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Experimental Analysis of Thermo-Technical Parameters of Windows Glazing in the Pavilion Laboratory

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Abstract: Improving the energy performance of buildings in the context of external climatic conditions and the requirements of indoor environments is a hot topic in the construction industry. It primarily concerns reducing the energy used for heating and cooling in buildings. In the EU sector, this is addressed by the Energy Performance Directive (EPBD), which is followed by relevant national standards. The energy performance of buildings is strongly influenced by the window structures that are part of the building envelope. Their influence on energy performance is represented by the heat transfer coefficient, which differs in the actual built-in window construction from the design value given by the manufacturer. In this paper, the authors deal with its measurement in situ using the heat flux measurement method. The measurement was carried out in the pavilion laboratory of the Department of Building Engineering and Urban Planning (DBEUP), Faculty of Civil Engineering (FCE), University of Zilina (UNIZA), on three window constructions of different material bases. During the measurements, surface temperatures on the glazing, heat flux density, and air temperatures were recorded in minute increments. The influence of the year-round cycle of the outdoor environment on the embedded window structures is presented and the results are presented in the conclusion of the paper.

Keywords: window; U-value; surface temperature; heat flow density; pavilion laboratory

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1. Introduction

Thermal protection of buildings is a key factor in achieving the thermal comfort of occupants and reducing heat losses, which should result in reduced heating and cooling energy [1]. It is heating and cooling that is the area where energy consumption needs to be reduced, as this accounts for around 40% of all energy consumed in the EU. This problem is addressed in the EU area by the Energy Performance of Buildings Directive 2010/31/EU as amended [2]. This Directive targets reducing energy consumption in buildings by 20% by 2020 and up to 50% by 2050 compared to 1990 values. To achieve high energy savings in new construction or renovation of existing buildings, it is necessary to calculate the energy performance of the building to guarantee the right indoor environmental conditions for the occupants. An essential factor in calculating the energy performance of buildings at the design stage is the heat loss through the building envelope. The problem area in the envelope is the transparent part of the envelope, which is largely represented by the windows [3]. Although windows are important building elements that provide ventilation, daylighting, views, or passive solar gains, they are at risk of overheating the interior space in the summer and of high heat loss in the winter [4]. Window constructions naturally consist of a frame and glazing. The glazing is one of the most important elements of the window structure in terms of thermal and visual comfort [5,6]. Glazing has evolved over time from classical single glazing to today's types of glass systems [7,8], which include, for example, insulating double and triple glazing [9], low-emissivity glazing [10,11], electrochromic glazing [12,13], thermochromic glazing [14], and aerogel materials [15]. An important element in the interaction of the window frame with the glazing is the spacer strip [16]. One of the parameters needed for the calculation of the energy performance of buildings is the U-value, the heat transfer coefficient of the structure, whose calculated value differs from the actual value after the structure has been built into the building [17]. For this reason, frequent errors occur (e.g., condensation of water vapor or thermal bridges during the use of the building). There are several methods to obtain such data. The authors use the HFM in-situ heat flux measurement method in a pavilion laboratory in this study. Within the heat flux measurement method, surface temperatures and air temperatures from both the interior and exterior sides are recorded during the measurements along with the heat flux density. It is important to note that although such in-situ measurements may look simple, they can present several problems. The most serious of these problems is the non-stationary state of the outdoor environment. These claims are proven by several experimental studies that have addressed the problem. Aguilar-Santana J. et al. [3] measured and analyzed the performance of nine glazing samples using the HFM method under laboratory conditions, wherein the heat transfer coefficient Ug of the glazing was subsequently determined and compared between the samples. Giorgio Ficco et al. [18] measured and evaluated the wall heat transfer coefficient U using the HFM method, which was then compared with the estimated and proposed data in the analysis. Gaspar et al. [19] measured the heat transfer coefficient U using the in-situ HFM method. Their analysis says that the temperature difference for U-value measurement requires at least 19 °C and the analysis should take a longer test time. Bienvenido-Huertas D. et al. [20] validated the HFM method in warmer climates. They performed measurements on eight wall samples. The results showed that in areas with warm climates, a temperature difference of 5 °C can be considered for the HFM method. Seo-Hoon K. et al. [21] analyzed the thermal properties of the walls using the HFM method and proposed the ASTR measurement method. Park S. et al. [22] proposed a method for measuring IR that would include both glass and frame for windows and thus could address the shortcomings of the HFM method. Our measurements were carried out in a pavilion laboratory, which is described in more detail in the Materials and Methods section. The mentioned laboratory was established in 2011 and several results have been published since then [23]. In this article, the results of the U-value heat transfer coefficient are published and discussed the heat flux density, which is influenced by the real outdoor environment within a year-long cycle.

2. Materials and Methods

The aim of this study was an experimental analysis of the thermo-technical parameters of windows installed in the pavilion laboratory of the DBEUP, FCE, UNIZA, which lasted for two years. The analysis of building elements in the pavilion laboratory over such a time span contributes to building design, construction implementation and building renovation with data measured in real climatic conditions. Figure 1 presents the analysis process of this study.

