RELIABILITY OF EXPERIMENTAL METHODS TO DETERMINE HEAT TRANSMISSION COEFFICIENT OF THE EXISTING BUILDING FAÇADE WALL

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Experimental methods are often only possible solution to determining heat transmission coefficient (U-value) of elements in existing buildings. These methods can be of great importance in developing countries which are tackling energy poverty by conducting deep energy retrofit of the existing building stock, such as in case of Bosnia and Herzegovina. ISO 9869-1 standard recognizes HFM (Heat-Flow-Meter) methodology as enough precise to give reliable results. However, this methodology predicts strict criteria under which measuring can be done, what is sometimes not possible. Other method standardized with ISO 9869-2 includes QIRT (Quantitative Infra-Red Thermography) which is much suitable to conduct in-situ, yet, for its non-contact properties it is not as reliable as previous one. This paper aims to show process of implementation of these methods and statistically compare them to theoretical method made according to ISO 6946. Compared to theoretical heat transmission coefficient of $U_{theor.}$=1.366 W/m^{2}K, results showed deviations ranging from S=-4.17% to S=+1.61% for HFM method, with mean value of U_{mean}=1.39 W/m^{2}K, and S=5.38% for QIRT method, with mean value of U_{mean}=1.29 W/m^{2}K. In this paper, a comparative overview is made to show importance and applicability of each method, their prerequisites and reliability in real context.

Key words*: TM (Theoretical Method), QIRT (Quantitative Infra-Red Thermography) method, HFM (Heat-Flow-Meter) method, building physics, energy efficiency, U-value, building energy retrofitting, statistics*

1. Introduction

Global problem of excessive energy use, energy production, and its availability is becoming more complex over time, causing the appearance of energy poverty in developing countries such as Bosnia and Herzegovina. The European Union has defined the goal of reducing greenhouse gases at least by 55% by 2030 (from the current 40%) and makes climate neutrality by 2050 [1]. On global scale, and especially in poor and developing countries, special emphasis must be placed on the construction sector, which is responsible for about 38% [2] of greenhouse gas emissions. In such a case, renovation of existing buildings certainly appeared as an effective method, which is certainly the primary goal of investment due to the impaired comfort of residents, as well as the often inability to finance a sufficient amount of energy to heat the entire space, resulting in partial heating of units or a decrease in thermal comfort. More precise, deep energy retrofitting is mostly applicable in this scenario. It can be explained as whole building retrofit, including building envelope and HVAC system retrofits, for achieving significant reductions in energy intensity (annual energy consumption per unit of floor area) [3]. Basic recommendations for accurate calculations of energy requirements are: use of unified climate data, architectural and construction characteristics of buildings reduced to project values, standardized values that take into account user behavior such as the number of heating hours and internal heat gains and assumed project temperature in the heated space of 20°C [4]. Based on the data published in the Typologies of Residential [5] and Public [6] Buildings, the energy need for heating of all buildings in Republic of Srpska is 8,427,652 MWh, of which 7,729,138 MWh belongs to residential buildings and 698,514 MWh to public buildings [7]. In the Republic of Srpska (Bosnia and Herzegovina), Energy indicator is the Energy need for heating ($Q_{h,nd}$). According to the Energy Strategy of Republic of Srpska up to 2030, the indicated Energy need for heating ($Q_{h,nd}$) in residential buildings is estimated between 230-250 kWh/m^2. [8] When taking into account the calculation of Energy need for heating ($Q_{h,nd}$), according to the ISO 52016-1:2017 [9] (previously ISO 13790:2008 [10]) standard, which is supported by all the Regulations related to energy efficiency in buildings in Republic of Srpska, it is estimated about 160 kWh/m^2, what is also shown in the Typology of Residential Buildings in Bosnia and Herzegovina. [5]

In the process of building renovation, primarily the building envelope, it is necessary to determine the condition of its non-transparent and transparent parts. Building envelope is important for its function and direct influence to health and wellbeing of inhabitants since it serves as the enclosure and controls indoor environment, thus necessity for heating, ventilation and air conditioning which are contributing to total energy consumption in buildings. Over the time, condition of the envelope can become worse due to material aging, usual wear and tear, physical and unplanned damages caused by human or other factor, occurrence of mold, chemical reactions with the environment etc. Condition of the building envelope is determined by its hygro-thermal properties – primarily heat transmission and vapor diffusion parameters. There are several methods to evaluate current state of the envelope – by visual periodical and standardized inspection [11] [12] made by the professional it is possible to notice many of irregularities prior to bigger damage, however, these inspections can sometimes be difficult and dangerous for necessity to reach high floors and hard reachable areas [13]. On the other hand, there are some irregularities caused by the design flaws and which can be detected only by using professional equipment; i.e. occurrence of thermal bridges or air infiltration on the seams between windows and walls etc. These faults can be detected by using drones or imaging devices e.g. Infra-Red Camera for thermal bridge inspection, Laser Scanners for deviations, RGB cameras and others to obtain visual information of the façade; and advanced measuring tools to precisely determine other physical properties such as heat transmittance and vapor diffusion.

