INFRARED THERMOGRAPHY FOR DYNAMIC THERMAL TRANSMITTANCE DETERMINATION

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Abstract

The aim of this paper is to show a new possibility for in situ U-value determination using infrared thermography (IRT) method and its comparison with heat flux method (HFM). It also gives procedure for conducting the experiment and for the analysis of measured data. Average method and dynamic method given in ISO 6869 were used for data analysis, and results obtained using dynamic method show higher level of accuracy than ones obtained by average method. Results obtained using IRT method are much closer to theoretical values with differences between 0-19% respectively of the method used to approximate surface heat transfer coefficient. Since dynamic method is much more sophisticated than average method, its procedure had to be implemented using Excel VBA. The main conclusion was that use of infrared thermography could be used, together with dynamic method of analysis, for relatively fast and accurate in situ U-value determination.

Keywords: heat transfer coefficient, infrared thermography, heat flux method, dynamic method, average method

1. INTRODUCTION

Thermal properties of building elements are determined by heat transfer coefficient or U-value [W/m^{2}K], which is the initial parameter for determining heating and cooling energy demands [1]. If one dimensional heat flow is assumed, then thermal transmittance, or U-value, is determined as the inverse value of total thermal resistance according to ISO 6946 [2] – equation (1).

$$U = \frac{1}{1/h_{si} + \sum_{k=1}^{n} d_k/\lambda_k + 1/h_{se}} \tag{1}$$

where d_k is thicknesses [m] and λ_k are thermal conductivities [W/(m K)] of each layer, and h_{si} and h_{se} are surface heat transfer coefficients [W/(m^2 K)] which quantify heat transfer from internal and external air to element surface.

U-value determined using equation (1) does not consider the irregularities of the materials and degradation of external coating elements caused by aging, and these effects can significantly affect the difference between the theoretical and actual U-value of the element [3]. It is necessary to measure the heat transfer coefficient in situ in real atmospheric conditions to check if real heat losses through building elements are close to designed values. In the case of existing buildings energy efficiency (thermal characteristics) will decline during period of exploitation. These buildings require a means of reducing energy consumption and improving energy efficiency, but to know a baseline value of energy consumption, and to be able to calculate energy savings as well as return on investment, one needs to know the real U-value of building elements [4].

ISO 9869 [5] gives easy and efficient method for determining real thermal resistance and U-value using a heat flow meter method (HFM). Method described is based on measuring heat flow density while simultaneously measuring inside and outside air temperature. Main disadvantage of HFM method is that it gives results only for one or few data points (depending on how many heat flux sensors are used). Furthermore, to get satisfactory results, minimal temperature difference of 10 °C is needed. Measurement is also influenced by thermal bridges, mould, humidity, adhesion between sensor and element surface, etc. Because of that real U-value differ from theoretical U-value and that difference is greatest in historical buildings where it can be up to 60% [6]. In their work Gaspar et al. [7] use dynamic method to show its superiority over average method. They showed that the difference between the theoretical and measured U-value is lower when dynamic method is used. When the environmental conditions for carrying out in-situ measurements were optimal the differences were lower than ±5% when average method is used, but lower than ±1% when dynamic method was used. If average method is used for data analysis, then it is not possible to capture effect of heat storage in the building elements. Average method is valid for heavier building elements with specific heat per square meter greater than 20 kJ/(m^2 K) [5]. If large variations occur in measured temperatures and heat flow rates, then dynamic method must be used. In practice, however, HFM method can, with above disadvantages, be too expensive and time-consuming. With ideal boundary conditions, measuring time should be 72 hours, otherwise it should be more than 7 days.

This paper suggests a new method which, unlike HFM method that measures heat flux, is based on approximation of heat flux from measured surface temperatures of the element using Infrared thermography (IRT) method, and data analysis using dynamic method. Comparison of U-value calculated using theoretical formulae, HFM and IRT method is also given.

2. HEAT FLUX METHOD

2.1 U-value determination according to ISO 9869

ISO 9869 gives two methods for analysing measured data: average and dynamic method.