2.1. Analysed Window Constructions

The analyzed window constructions in this article are built into the Pavilion Laboratory DBEUP, which currently consists of three separate room-pavilions, with research focused on envelopes for almost zero-energy building envelopes. The wall in which the windows are embedded faces south with a slight westward tilt (15°). The composition of the window wall consists of 300 mm thick aerated concrete masonry, which is insulated on the exterior side with 160 mm thick mineral wool and on the interior side with 100 mm thick expanded polystyrene. There are three windows in the laboratory on different material bases. These are aluminum—A, PVC—P, and wooden—W (see Figure 2; the plan of the laboratory is shown in Figure 3). The glazing of these windows consists of triple glazing. The indoor climate of the room is regulated by an air conditioning unit according to the standards of the Slovak standard STN 730540-2+Z1+Z2: 2019 [24] in relation to EN ISO 52000-1 [25], which set the indoor air temperature at 20 °C and the humidity at 50%. The indoor temperature is recorded and shows an amplitude of about ±1 °C, in winter during severe frosts about ±2~3 °C. The outdoor climate is represented by real climatic data recorded by a meteorological station located on the roof of the laboratory [26,27]. Table 1 contains the manufacturer's parameters of the analyzed windows.

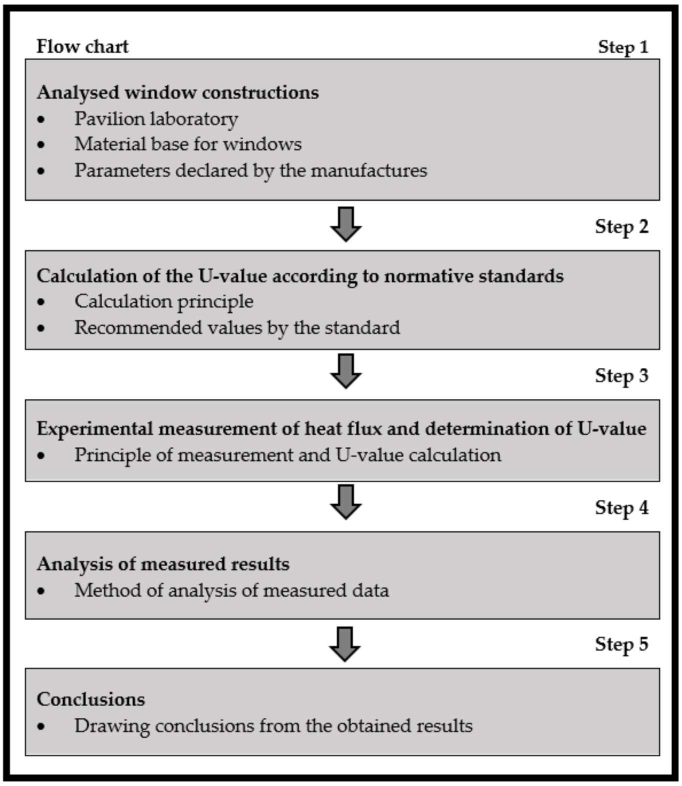


Figure 1. Flowchart of the analysis process.

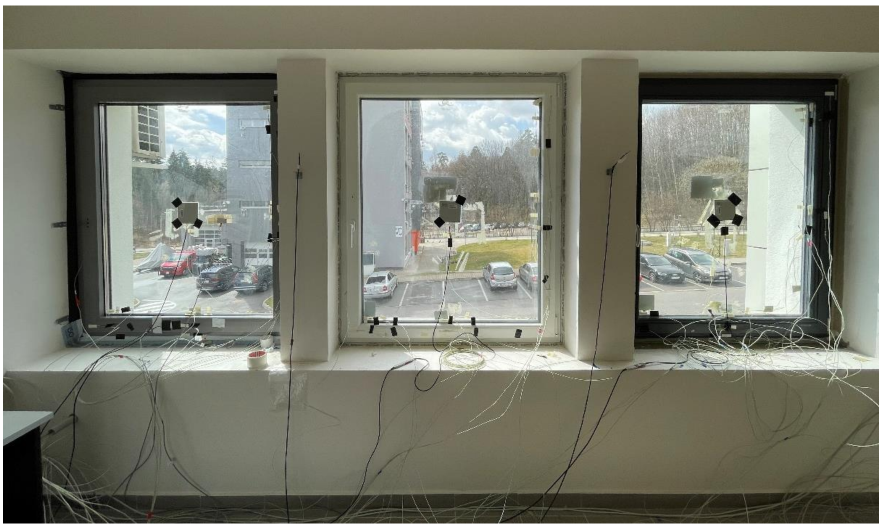


Figure 2. Window constructions were installed in the pavilion laboratory.

HFP digital heat flux plates were used to measure the heat flux density and were mounted in the center of the glazing on the interior side of each window analyzed. Surface temperature measurements were provided by NiCR-Ni thermocouples, which were mounted on both the interior and exterior sides of the analyzed windows in the same positions. The indoor air temperature was recorded by a miniature FH0D 46-C multi-sensor module. All of these data were recorded by a central measuring station—Datalogger. The outside air temperature was recorded by a mobile weather station. The specification of the measuring devices is shown in Table 2.