2. Materials and Methods

There are two approaches to analyzing the condition of the building envelope – non-destructive and no-contact (simple and detailed visual inspection, thermal imaging using Infra-Red camera); and contact methods (Heat-Flow-Meter, electrodes for analyzing Relative Humidity) etc. Visual-and-instrumental inspection is widely used to determine general thermos-technical state of buildings, while

Latent defects of building envelope can be revealed through modern non-destructive methods of thermo-vision control [14].

This paper focuses on experimental methods. In the absence of building project documentation, it is often hard to gather all data, however, there are experimental methods available to calculate U-value. According to ISO 9869-1 [15], only reliable method is by using equipment for determination the heat transmittance consisting of a heat flux sensor and temperature sensor (interior ambient temperature and exterior ambient temperature probe) which are placed on a north wall in order to avoid direct solar radiation. Reliability of obtained results is affected by weather conditions such as sun, rain, wind, and temperature. However, in practice, there are difficulties to fulfill all requirements to conduct this method, what for there is an additional method that is measuring by using Infra-Red Camera. It calculates heat transmittance by measuring emission of the object, reflection temperature, surface temperature and temperature of the interior ambient temperature and exterior ambient temperature [16]. The measurement process used in this paper was followed using a high-precision multi-channel measuring device Almemo Albhorn 2690-8 (Table 1). This instrument allowed detailed and continuous monitoring. The data collection spanned for 72 hours, during which 144 data sequences were recorded, with measurements being taken every 30 minutes. This consistent and systematic approach ensured a comprehensive capture of the environmental conditions and their impact on the parameters being studied. Further thermal inspection, used in the QIRT method, was made with thermal image cameras FLIR b60 and InfRec Thermo GEAR G100 (Table 2).

Table 1. Properties of the measuring device Almemo Albhorn 2690-8 [17]

Precission class	AA
Measuring rate	50 mops (measuring operations per second)
Measuring inputs	5 input sockets
Measuring range	Over 65 measuring ranges
Sensor power supply (rechargeable batteries)	6/9/12 V, maximum 0.5 A
Atmospheric pressure sensor measuring range	700 to 1100 mbar
Atmospheric pressure sensor accuracy	± 2.5 mbar (at 23°C ±5 K)

Table 2. Properties of IR Camera FLIR b60 [18] and Thermo GEAR G100 [19]

	FLIR b60	Thermo GEAR G120/G100
Field of View	25° × 25°	32°(H) x 24°(V)
Thermal Sensitivity	< 0.1°C (0.25°C) / 100 m	0.06°C
Detector type	Uncooled microbolometer	Uncooled Focal Plane Array (microbolometer)
Spectral range	7.5–13 μm	8～14 μm
IR resolution	180 x 180 pixels	320(H) x 240(V) pixels
Object temperature range	-20°C to +120°C	-40°C to 500°C
Accuracy	±2°C or ±2% of reading	±2°C or ±2% of reading, whichever is greater
Emissivity table	0.1 to 1.0 adjustable or selected from list of materials	
Operation temperature range	-15°C to +50°C	-15°C to +50°C,
Humidity (operating and storage) range	24h 95% relative humidity	90% RH

2.1. Determining U-value using Theoretical Method – Case study of north-oriented façade wall

In order to theorethicaly determine U-value, several important indicators need to be evaluated, what is described in following chapter. First important unit is the Heat flux density (q) that presents a heat flux (Φ) which is transmitted through unit area (S), or in other words, heat quantity Q that is transferred in the measure of time $d\tau$ through unit area of the substance S [20].