2.1.1 Average method

This method assumes that the U-value can be obtained by dividing the mean density of heat flow rate by the mean temperature difference, the average being taken over a long enough period. U-value is calculated by equation (2):

$$U = \frac{\sum_{j=1}^{N} q_j}{\sum_{j=1}^{n} \left(T_i - T_e\right)_j} \tag{2}$$

where q_j is heat flux density [W/m^2], T_i and T_e are internal and external air temperatures air temperatures [K] and index j enumerates the individual measurement.

If IRT method is used instead of HFM method then U-value is calculated using equation (3):

$$U = \frac{\sum_{j=1}^{N}\left(q_{rad} + q_{conv}\right)_j}{\sum_{j=1}^{n}\left(T_i - T_e\right)_j} \tag{3}$$

where q_{rad} and q_{conv} are radiative and convective heat flux densities and their sum approximates the heat flux [W/m^2]. Their determination is given in chapter 3.

2.1.2 Dynamic method

The dynamic analysis method is a sophisticated method which may be used to obtain the steady-state properties of a building element from HFM measurements when large variations occur in temperatures and heat flow rates. It considers the thermal variations using the heat equation. The building element is represented in the model by its thermal conductance and several time constants τ [4].

The assumption of the dynamic method is that the heat flux rate in some time j is a function of the temperature in that time and all the preceding times – equation (4).

$$\begin{aligned} q_j = {} & U \cdot \left(T_{i,j} - T_{e,j}\right) + K_1 \cdot \dot{T}_{i,j} + K_2 \cdot \dot{T}_{e,j} \\ & + \sum\nolimits_n P_n \cdot \sum\nolimits_{k=j-p}^{j=1} T_{i,k} \cdot \left(1 - \beta_n\right) \cdot \beta_n \cdot \left(j - k\right) \\ & + \sum\nolimits_n Q_n \cdot \sum\nolimits_{k=j-p}^{j=1} T_{e,k} \cdot \left(1 - \beta_n\right) \cdot \beta_n \cdot \left(j - k\right) \end{aligned} \tag{4}$$

where K_1, K_2, P_n and Q_n are dynamic characteristics of the wall and they have no physical significance. In equation (4) p represents subset of data points used for numerical integration corresponding to sum over j. The variables β_n are exponential functions of the time constant τ_n.

Dynamic method given in ISO 9869 is used for analysis of data collected using HFM method. The aim of this paper is to use dynamic method in combination with IRT without the need of measuring heat flux using heat flux meters. $\dot{T}_{i,j}$ and $\dot{T}_{e,j}$ represent backward difference derivatives of temperatures T_i and T_e in every time increment Δt.

Using enough sets of data at various times, an overdetermined system of linear equations is created using equation (5):

$$\{q\} = [X] \cdot \{Z\} \tag{5}$$

If m time constants are chosen (τ_1, τ_2, … τ_m), then we have 2m + 3 unknown parameters which are given by equation:

$$U, K_1, K_2, P_1, Q_1, P_2, Q_2, \ldots, P_m, Q_m \tag{6}$$

Writing equation (4) 2m + 3 times for 2m + 3 sets of data at various times, a system of linear equations can be solved to determine parameters given by equation (6). First solution of that system of equations is heat transfer coefficient or U-value.

According to ISO 9869 one to three time constants are needed ($\tau_1 = r \cdot \tau_2 = r^2 \cdot \tau_3$) to properly represent interrelation between q, T_i and T_e, where r is the ratio between time constants.

Even though dynamic method is more robust than average method it can be used for relatively fast and accurate in situ U-value determination. Equation (5) is solved by least square method by varying time constants τ_n through the procedure described in ISO 9869 (Figure 1).

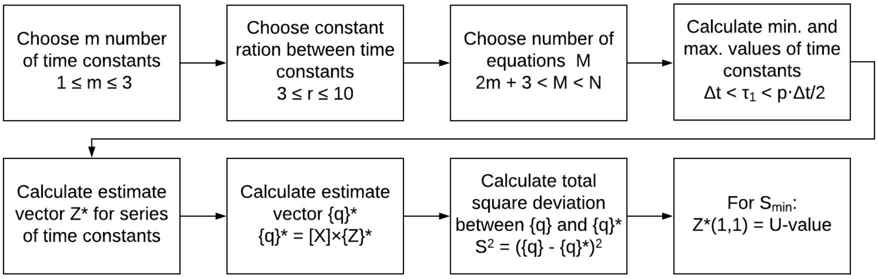

Figure 1 : Procedure for least square method described in ISO 9869

Procedure shown in Figure 1 was implemented in Excel VBA.