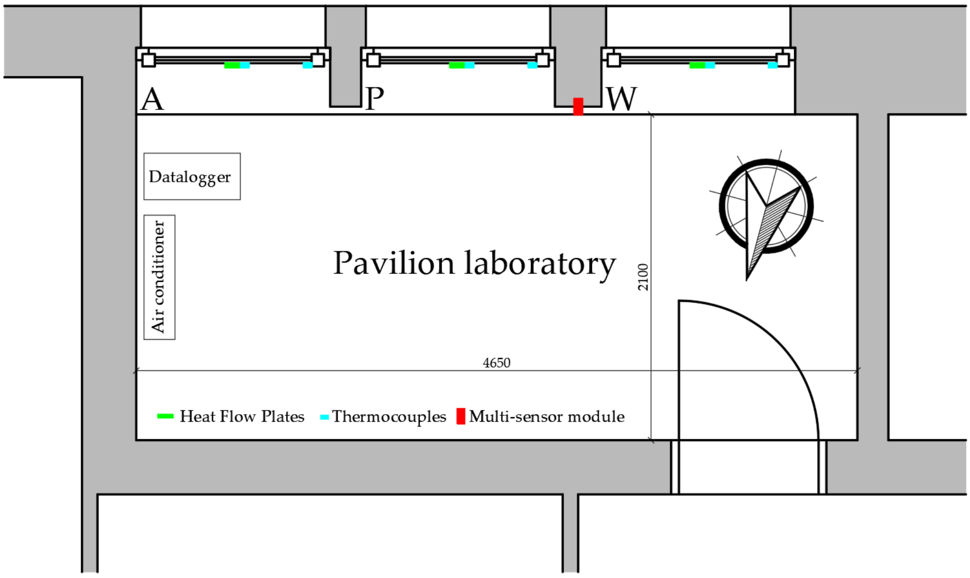


Figure 3. Plan of the pavilion laboratory.

Table 1. Parameters of window construction.

Parameter	A	P	W
Window dimension [mm]	1250 × 1500	1250 × 1500	1250 × 1500
Frame material	Aluminum with thermal bridge break	PVC	wood
Frame [mm]	80	86	88
Color	grey	white	grey
Glazing [mm]	triple (4 + 16 + 4 + 16 + 4)	triple (4 + 16 + 4 + 16 + 4)	triple (4 + 16 + 4 + 16 + 4)
Gas	argon	krypton	argon
Heat transfer coefficient of the window U_w [W/(m^2.K)]	0.90	0.78	0.79
Heat transfer coefficient of the frame U_f [W/(m^2.K)]	0.90	0.85	0.80
Heat transfer coefficient of the glazing U_g [W/(m^2.K)]	0.60	0.50	0.60

Table 2. Specification of measuring devices.

Device/Sensor	Parameters	Values
Datalogger	Overload	Max ± 12 V
	Input current	500 pA
	Measuring rate	2.5/10/50/100 mops
	System accuracy	0.02% ± 1 digit (at 2.5 and 10 mops) 0.05% ± 3 digits (at 50 mops)
Heat Flow Plates FQAx	Temperature stability	−40 to +80 °C
	Calibration accuracy	5%
Miniature multi-sensor module FH0D 46-C	Temperature range	−40 to +85 °C
	Accuracy	−20 to 85 °C–max 0.7 °C
	Reproducibility	±0.1 °C
Thermocouples NiCR-Ni	Temperature range	−40 to 1200 °C
	Accuracy	±2.5 °C

2.2. Calculation of the U-Value according to Normative Standards

The standardized procedure for calculating the heat transfer coefficient of opening constructions based on standardized values of the framing system and the applied glazing is contained in the set of standards STN EN ISO 10077-1 [28] and STN EN ISO 10077-2 [29], which are based on European and international standards. This procedure combines within the calculation the influence of the shape geometry and the thermal-technical quantification of the translucent and opaque parts of the window openings. For this article, the U-value calculations will specifically focus on the glazing heat transfer coefficient U_g. The glazing heat transfer coefficient of a multiple glazing system is described in ISO 10292 [30]. The relationship for the calculation is shown in Equation (1).

$$U_g = \frac{1}{R_{si} + \sum \frac{d_j}{\lambda_j} + \sum R_{g,j} + R_{se}} \quad (1)$$

where,

U_g Heat transfer coefficient of glazing [W/(m^2.K)].
R_{si} Internal surface resistance [(m^2.K)/W].
R_{se} External surface resistance [(m^2.K)/W].
$R_{g,j}$ Thermal resistance of the layer filled with inert gas [(m^2.K)/W].
d_j Thickness of the glass layer [mm].
λ_j Thermal conductivity coefficient of the glass layer [W/(m.K)].

The Slovak standard recommends the use of glazing with a glazing heat transfer coefficient $U_g \leq 0.6$ W/(m^2.K) to meet the requirements for the heat transfer coefficient of the window U_w [24].

The theoretical calculation according to the standards differs from the experimental measurements mainly since the theoretical calculations consider the stationary boundary conditions that are contained in the standards, whereas in experimental measurements, the non-stationary state of the surrounding environment enters the calculations.