$$q = \frac{\Phi}{S} = \frac{Q}{S_\tau} \tag{1}$$

Furthermore, when the unified element with planar surfaces is observed, such as building wall, Heat flux density (q) is determined as following [20]:

$$q = \frac{t_{wi} - t_{we}}{R_w} = \frac{t_{wi} - t_{we}}{\frac{d}{\lambda}} \tag{2}$$

where t_{wi} is the interior surface temperature of the building element, t_{we} is the exterior surface temperature of the building element, R_w is heat resistance to heat transmission of the flat wall layer, d represents the thickness of the wall, and λ is the thermal conductivity of the material). When the multilayer structure is observed, such as building façade wall, and when heat transfer coefficient from interior air to the wall (α_i) and from the wall to the exterior air (αe) is added, the following equation for calculating heat flux density is used [20]:

$$q = \frac{t_i - t_e}{\frac{1}{\alpha_i} + \sum_{i=1}^{n} \frac{d_i}{\lambda_i} + \frac{1}{\alpha_e}} \tag{3}$$

Finally, reciprocal value of the heat resistance to multilayered flat wall is called Heat Transmission Coefficient (U – Value) and is defined with following equation which is used to calculate U-values ($W/(m^2K)$) of the case study.

$$U = \frac{1}{R_t} = \frac{1}{\frac{1}{\alpha_i} + \sum_{i=1}^{n} \frac{d_i}{\lambda_i} + \frac{1}{\alpha_e}} \tag{4}$$

For precise calculations and preparation of project documentation for energy retrofit, a comprehensive analysis of current condition of the building is necessary. Most important determinant are thermal properties of the envelope, which directly influence to the thickness of thermal insulation, according to desired energy grade. Heat transmittance coefficient (U – value, W/m^2K) is defined by ISO 7345 standard as heat flow rate in the steady state divided by area and by the temperature difference between the surroundings on each side of a system [21].

$$U = \frac{q}{t_i - t_e} \tag{5}$$

that is, the U-value can be obtained by measuring the heat flux density (q) and the temperature difference between the interior environmental (ambient) temperature (t_i) and exterior environmental (ambient) temperature (t_e) air during stationary heat transfer.

Most precise method to determine U-value of the wall is the theoretical one, for which the following parameters need to be known - heat transfer coefficient from interior air to the wall (α_i) and from the wall to the exterior air (α_e), thickness of the materials in the element and their respective thermal conductivity λ. Briefly, below is shown a process of defining U-value according to Theoretical Method whose values will be reference for other two experimental methods.

ISO 6946:2017 standard defines this method as a way to calculate heat resistance and heat 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 or resistances of materials. This approach is applicable to components and elements composed of thermally consistent layers, which may incorporate air layers [22]. For the calculation, and in accordance to ISO 6946:2017, internal surface heat resistance (R_{si}) and external surface heat resistance (R_{se}) is taken in the following values: $1/\alpha i = R_{si} = 0.125\ m^2K/W$; $1/\alpha e = R_{se} = 0.04\ m^2K/W$.

Finally, calculated U-value for the element (eq. 4), according to theoretical method is U = 1.366 W/m^2K.

2.2. Determining U-value of north-oriented façade wall using Heat-Flow-Meter Method

In order to experimentaly asses the U-value for the sample in the façade wall, an on-site measurement using Heat-Flow-Meter method was performed according to ISO 9869 – 1 [15]. Heat flux density, interior and exterior ambient temperature, and envelope temperatures on the surfaces of ending elements were measured on the case study of the building from Figure 1.

Figure 1. Case study building from the period of 1971-1980 in Banja Luka, Republic of Srpska, Bosnia and Herzegovina

Before defining the measurement location, an inspection of the envelope was carried out with a thermal imaging camera, in order to avoid two-dimensional and three-dimensional loses of heat through the envelope (thermal bridges), and various irregularities of the element caused by time. After the surveying, the western-oriented parapet wall in the loggia on the second floor is chosen for further calculations. It is also a characteristic element of the envelope (d = 33.5 cm) consisting of following layers - cement mortar 1.5 cm, thermal block 30 cm, cement mortar 2 cm (Table 3).

Table 3. Physical properties of the material in the wall ensemble

Wall 1	Layer thickness [cm]	λ - Thermal Conductivity [W/mK]	Density [kg/m^3]
Cement mortar (exterior)	2	0.70	1900 kg/m^3
Cinder block	30	0.58	1400 kg/m^3
Cement mortar (interior)	1.5	0.70	1900 kg/m^3

For measuring point on the envelope of the room (living room), due to the measurement demands defined by ISO 9869 - 2 [23], the windows were completely closed for three days (72 hours), while the door of the room was in an open position. The measuring device plate is placed on the inside of the parapet wall vertically in the middle from the floor to the window, as well as horizontally from the heating element (radiator) to the partition wall.

