which are divided into theoretical, destructive, and non-destructive methods. Although there are different methods of on-site measurement in practice, not all of them are accepted as sufficiently precise to be applicable, while the decision on the most favorable method depends on many factors, which will be discussed in the following text. According to ISO 9869-1:2014 [2], equipment for determining the heat transmittance consists of a heat flux sensor and temperature sensor (indoor and outdoor temperature probe), which are usually placed on a north wall in order to avoid direct solar radiation. The reliability of the obtained results is affected by conditions such as sun, rain, wind, and temperature. However, non-invasive and non-destructive methods like thermography are advised to be performed prior to precise measurements since different structural abnormalities can be found in the wall, making it easier to choose the exact wall and spot where to install the measuring units.

2. OVERVIEW OF THEORETICAL AND EXPERIMENTAL METHODS TO DETERMINE THE U-VALUE OF THE OPAQUE FAÇADE WALL ELEMENT

In practice several methods are present, and theirs benefits and downsides range from being non-destructive to the ones which are leaving marks on the walls; secondly, some are easier to conduct since they require easy to use and install equipment and do not require repetitive measuring process, while others require 72 hours sequential measurements; thirdly, not all require entrance to the interior space leaving tenants unbothered. General spectrum is as following:

Theoretical method (ISO 6946:2017) [3] [4] explained theoretical approach to calculation of the thermal transmittance - U-value, which is described using the following equation:

$$U = \frac{1}{\mathrm{Rtot}} = \frac{1}{1\mathrm{Rs,i} + \sum_{i}^{n} R_i + \mathrm{Rs,e}}, \tag{2}$$

where Rtot is the thermal resistance of the wall, and $R_{s,e}$ and $R_{s,i}$ (m^2 K)/W are the thermal resistances of the outer and inner surfaces [5]. ISO 6946:2017 [3] defines this method as a way to calculate the thermal resistance and thermal transmittance of building components and elements, excluding doors, windows, glazed units, curtain walling, components transferring heat to the ground, and those designed for air permeation. The calculation relies on the designated thermal conductivities and ticknesses of the building element layers (resistances of the material layers). This approach applies to components and elements composed of thermally consistent layers, which may incorporate air layers.

Heat-flow meter method (HFM) (ISO 9869-1:2014) [5] - The ISO standard details the utilization of heat flow meters for evaluating the thermal transmission properties of flat building components. These components, primarily composed of opaque layers perpendicular to heat flow, are assessed for their thermal resistance (R), thermal conductivity (λ), overall thermal resistance (R_t), and transmittance (U) between defined environments. The thermal transmittance of a wall is determined by measuring the heat flux through the wall and the temperatures of the environment on either side of it. [2] This method is highly accurate and non-destructive, however, its downside is the lack of possibility for thermal bridge analysis due to the very local measuring zone, the requirement to access the building, limitations where probes often make marks and small damages on the wall, and the difficulty of ensuring a thermal gradient of > 10 °C while performing measurements. This method is commonly used when temperature differences are greater, i.e., in the winter, when internal space is heated, or in the summer, when it is cooled, etc. According to ISO 9869-1:2014 [2], there are three criteria that need to be met:

- The measurement period should last at least 72 hours, with a specific range of sampling and logging intervals.
- The R_c value (conductive thermal resistance (m^2KW^{-1})) obtained from the last two measurement days should not differ by more than 5%.
- The difference between R_c values obtained from the first and last certain number of days is within 5% [5] [6].