2.3. Experimental Measurement of Heat Flux and Determination of U-Value

The principle of measurement in the said laboratory of the department is based on the instantaneous recording of heat flux density, indoor and outdoor surface temperature as well as indoor and outdoor air temperature. As it is a pavilion laboratory, which is exposed to real climatic conditions, the said variables are influenced by a non-stationary state. The above-mentioned measurement principle in the laboratory is shown in Figure 4. The method of determining the U-value from the measured data is based on calculations according to the equations summarized in ISO 9869-1 [31].

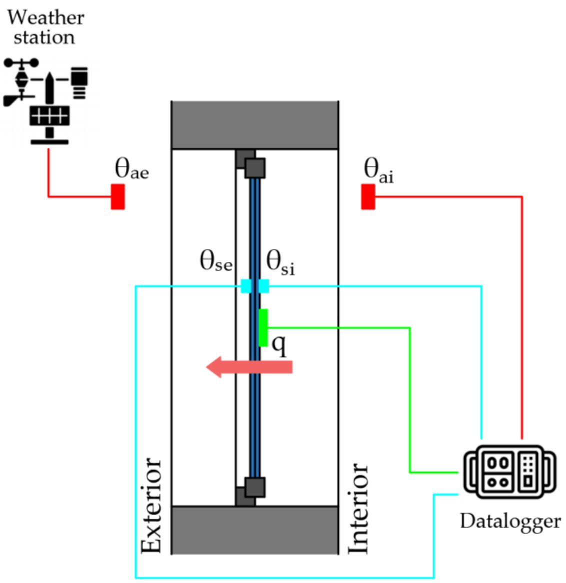


Figure 4. The principle of experimental measurement in the pavilion laboratory.

The U-value heat transfer coefficient, unlike the thermal conductivity, also includes the heat transfer characteristics of the outer and inner surfaces. The U-value is the inverse of the total thermal resistance, where the total thermal resistance is the sum of the heat conduction resistance and the heat transfer resistances at the surface. This relationship is expressed by Equation (2).

$$U = \frac{1}{R_0} = \frac{1}{R_{si} + R + R_{se}} = \frac{1}{\left(\frac{1}{h_i} + \frac{1}{\Lambda} + \frac{1}{h_e}\right)} \quad (2)$$

We calculate the thermal conductance Λ based on Equation (3).

$$\Lambda = \frac{q}{(\theta_{si} - \theta_{se})} \quad (3)$$

Calculate the heat transfer coefficient at the internal surface using Equation (4).

$$h_i = \frac{q}{\theta_{si} - \theta_{ai}} \quad (4)$$

Calculate the heat transfer coefficient at the external surface using Equation (5).

$$h_e = \frac{q}{\theta_{se} - \theta_{ae}} \quad (5)$$

where,

U Heat transfer coefficient [W/(m^2.K)].
R_{si} Internal surface resistance [(m^2.K)/W].
R_{se} External surface resistance [(m^2.K)/W].
R_0 Heat transfer resistance of the structure [(m^2.K)/W].
R Thermal resistance [(m^2.K)/W].
h_i Heat transfer coefficient at internal surface [W/(m^2.K)].
h_e Heat transfer coefficient at external surface [W/(m^2.K)].
Λ Thermal conductance [W/(m^2.K)].
q Heat flow density [W/m^2].
θ_{si} Internal surface temperature [°C].
θ_{se} External surface temperature [°C].
θ_{ai} Indoor air temperature [°C].
θ_{ae} Outdoor air temperature [°C].

2.4. Procedure for Measurement and Analysis of Measured Results

The subject of this article is the analysis of long-term measurements of the thermo-technical parameters of the window constructions, which started in January 2021 and ended in December 2022. The total period of measurements was two years. The data recording interval was one minute. The measurements monitored the glazing at several locations such as the center of the glazing, the side, bottom, and top edges of the glazing. The position of the measuring devices is the same for all three windows to allow comparison between them. An overview of the location of the monitoring devices is shown in Figure 5.

Several factors influence the accuracy of the results from experimental measurements, such as:

- Direct solar radiation
- The standards recommended difference between indoor and outdoor temperature is $\geq$15 °C.

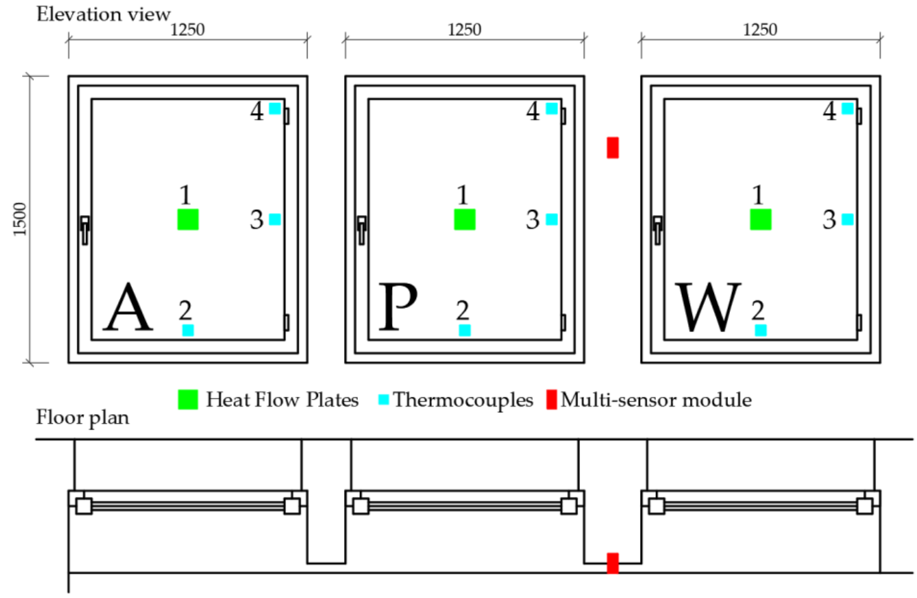


Figure 5. Location of monitoring devices.