The measurement began early in the week, specifically on Monday morning at 8 a.m., and continued uninterrupted until Thursday morning at 7:30 a.m. During this period, the external environmental conditions were carefully observed and noted what is visible from the Figure 2. The average outside temperature was recorded at approximately -5.4°C, with the weather remaining clear and free of precipitation. This stable external environment contributed to the reliability of the data collected, as fluctuations due to varying weather conditions were minimal. The average measured interior ambient temperature (t_i) was 21.8°C.

After collecting data, there are three different approaches to determine U-value. All three approaches are made for 144 measured points (each on 30 minutes of difference). In the following text only the median U-value for each method will be presented, and, afterwards, they will be compared to show a statistical difference between three of them.

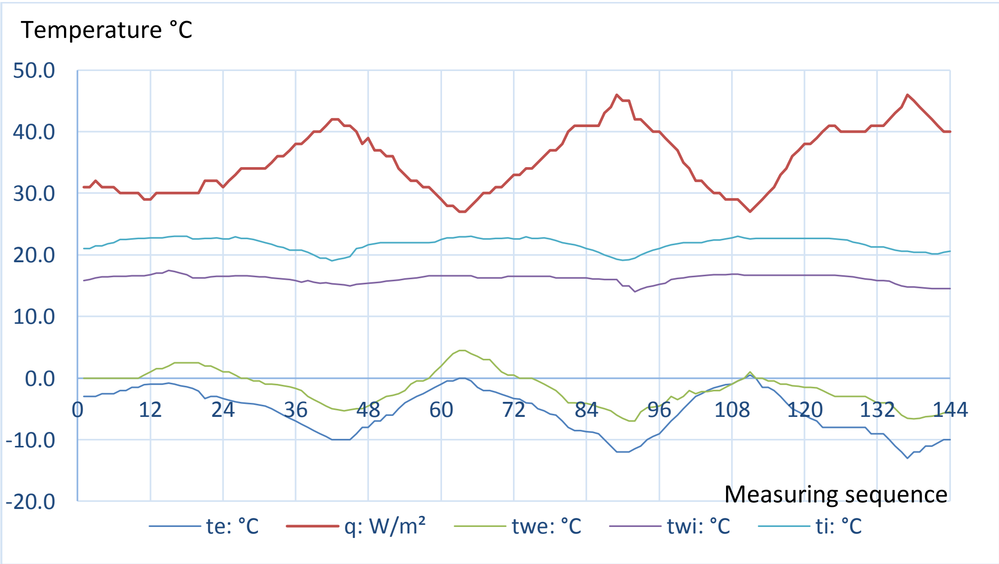

Figure 2. Extracted values through 72 h measuring period; t_e – exterior ambient temperature, q – heat flux density, t_{we} – exterior surface temperature, t_{wi} – interior surface temperature of the building element, t_i – interior ambient temperature

The basic relation (equation 5) when, in addition to the value of the heat flux density (q), the parameters of the air temperature inside (t_i) and outside the room (t_e) take part in the calculation. According to this relation, U-value has been calculated for all of the 144 measured points in time, and the mean U-value is U = 1.365 W/m²K.

Furthermore, from the basic relation (equation 5), and assuming stationary conditions, two more relations can be derived (eq. 6 and eq. 7), to justify the application of Internal surface thermal resistence ($R_{si} = \frac{1}{\alpha i} = 0.125\ m^2K/W$), and External surface thermal resistence ($R_{se} = \frac{1}{\alpha e} = 0.04\ m^2K/W$).

In the case when interior ambient temperature (t_i) changes its values (i.e. temperature difference among z axis where warmer air naturally streams upwards), besides heat flux density (q), exterior surface temperature (t_{we}), and interior ambient temperature (t_{wi}), as well as R_{si} and R_{se} is taken in the consideration:

$$U = \frac{1}{\frac{1}{\alpha_i} + \frac{t_{wi} - t_{we}}{q} + \frac{1}{\alpha_e}} \tag{6}$$

According to this relation, U-value has been calculated for all of the 144 measured points in time, and the median U-value is U = 1.5 W/m²K.