Infrared method/ Quantitative infra-red thermography (QIRT) [6] **-** This is non-contact, non-destructive and rapid method which utilizes the amount of irradiance of the regions in contact with outside air from the surface temperature, total heat transfer coefficient and environmental temperature. The indoor surface temperature distribution is measured using an Infra-Red (IR) camera, the indoor environmental temperature is measured by installing Environmental Temperature (ET) sensor on the surface of the building component, and the indoor total heat transfer coefficient of the surface of the building component is measured using a heat transfer coefficient sensor [6]. Additionally, some researchers suggest the use of a hot-wire anemometer to monitor variations in wind speed near the wall [7]. In conclusion, the IR method calculates heat transmittance by knowing the emissivity of the material, measuring reflection temperature, surface temperature, and temperature of the internal and external environments [8]. Besides being used in determining the U-value, this method opens possibilities for detecting thermal anomalies such as thermal bridge occurrence, air infiltration, the presence of moisture or leakage in the wall, etc. Furthermore, it is useful to measure barely reachable areas.

The simple hot-box flow meter method (SHB-HFM) combines the Guard Hot Box (GHB) and Calibrated Hot Box (CHB) methods [9] - Hot box methods are laboratory tests characterized by controlled temperature of the environment, and are thus not limited by climate conditions, and have low measurement errors [10]. However, usual HB-HFM methods are rarely useful for in-situ measurements so recent studies have focused on developing in-situ hot box methods. Temperature-Control-Box (TCB-HFM) is one of such and it consists of a hot box mounted to the inner surface, which heats or cools air (depending on the season) to ensure optimal thermal gradient of > 10 °C while performing measurements. The items required to perform this methodology are: (1) a simple hot box; (2) three heat flux plates; (3) a temperature probes; (4) surface temperature probes; and (5) a data logger [11] [12].

Thermometric method (THM) [4], also called the air-surface temperature ratio method, is a non-destructive method that determines thermal transmittance by measuring the internal surface temperature of the wall and the temperatures of the environments divided by the wall [4]. Considering this technique, its main advantage is the absence of heat flow sensors, which only involves temperature sensors that are tightly mounted on the wall. This method can be combined with infra-red thermography to ensure that the probes are placed tightly and in the correct position [13].

3. USING QUANTITATIVE INFRA-RED THERMOGRAPHY (QIRT) TO DETERMINE THE U-VALUE OF AN OPAQUE FAÇADE WALL ELEMENT

All objects with a temperature higher than absolute zero emit infra-red radiation as a function of their temperature. Thermal imaging is a non-invasive method that enables non-contact measurement of surface temperature based on the emitted electromagnetic radiation in the long-infra-red range.

According to Stefan Boltzmann's law, the net radiated power per unit area (q) is proportional to the fourth power of the absolute temperature (T) and also depends on the emissivity (ε) of the body:

$$q = \varepsilon \sigma T^4 \tag{3}$$

Where $\sigma = 5.67 \cdot 10^{-8} \frac{W}{m^2 K^4}$ is Stefan Boltzmann's constant. The emissivity coefficient is defined as the ratio of the energy emitted by a certain material to the energy emitted by an absolute black body of the same temperature. According to the definition, it can have values in the range 0-1.0. Emissivity depends on the wavelength, material finish, and temperature of the surface.

Based on the amount of infra-red energy that is emitted, transmitted, and reflected from the surface, a thermal image in which the different temperatures are represented by different colors is obtained. This imaging method can be applied for non-destructive testing, quality inspection in materials, civil engineering, and building sciences [14]. Inhomogeneities in the material near the surface of the structural elements will result in a different temperature and color; this is especially important in the case of moisture. In the building analysis, active and passive methods of infra-red thermography are implemented, with the active method being further distinguished into pulsed thermography (PT) and lock-in thermography (LT) [15]. Pulsed thermography (PT) presents an active thermographic method that involves the use of a heat source to stimulate an object with a heat pulse. An infra-red camera then records a video of the object to measure the cooling process on the object's surface [16]. Lock-in thermography (LT), whose principle is based on the application of the periodic input energy wave to the surface of the object being examined and analyzing the resulting local temperatures on the surface of the object [17].

IRT building diagnostics includes the determination of thermal characteristics of the envelope, detection of thermal bridges and areas of increased heat loss, air leakage, thermal insulation damage, and the presence of moisture [15].