For this reason, measurements taken during night hours between 21:00 and 3:00 were selected for the calculation to eliminate direct solar radiation. As this is a year-round measurement, the temperature difference ≥15 °C especially in summer was not observed. The paper will present the average values of the heat transfer coefficient through the glazing for each month and a subsequent comparison of selected days in winter and summer. This analysis aims to trace the behavior of the U-value of the glazing throughout the year, under the influence of the real outdoor climate.

3. Results and Discussion

This study was carried out with the intention of monitoring the glazing parameters of windows exposed to real climatic conditions throughout the year. The outdoor air temperature in 2021 and 2022 is shown in Figure 6. We can see that the outdoor environmental conditions are similar in terms of air temperature.

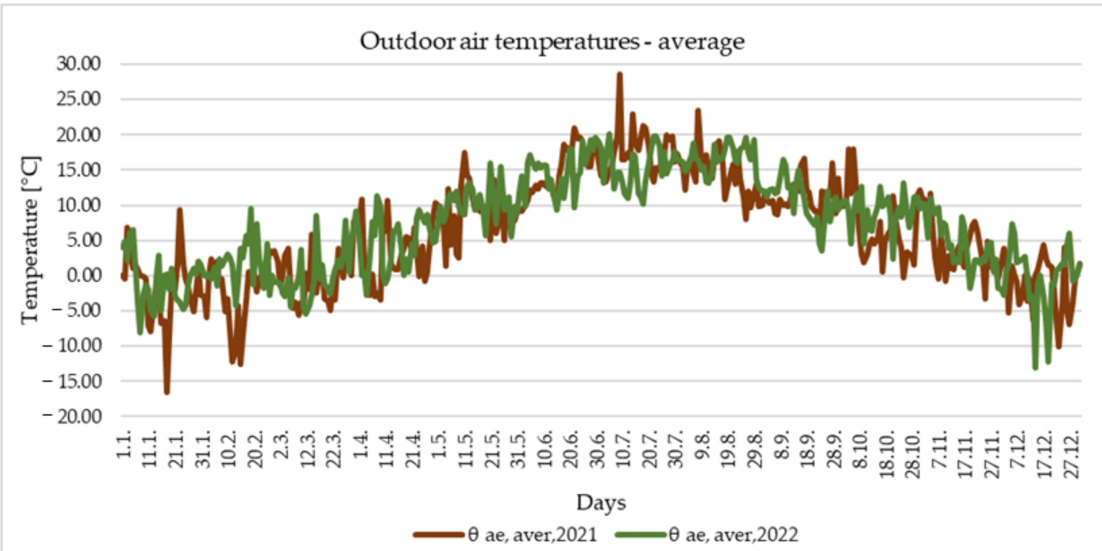
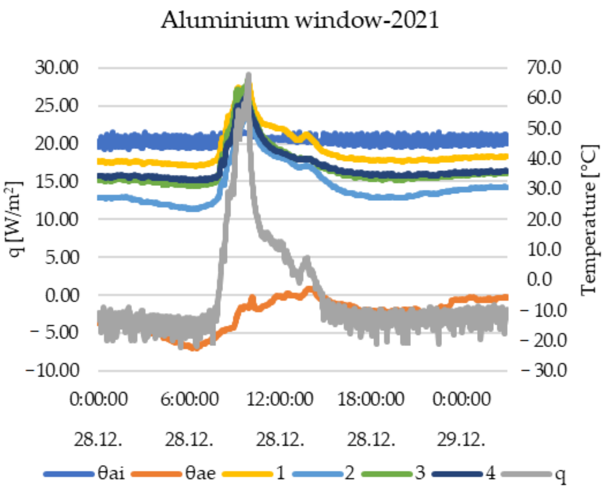


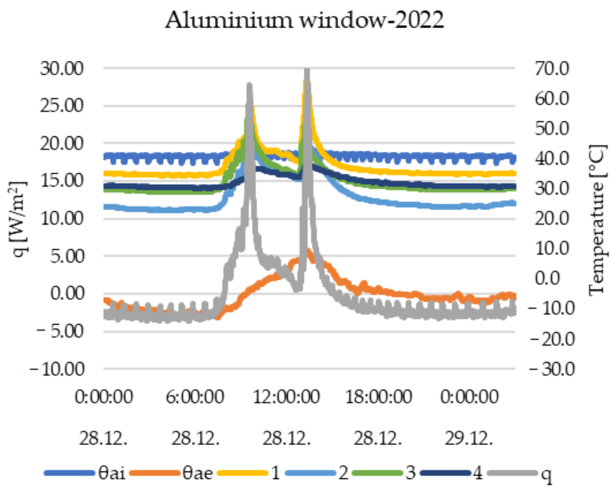
Figure 6. Average outdoor air temperatures in 2021 and 2022.