To evaluate the quality of results, uncertainty is calculated according to the following equation:

$$I = \sqrt{S^2 \cdot Y(1,1)/(M-2\cdot m-4)} \cdot F(P, M-2\cdot m-5) \tag{7}$$

where S^2 is total square deviation between $\{q\}$ and its estimate $\{q\}^*$, $Y(1,1)$ is the first element of the matrix $[Y] = ([X]^T \times [X]^{-1})$ and F is the significance limit of Student's t-distribution, where P is the probability (P = 0,95) and M – 2m – 5 is the degree of freedom.

In the case I is smaller than 5% of U-value, than the computed U-value is generally very close to the actual value.

3. APPROXIMATION OF HEAT FLUX USING IRT METHOD

Since heat transfer by conduction, in steady state conditions, is equal to the sum of radiative and convective heat transfer it is possible to determine the heat flux that causes transfer of heat from the fluid to the surface and vice versa – equation (8):

$$\begin{aligned} q_{cond} &= q_{conv} + q_{rad} \\ q_{conv} &= h_c \cdot (T_i - T_{si}) \\ q_{rad} &= h_{rad} \cdot (T_i - T_{refl}) \end{aligned} \tag{8}$$

where q_{cond}, q_{conv} and q_{rad} are conductive, convective and radiative heat transfer rate [W/m^2], h_c and h_r are convective and radiative surface heat transfer coefficient [W/(m^2 K)], T_i and T_{si} are inner air temperature and surface temperature [K].

For temperatures which occur in building physics (i.e. -10 °C up to 50 °C), radiative heat transfer is calculated using equation (9).

$$h_r = \varepsilon \cdot \sigma \cdot (T_i^4 - T_{refl}^4)/(T_i - T_{si}) \tag{9}$$

where ε is surface emissivity, σ is Stefan-Boltzmann constant ($\sigma = 5{,}67\times10^{-8}$ W·m^{-2} K^{-4}) and T_{ref} is reflected temperature [K].

On the other hand, the convective heat transfer coefficient is influenced by several factors, such as the geometry of the building element, element surroundings, the position at the building envelope, the building surface roughness, wind speed, wind direction, local air flow patterns and surface to air temperature differences [8–11]. There are different values to determine convective heat transfer coefficient – analytical, numerical and experimental methods. Experimental methods showed like the main source for calculating convective heat transfer coefficient. These experiments lead to empirical formulae that are derived from a wide range of situations where the reference temperature is typically chosen at a position close to the wall or in the middle of the test rom. Surface heat transfer coefficient can be determined by least square curve fitting using equation (10) from experimental data. In the case of natural convection coefficient h_c can be expressed using equation (10) for all surfaces.

$$h_c = C \cdot \Delta T^n \tag{10}$$

where C and n are constants that are used for curve fitting and $\Delta T = T_i - T_{si}$. Table 1 shows various choices for constants C and n together with authors who studied the natural convection and derived the corresponding empirical expressions.

Table 1: The convective heat transfer coefficients in the case of the natural convection [12]

Authors	**h_c [W/(m² K)]**	**Authors**	**h_c [W/(m² K)]**
Awbi et al. [13]	$1{,}49 \times \Delta T^{0{,}345}$	Nusselt [17]	$2{,}56 \times \Delta T^{0{,}250}$
Khalifa et al. [14]	$2{,}07 \times \Delta T^{0{,}230}$	Heilman [18]	$1{,}67 \times \Delta T^{0{,}250}$
Michejev [15]	$1{,}55 \times \Delta T^{0{,}330}$	Wilkers et al. [19]	$3{,}04 \times \Delta T^{0{,}120}$
King [16]	$1{,}51 \times \Delta T^{0{,}330}$	ASHRAE [20]	$1{,}31 \times \Delta T^{0{,}330}$

4. EXPERIMENTAL SETUP

Measurement was carried out at the Faculty of Civil Engineering, University of Zagreb. Examined wall is composed of the following layers: thermal insulating plaster on exterior side, concrete and lime cement mortar on interior side. Figure 2 shows thicknesses and thermal properties of each component built in the wall. Using those values theoretical U-value is determined: $U_t = 1{,}67 - 1{,}76$ W/(m² K). Since properties of the concrete used in the wall are not known, λ is taken in the range from 2,00 for regular concrete to 2,60 for reinforced concrete as shown in Figure 2.