An example presented in this paper is the usage of an IC camera on the wall of a residential building from the period 1970 – 1980, whose envelope condition is in need of renovation. Thus, this method can provide insights into the current condition of the envelope and approximately determine the U-value as the main input parameter for the further process of designing envelope refurbishment. Measurements on the envelope are performed in accordance with the standard ISO 6781-1:2023 [18] (previously used as ISO 6781-1983) and EN 13187:1998 [19]. Thermal inspection was made with the thermal image camera FLIR b60. Table 1. shows thermal image camera specifications.

Table 1. Properties of IR Camera used for the U-value measurement [20]

Parameter	Value
Field of View	25° × 25°
Thermal Sensitivity	< 0.1°C (0.25°C) / 100m
Image frequency	9 Hz
Detector type	Uncooled microbolometer
Spectral range	7.5–13 µm
IR resolution	180 x 180
Object temperature range	-20°C to +120°C
Accuracy	±2°C or ±2% of reading
Emissivity table	0.1 to 1.0 adjustable or selected from list of materials
Operation temperature range	-15°C to +50°C
Storage temperature range	-40°C to +70°C
Humidity (operating and storage) range	24h 95% relative humidity

In the case of thermal transmittance coefficient value assessment by IRT application, there is no prescribed normative. However, in some papers, suggestions were given in order to determine the thermal transmittance coefficient value (U-value) using non-contact and non-invasive methods. According to Albatici and Tonelli [7] as well as Nardi et al. [21], the U-value can be determined through IRT by measuring the surface temperature of the element T_w, the indoor environment temperature T_{int}, the outdoor environment temperature T_{out}, the wind velocity v, and the emissivity of the material ε_{tot}:

$$U = \frac{5{,}67 \cdot \varepsilon_{tot}\left[\left(\frac{T_w}{100}\right)^4 - \left(\frac{T_{out}}{100}\right)^4\right] + 3{,}8054\ (T_w - T_{out})}{(T_{int} - T_{out})} \tag{4}$$

Furthermore, some of the authors have suggested a new methodology based on measuring inside and outside air temperatures and the inner wall surface temperature in order to avoid the influence of external climatic conditions [22].

4. IMPLEMENTING QIRT TO THE CASE STUDY OF AN OPAQUE NORTH-ORIENTED FAÇADE WALL ELEMENT

For experimental purposes, existing residential building, from the period 1970-1980, is taken into consideration (Figure 1). The building is a representative sample of the mentioned period and has a skeleton structural system of precast prestressed columns and floors with walls of prefabricated sandwich panels and thermal blocks plastered on both sides with cement mortar.

The average wind speed measured around this sample does not exceed 1 m/s, i.e., the west-northwest, which is the most frequent, is 0.3 m/s, followed by two more dominant directions: north-northwest (0.4 m/s) and north-northeast (0.6 m/s), and they do not additionally affect the calculation of the thermal resistance and thermal transmittance coefficient values of the building, which are not already provided for by the standard [3]. Since the orientation of the wall where QIRT measurements are made is north – northeast, wind velocity of 0.6 m/s is used for further calculations. Based on these values, thermal resistance of the outer surface is R_{se} = 0.040 m^2K/W.

Figure 1. Layout of building and position in Borik neighbourhood, Banja Luka

The thermal transmittance coefficient value (U-value) for a representative part of the façade was evaluated using the theoretical method. The values for the wall components are given in Table 2: density, thickness, thermal conductivity coefficient, and estimated U-value. The physical properties of the materials are taken according to mean values of such types of materials and according to material properties present at the time of construction. The calculated U-value using a theoretical model based on the composition and thermal properties of the sampled wall is 1.37 W/m^2K (table 2). This U-value is in line with the average U-value for buildings from this period, as stated in the Typology of the Residential Buildings in Bosnia and Herzegovina [23]. According to the Rulebook on minimum requirements for the building energy characteristics currently used in the Republic of Srpska [24], the prescribed U-value for the opaque façade elements is U = 0.30 W/m^2K. The calculated U-value is too high and does not meet the prescribed requirement.