Since a temperature difference between outdoor and indoor air temperature of at least 15 °C is ideal for the validity of the results, two winter days, namely 28 and 29 December, were selected for a more detailed overview of the surface temperature, heat flux and U-value.

Figure 7 shows the measured indoor surface temperatures at the center of the glazing, outdoor and indoor air temperatures, and heat flux density, for all three window constructions, for specific selected days for the years 2021 and 2022. The surface temperatures show a consistent pattern in all cases. Indoor air temperature in 2022 shows a slight decrease compared to 2021, about 1.5 °C. The heat flux density of aluminum and wooden windows follows the outside air temperature, except for the part in the middle of the day when solar radiation heats up the glazing and significantly affects the value of the heat flux density. In the case of a PVC window, we also observe a significant increase in the heat flux density value due to the effect of solar radiation on the glazing. However, during the whole selected interval, we can notice that there is a larger difference between the heat flux density values and the outside air temperature of the PVC window than in the case of aluminum and wooden windows. This difference is reflected in the calculation of the U-value, where the heat transfer coefficient through the glazing of the PVC window is significantly worse than the heat transfer coefficient through the glazing of the aluminum and wood windows.



(**a**)



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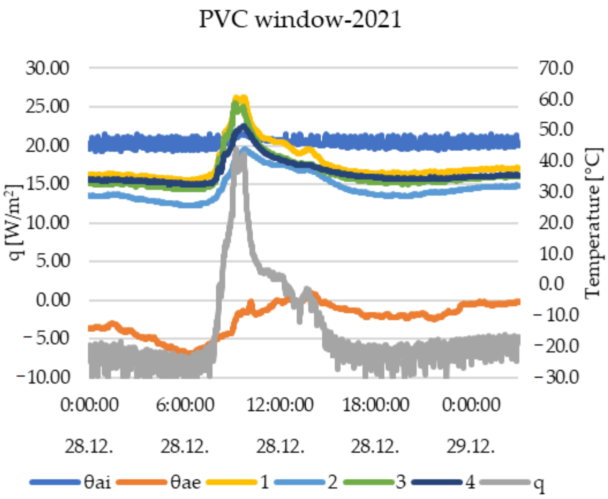

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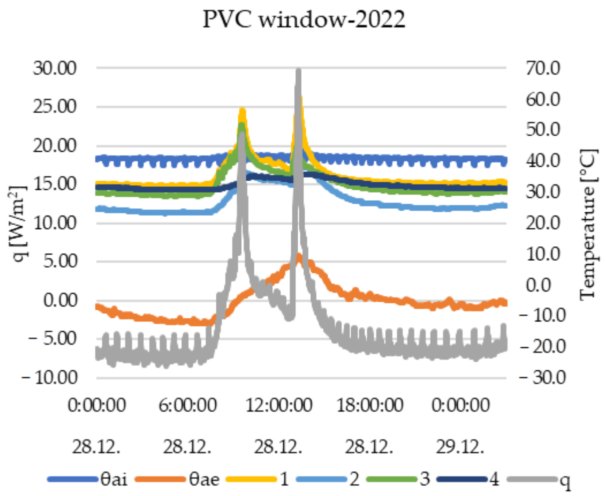
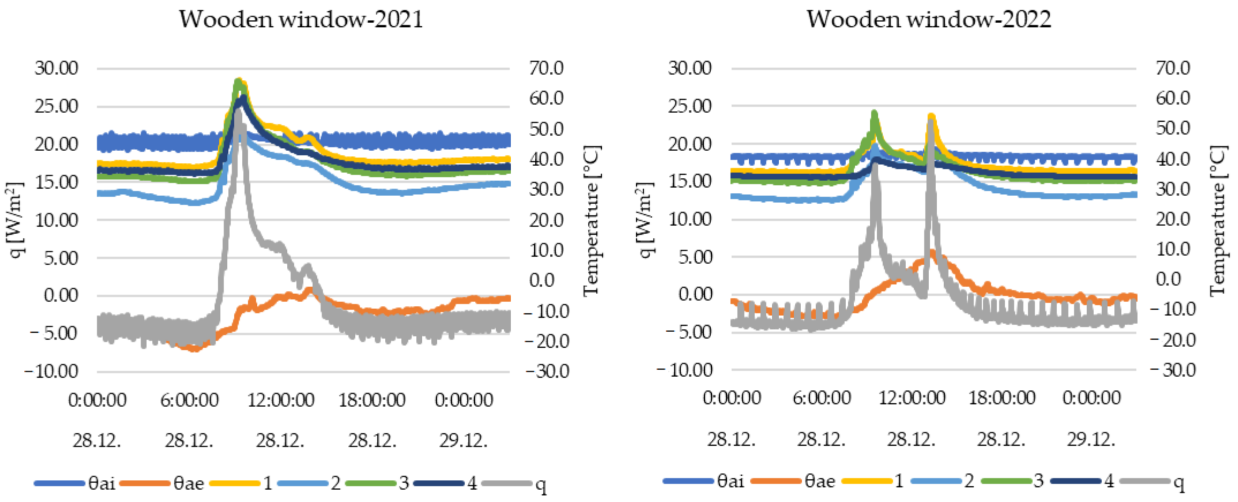