The sensors of the measuring device are sensitive to direct solar radiation, precipitation and wind, and in order to completely exclude such meteorological influences, the equation 7 is used:

$$U = \frac{1}{\frac{1}{\alpha_i} + \frac{t_{wi} - t_e}{q}} \tag{7}$$

In addition to the heat flux density, temperature of interior surface temperature (t_{wi}) and the exterior air temperature (t_e) are used. According to this relations, U-value has been calculated for all of the 144 measured points in time, and the mean U-value is U = 1.3 W/m²K.

By comparing the results from all three equations (Table 4), there is a noticeable deviation when using equation (5) - U (q, t_i, t_e), and (6) – U (q, t_{wi}, t_{we}). Analyzing this data, most reliable approach is to implement equation (7) and use parameters for heat density flux (q), temperature of interior surface temperature (t_{wi}), and exterior ambient temperature (t_e), since it has least differences through all measuring points related to theoretical U-value.

Table 4. Heat transmission coefficient (U-value) according to measured data using HFM method

Equation	Eq. (5)	Eq. (6)	Eq. (7)	Mean value
	$U1 = \frac{q}{t_i - t_e}$	$U2 = \frac{1}{\frac{1}{\alpha_i} + \frac{t_{wi} - t_{we}}{q} + \frac{1}{\alpha_e}}$	$U3 = \frac{1}{\frac{1}{\alpha_i} + \frac{t_{wi} - t_e}{q}}$	$U = \frac{U1 + U2 + U3}{3}$
U - value	U = 1.365 W/m²K	U = 1.5 W/m²K	U = 1.3 W/m²K	U = 1.388 W/m²K

Three U-value measurements —1.365 W/m²K, 1.5 W/m²K, and 1.3 W/m²K, were analyzed to derive key statistical insights. The mean U-value is calculated to be 1.388 W/m²K, indicating the average heat transmittance across the samples. The standard deviation (S), which measures the variation of the values, was found to be 0.102 W/m²K, reflecting a moderate level of dispersion around the mean what can be seen in equation 8.

$$S = \sqrt{\frac{\Sigma(x_i - \bar{x})^2}{n-1}} = \sqrt{\frac{(1.365-1.388)^2+(1.5-1.388)^2+(1.3-1.388)^2}{3-1}} = 0.102 \text{ W/m}^2\text{K} \tag{8}$$

The range, calculated as the difference between the maximum and minimum U-values, was 0.2 W/m²K, highlighting the extent of variation in the measured values. Together, these statistics provide a comprehensive view of the reliability and consistency of the U-value measurements (Figure 3).