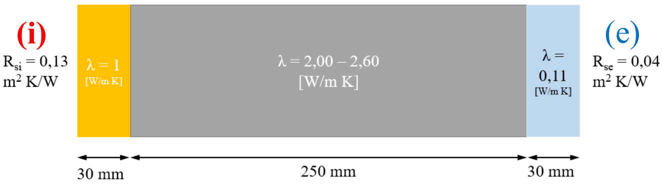

Figure 2: Thicknesses and thermal properties of examined wall

4.1 Measuring procedure

Time step for data collection was set to 10 minutes. Measurement was carried out in the period between 14th of December 2018. and 17th of December 2018. Measurement time duration was 72 hours (433 data points). Heat flux sensor was placed on the same wall with thermocouples for measuring internal and external air temperatures (Figure 3a). Surface temperature was measured using duct tape of known emissivity (ε = 0,95) with Box ROI named “Wall temp.” shown in Figure 3b. After extensive background analysis of the influence of the position of Box ROI on the results (U-value, convective coefficients) it was concluded that position of Box ROI was not an important parameter – U-value for different positions varied from around 3 to 5%. Reflected temperature was measured using aluminium foil with Box ROI named “Refl. Temp” shown in Figure 3b. Both surface temperature and reflected temperature were calculated as average temperatures inside of used Box ROI. Analysis was done with both average and dynamic method for both IRT and HFM method. Exterior wall surface is not exposed to outside environmental conditions – rain, direct solar radiation, etc. Camera parameters were set as: reflected temperature 25,0 °C, relative humidity (RH) 60%, atmospheric temperature 22,5 °C and distance of camera from the surface 2,70 m.

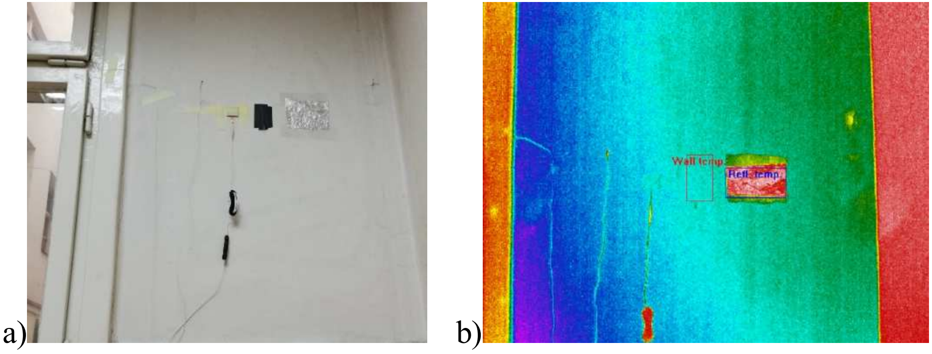

Figure 3: a) Measurement setup (IRT and HFM method); b) One of the thermograms used for analysis in IRT method

5. RESULTS

The collected datasets of 433 readings were used to calculate the U-value and uncertainties using the average method (**U$_{avg}$**) and the dynamic method (**U$_{dyn}$**). One time constant was adopted because it gave best confidence interval (from 2,13 to 3,87%).

Figure 4 shows comparison between U-values determined using HFM and IRT method and their comparison to theoretical U-value. U-value determined using IRT method is closer to the theoretical value – maximum error is around 19% at the end of the measuring period.