(**d**)

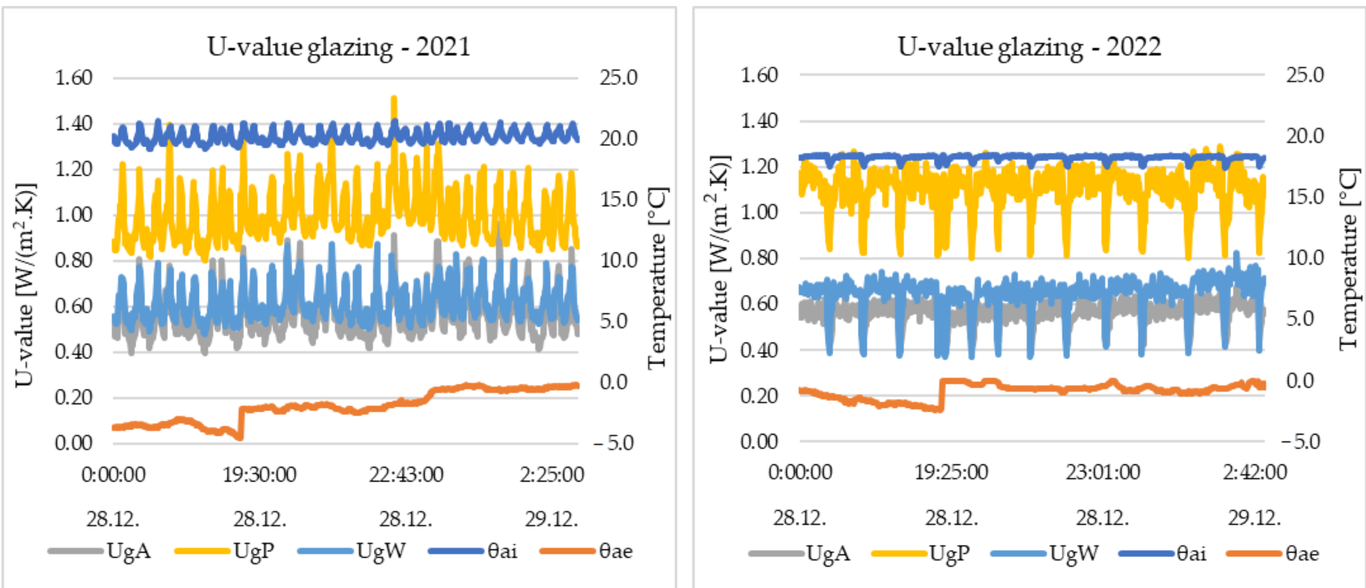
Figure 7. *Cont.*



(**e**) (**f**)

Figure 7. Measured data on all three window constructions on the selected date: (**a**) Aluminum window in 2021; (**b**) Aluminum window in 2022; (**c**) PVC window in 2021; (**d**) PVC window in 2022; (**e**)Wooden window in 2021; (**f**) Wooden window in 2022.

Figure 8 shows the U-value of the glazing during selected days in 2021 and 2022. In the case of aluminum and wood windows glazing, we observe the same pattern with a slight amplitude, about 0.05 [W/(m^2.K)]. As for the PVC window glazing, the U_g value is significantly higher compared to the first two mentioned. The given results are also confirmed by the seasonal pattern of the average U-values.



(**a**) (**b**)

Figure 8. U-value glazing of all three window constructions on the selected date: (**a**) 2021; (**b**) 2022.

From the measured data, the average glazing U-value and thermal conductance values were calculated and are summarized in Table 3. For comparison, the glazing U-value was also calculated based on normative standards. These values are shown in Table 4.

Table 3. Data measured in the pavilion laboratory.

Year	Aluminium Window		PVC Window		Wooden Window	
	Thermal Conduc. $\Lambda_{,A}$ [W/(m^2.K)]	U-Value Glazing $U_{g,A}$ [W/(m^2.K)]	Thermal Conduc. $\Lambda_{,P}$ [W/(m^2.K)]	U-Value Glazing $U_{g,P}$ [W/(m^2.K)]	Thermal Conduc. $\Lambda_{,W}$ [W/(m^2.K)]	U-Value Glazing $U_{g,W}$ [W/(m^2.K)]
2021	1.0342	0.5449	1.5643	0.9467	1.1963	0.6193
2022	0.7820	0.5269	1.4884	0.9639	0.9597	0.6106

Table 4. Data calculated according to the standard.