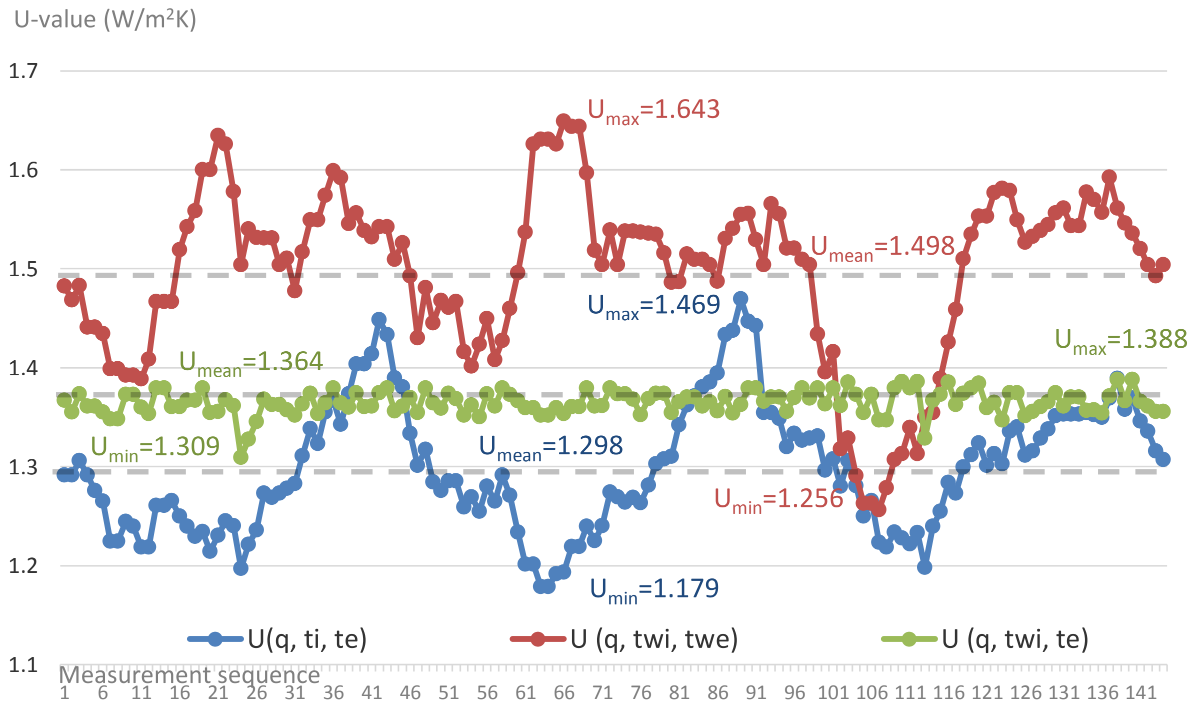

Figure 3. Comparing the results of three relations in 72 h period (144 samples)

This process involved meticulous data collection using the HFM method, which is known for its precision in measuring heat flux and temperature gradients across a material or building component. By employing various calculation methods, each utilizing the same set of experimental parameters, a comprehensive understanding of the U-value was obtained. The consistency in the derived U-value across different approaches underscores the reliability of the HFM method. Furthermore, Figure 3 shows the difference between three relations during 72 hours period (144 examples).

2.3. Determining U-value using Quantitative Infra-Red Thermography (QIRT) (ISO 9869 – 2) – Case study of north-oriented façade wall

Thermal imaging is a non-invasive method that enables non-contact determination of surface temperature based on the emitted electromagnetic radiation in the long-infrared range. According to Stefan Boltzmann's law the net radiated power per unit area (q) is proportional to the fourth power of absolute temperature (T) and also depends on the emissivity (ε) of the body (type of material):

$$q = \varepsilon \sigma T^4 \tag{9}$$

where σ is Stefan Boltzmann's constant $\sigma = 5.67\times10^{-8}$ W/(m^{2}K^4).

From the date of the temperature distribution on a surface, as well as the amount of infrared energy that is emitted, transmitted, and reflected, a thermogram is obtained - an image in which the different temperatures are represented by different colors. This imaging method can be applied for non-destructive testing, quality inspection in materials, civil engineering and building sciences [24]. Inhomogeneities in the material near the structural elements surface will result in a different temperature and color; this is especially important in the case of moisture presence. IRT building diagnostic includes determination of thermal characteristics of the envelope, detection of thermal bridges and areas of increased heat loss, air leakage, thermal insulation damage, presence of moisture [25].

Case study in this paper is existing wall of the building from the period of 1970 - 1980 whose envelope condition is in the state in need of renovation. Thus, this method can provide insights to the current condition of the envelope and approximately determine existing U-value as main input parameter for further process of designing envelope refurbishment. Measurements on the envelope are performed in accordance with the standard ISO 6781-1:2023 [26]. In the case of U-value assessment by IRT application, there is no prescribed normative. However, in some of papers suggestions were given in order to determine the U-value in non-contact and non-invasive manner. According to Albatici and Tonelli [27] as well as, Nardi et al. [28] the transmittance value can be determined through IRT, by measuring surface temperature of element T_w, interior ambient temperature T_{int}, and the exterior ambient temperature T_{out}. The following relation also requires defined the wind velocity v and emissivity of the material ε_{tot}:

$$U = \frac{5.67 \cdot \varepsilon_{tot} \left[\left(\frac{T_w}{100} \right)^4 - \left(\frac{T_{out}}{100} \right)^4 \right] + 3.8054 v (T_w - T_{out})}{(T_{int} - T_{out})} \quad (10)$$

It should be noted that some of the authors have suggested a new methodology based on the measuring exterior and interior ambient temperature and the interior surface temperature in order to avoid the influence of external climatic conditions [29].

Qualitative method is conducted using Infra-Red camera FLIR b60. Thermal image of the sample is shown of the Figure 4 which shows following parameters – wall temperature (-0.1°C), material emissivity ε = 0.97), and temperature gradient (range (-7°C) – 21°C). For accuracy purposes, and to get statisticaly as precise data, thermal imaging is redone with other thermal imaging camera (Figure 5).