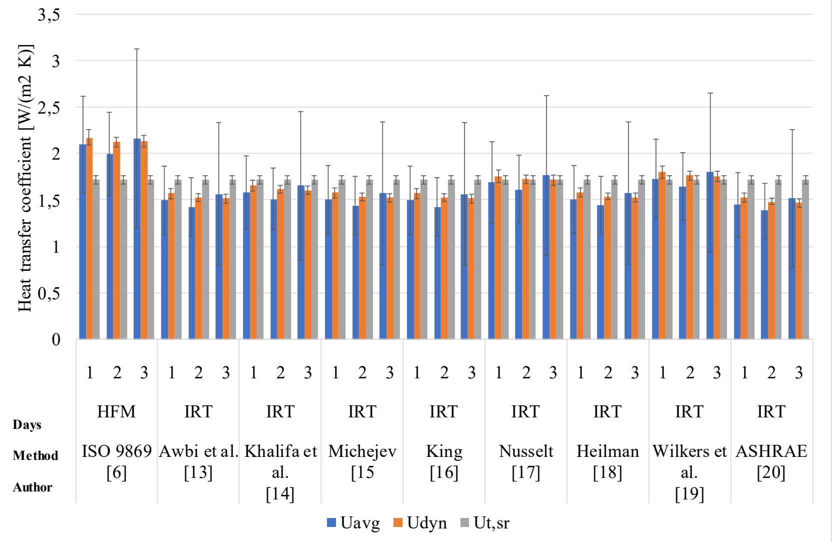

Figure 4: Theoretical U-value and measured thermal transmittance using the average and dynamic methods for HFM and IRT methods

On the other hand, if Wilkers et al. [19] empirical formula is used for determining convective heat transfer coefficient, then difference between theoretical and dynamic U-value is only 0,11%. U-value calculated using HFM method differs from theoretical value by 22 to 30% if measuring period is equal to 3 days (for both Average and Dynamic method). It can be observed in Figure 5 that dynamic method is more stable than average method for any measuring period – difference between U-value calculated after 1 and 2 days is less than 2% of U-value after 3 days. If average method is used maximal difference is around 8%.

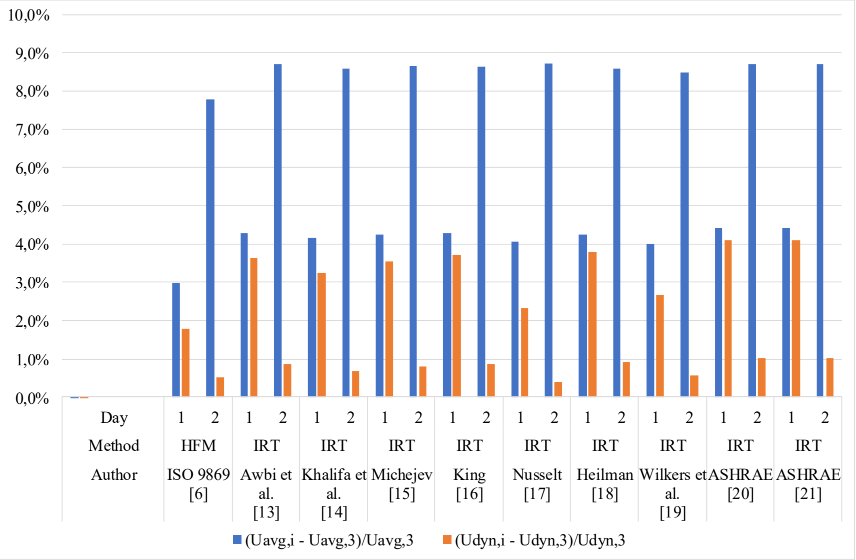

Figure 5: Relative errors between calculated U-values for different measuring period (i = 1,2 days)

6. CONCLUSIONS

This paper shows that there is potential for using IRT for calculation of U-value in real environmental conditions in situ, but firstly case study for different types of building elements and different environmental condition is needed to determine method credibility.

Real environmental conditions were used to determine U-value and even though surface was not ideal (isothermal) it was shown that using IRT method it is possible to determine U-value that is close to the theoretical with difference between 0-19% respectively of the method used to calculate convective heat transfer coefficient. Furthermore, it was shown that dynamic method, in combination with IRT method, could be used for relatively fast and accurate in situ U-value determination.

Determination of U-value by infrared thermography is still under development. To improve the given model, both HFM and IRT methods should be simultaneously used so surface heat transfer coefficient can be determined and correlated for future reference. These measurements will give further insight into why these differences occur and which method is better and under which conditions.

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