Table 2. The composition and thermal properties of the sampled wall

Wall	Layers of the element				
Sample north oriented opaque façade wall	Material	Density ρ (kg/m³)	Layer thickness d (m)	Thermal conductivity coefficient λ (W/mK)	Thermal resistance R (m²K/W)
	Cement mortar	1900	0.015	0.70	0.021
	Thermal block	1400	0.30	0.58	0.517
	Cement mortar	1900	0.02	0.70	0.029
	Thermal resistance of the inner surface			Rsi	0.125
	Thermal resistance of the outer surface			Rse	0.040
	Heat transfer coefficient (U-value)			U (W/m²K)	1.37

The theoretical method is followed by the qualitative method using the infrared camera FLIR b60. A thermal image of the sample is shown in Figure 2 where the following parameters can be seen: wall temperature (- 0.1°C), material emissivity (ε = 0.97), and temperature range (-7°C to 21°C).

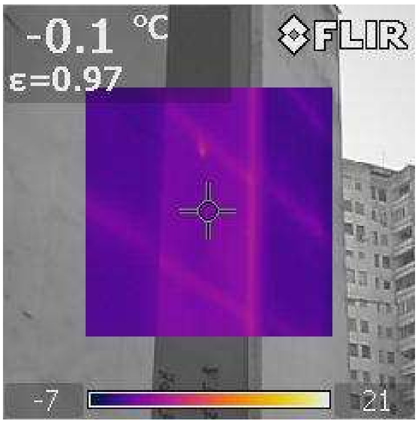

Figure 2. Thermal image of the north-oriented façade wall

After the theoretical value has been estimated and the sample wall screened using a thermal imaging camera, there are all the parameters necessary to calculate the U-value using the previously shown equation 4. Table 3. shows an overview of in-situ measured parameters used for further evaluation of the U-value.

Table 3. Parameters that are necessary for the calculation of the U-value.

Parameter/ unit		Measured	T (K)
t_{int} (℃)	indoor environment temperature	21.8	294.95
t_{out} (℃)	outdoor environment temperature	-5.4	267.75
t_w (℃)	surface temperature of element	-0.1	273.05
ε	emissivity of the material	0.97	-
v (m/s)	wind velocity	0.6	-
U (W/m²K)– value			1.29

The calculated U-value, based on the characteristics of the sampled wall, is 1.37 W/m^{2}K, while the U-value obtained by applying the QIRT method is 1.29 W/m^{2}K. By comparing the results of the theoretical method and the QIRT measurement method, it can be concluded that the U-value matches adequately, with a difference of around 5%. Still, it is possible to obtain more precise results by repeating the measurement at multiple points on the wall and obtaining an average U-value.

5. CONCLUSION

This paper provides an overview of potential methods to determine the U-value, beginning with theoretical and moving through a range of experimental methods. The significance of thermal imaging is well known in the detection of anomalies. However, studies are showing that its use can be useful to determine the thermal transmittance coefficient value of the wall without causing damage to the element. With the wide range of methodologies currently being used to experimentally determine the thermal transmittance this method showed as easy to conduct while providing the immediate results. In comparison to other methods, it does not require 72 hour measurement range, and can be used from outside without compromising the privacy of the tenants. By applying the QIRT methodology, this paper showed promising results in terms of reliability in determining the U-value of the opaque façade element, with an accuracy of 5% compared to the U-value obtained by the theoretical method. This is of great importance, taking into account the ease of use and the measuring process, which is not as complex compared to other experimental methods. Future research should be made by comparing measuring outcomes from several points on the wall, hence the sampling results could be statistically approved. Furthermore, the results obtained with the QIRT method can be compared with those obtained with the HFM method to determine compatibility and relevance in architectural practice.

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