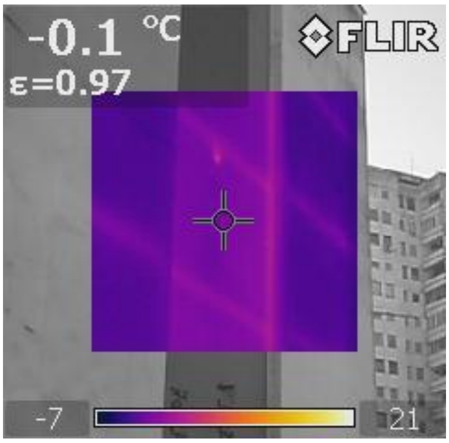

Figure 4. Thermal image of the north oriented façade wall made with FLIR b60

Thermal image (Figure 5) of the north-oriented façade wall, captured using the Thermo GEAR G100, shows temperature variations across the surface. Measured temperature points on the surface will be used to determine the U-value using experimental method. This analysis will help identify areas of heat loss or insulation issues, providing valuable insights into the building's energy efficiency and structural performance.

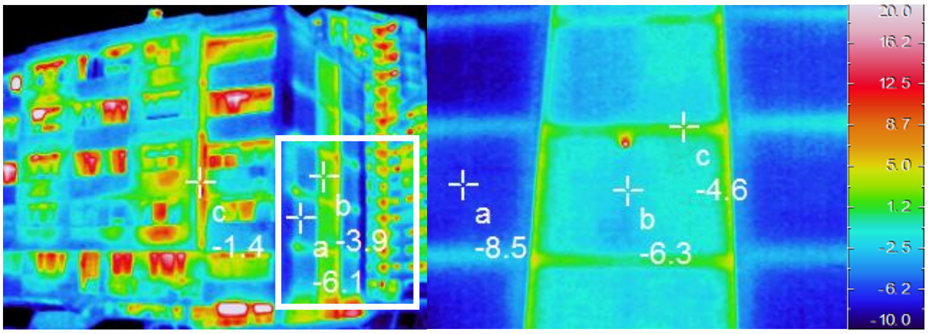

Figure 5. Thermal image of the north oriented façade wall made with Thermo GEAR G100

Thermal images of non-transparent elements show that the same elements viewed from different distances have different values. Looking at the same element as previously, which is north oriented façade wall (Table 3), thermal image made with different camera shows temperature of external surface of the wall (t_{we}) – point b (-6.3°C). It should be noted that environment conditions when the object is screened were also different with outside temperature of -11°C. The average wind speed measured around this sample does not exceed 1 m/s, i.e., the west – north-west, 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 heat transmittance coefficient values of the building, which are not already provided for by the standard [22].

Table 5. shows the data gathered using two cameras together with climatic data in that period.

Table 5. Measured data for calculation of U-value using two IR Cameras

		FLIR b60		Thermo GEAR G100	
Parameter/ unit		Measured	Conversion	Measured	Conversion
t_{int}	indoor environment temperature	21.8°C	294.95 K	20.4°C	293.55 K
t_{out}	outdoor environment temperature	-5.4°C	267.75 K	-11°C	262.15 K
t_{we}	exterior surface temperature	-0.1°C	273.05 K	-6.3°C	266.85 K
ε	emissivity of the material	0.97	/	0.97	/
v	wind velocity	0.6 m/s	/	1 m/s	/
U - value		1.292482 W/m²K		1.1789 W/m²K	

3. Results and discussion

The methods previously demonstrated for determining the U-value have yielded notably accurate results, especially when considering that these methods are inherently experimental and subject to external factors that are often difficult to control. Despite these challenges, the procedures described are relatively straightforward to perform. Among them, the Heat Flow Meter (HFM) method stands out as the most reliable experimental approach recognized by ISO standards. While the HFM method has been rigorously analyzed, yielding minimal deviations ranging from -4.17% to +1.61% in the case of equation (7), the Quantified Infrared Thermography (QIRT) method also produced remarkably accurate results. The deviations observed using the QIRT method ranged from -5.38% to -13.70% when compared to the theoretical U-value. Such deviations are within acceptable limits, reinforcing the viability of QIRT as a practical method for U-value determination.

In the analysis of the HFM method, a particular emphasis was placed on equation (7), which employed three critical parameters: the external air temperature (t_e), heat flux density (q), and the internal surface temperature of the wall (t_{wi}), along with the heat transfer resistance coefficient (R_{si}) from the interior air to the wall.

For each method, the mean U-value was calculated, and deviations from the theoretical value were recorded, leading to the final determination of the heat transmittance coefficient (U-value) as summarized in Table 6.

Table 6. Comparison of the results from the three methods to calculate U-value with a show of minimum and maximum calculated U-values, mean value and deviations to theoretical U value.

Method	ISO standard	U-value (variants) W/m²K	U_{min}	U_{max}	U_{mean}	Deviation to TM U-value	U-value final
TM	ISO 6946:2017	1.366	1.366			0 %	1.366
HFM	ISO 9869 – 1	$U1 = \frac{q}{ti - te}$	1.179	1.469	1.365	- 13.68 % to + 7.54 %	1.39
		$U2 = \frac{1}{\frac{1}{\alpha i} + \frac{twi - twe}{q} + \frac{1}{\alpha e}}$	1.256	1.643	1.50	- 8.05 % to + 20.27 %	
		$U3 = \frac{1}{\frac{1}{\alpha_i} + \frac{t_{wi} - t_e}{q}}$	1.309	1.388	1.30	- 4.17 % to + 1.61 %	
QIRT	ISO 9869 – 2	Flir b60 camera	1.292482			- 5.38 %	1.29
		Thermo GEAR G100 camera	1.1789			-13,70 %	1.1789

This comprehensive analysis demonstrates that all three methods are viable for U-value determination. However, the precision of each method is dependent on the specific parameters employed in the calculations, the quality of the equipment used, and the influence of environmental factors. In the end, while each method has its strengths and limitations, the choice of method should be guided by the desired accuracy, available resources, and the specific conditions of the environment where the measurements are conducted. By carefully selecting and controlling the parameters and equipment, it is possible to achieve reliable and precise U-value measurements across different methods.

4. Conclusion

- This paper presented three methods to determine the heat transmission coefficient (U-value) in existing opaque façade walls. The methods are valuable for evaluating the condition of the building envelope when project documentation is unavailable. Each method presented in this paper has its benefits and downsides, with some being easier to conduct than others due to the difficulty in meeting standard prerequisites for accurate results.
- Physical properties such as thermal irradiation, interior and exterior temperatures, wind properties, and transmittance resistance are crucial in determining the U-value — an essential parameter for building retrofitting. Hygro-thermal properties of the envelope can be assessed through visual inspection while thorough evaluation requires specialized equipment (IR camera, Heat Flow Meter, moisture measuring electrodes, wind velocity measuring device or data etc.).
- Statistical analysis showed differences in the clarity and precision of each method, with each yielding promising results in the experimental determination of the U-value. Results showed

deviations from the theoretical U-value ($U_{theor.}$ = 1.366 W/m²K), with the HFM method showing deviations ranging from S = -4.17% to S = +1.61% and a mean U-value of U_{mean} = 1.39 W/m²K. The QIRT method showed a deviation of S = 5.38% with a mean U-value of U_{mean} = 1.29 W/m²K.

- The HFM method showed the closest results to the theoretical value, making it the most reliable for in-situ measurements. However, the deviation of slightly above 5% in the QIRT method is very promising, especially when the conditions are optimal, and when the availability of equipment is limited.
- Future research could explore developing methods like the heat box and analyze the relevance of each method under adjusted or in-situ conditions.

Acknowledgment

The authors acknowledge the support of the European Research Executive Agency (REA) for funding this research under the project "ENPOWER – Enhancing Scientific Capacity for Energy Poverty (101160253 — ENPOWER — HORIZON-WIDERA-2023-ACCESS-02)".

Nomenclature

TM – Theoretical Method
QIRT – Quantitative Infra-Red Thermography
IR – Infra Red Camera
HFM – Heat Flow Meter
GHG – Green House Gasses
t – temperature [°C]
U – heat transmittance coefficient [W/m^{2}K]
S – Surface Area [m^2]
R – thermal resistance coefficient from interior air to the wall [m^{2}K/W]
d – thickness of the material [cm]
v – wind velocity [m/s]
K – kelvins
V – variance
S – Standard deviation

Greek letters
α_e - thermal transfer coefficient from the wall to the exterior air [–]
α_i - thermal transfer coefficient from interior air to the wall [–]
λ – thermal conductivity [W/mK]
Φ – heat flow rate for the heating mode [kW]
q – heat flux density [W/m^2]
ε – emissivity of the material [–]
σ – Stefan Boltzmann's constant [5.67×10^{-8} W/(m^{2}K^4)]

Subscripts
$Q_{H, nd}$ – Energy need for heating [kWh] [mWh]
t_{int} - interior ambient temperature [°C] [K]
t_{out} - exterior ambient temperature [°C] [K]
t_w - surface temperature of the wall [°C] [K]

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Submitted: 10.08.2024.

Revised: 01.10.2024.

Accepted: 11.10.2024.