Value	Aluminum Window	PVC Window	Wooden Window
U-value glazing U'_g [W/(m^2.K)]	0.5580	0.5420	0.6270

We can say the following by comparing the U-values, calculated from measured data and according to the normative standards with the values from the glazing manufacturer. The U-values of the aluminum window glazing calculated from measured data in 2021 and 2022 differ from the value calculated according to the standard by about 5%. The manufacturer declares a value of U_g = 0.6 [W/(m^2.K)], which in this case means that the glazing shows favourable results. In the case of the U_g of a wooden window, the difference between the calculated values from the measurement and those according to the standard is approximately 1.5%. The manufacturer declares an U_g value of 0.6 [W/(m^2.K)], which, as in the case of the aluminum window, shows favourable results. When glazing a PVC window, a significant problem arises as the difference between the value from the measured data and the value calculated according to the standard is up to about 43%. Since the glazing manufacturer declares an U_g value of 0.5 [W/(m^2.K)], the window shows significantly unfavorable results. However, year-round monitoring and measurements show that the measured values have a similar pattern and therefore the difference between the values from the measured data compared to the calculated according to the standard and the one specified by the manufacturer is probably already due to a manufacturing defect (absence of gas filling), or damage to the low-emissivity layer on the glazing, or an unsuitable spacer frame. However, we cannot confirm these claims as it was not yet possible to determine the heat flow through the window when it was initially fitted into the construction.

Figure 9 presents the average glazing U-values that are shown for each season.

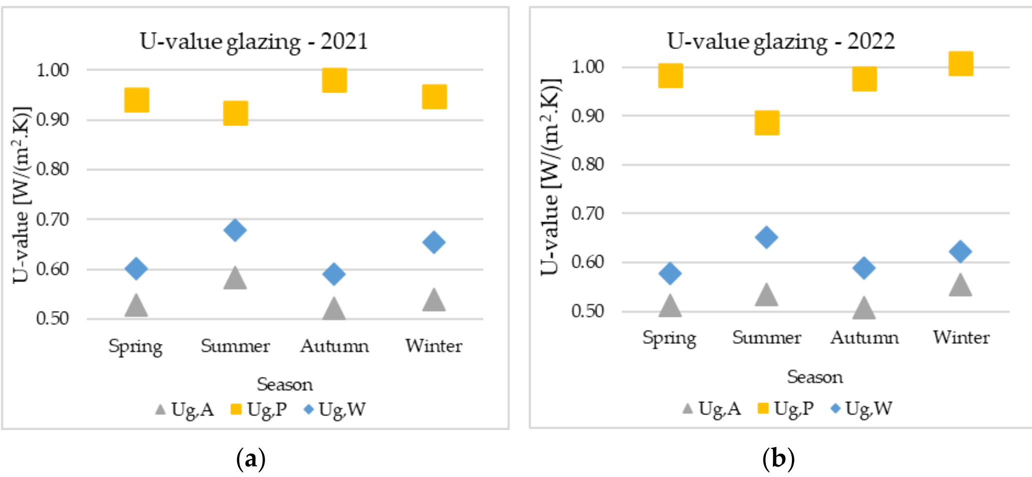


Figure 9. Average u-values for each year: (**a**) U-value in 2021; (**b**) U-value in 2022.

The course of average monthly glazing U-values as a function of surface temperature and outdoor and indoor air temperature is shown in Figure 10 for the year 2021 and Figure 11 for the year 2022.

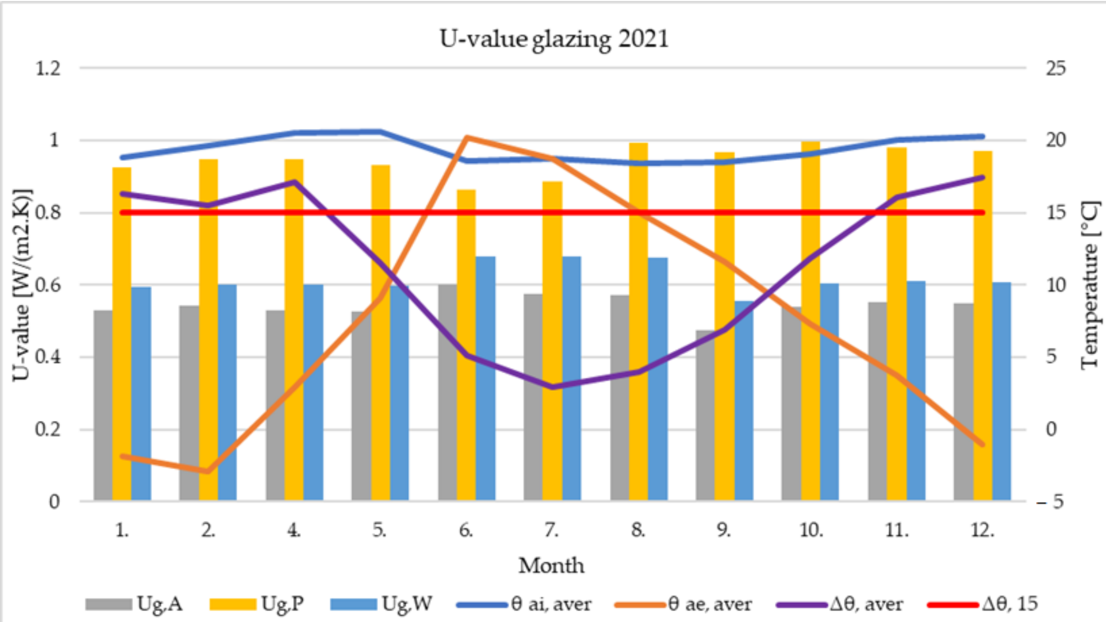


Figure 10. Average monthly U-values in 2021.

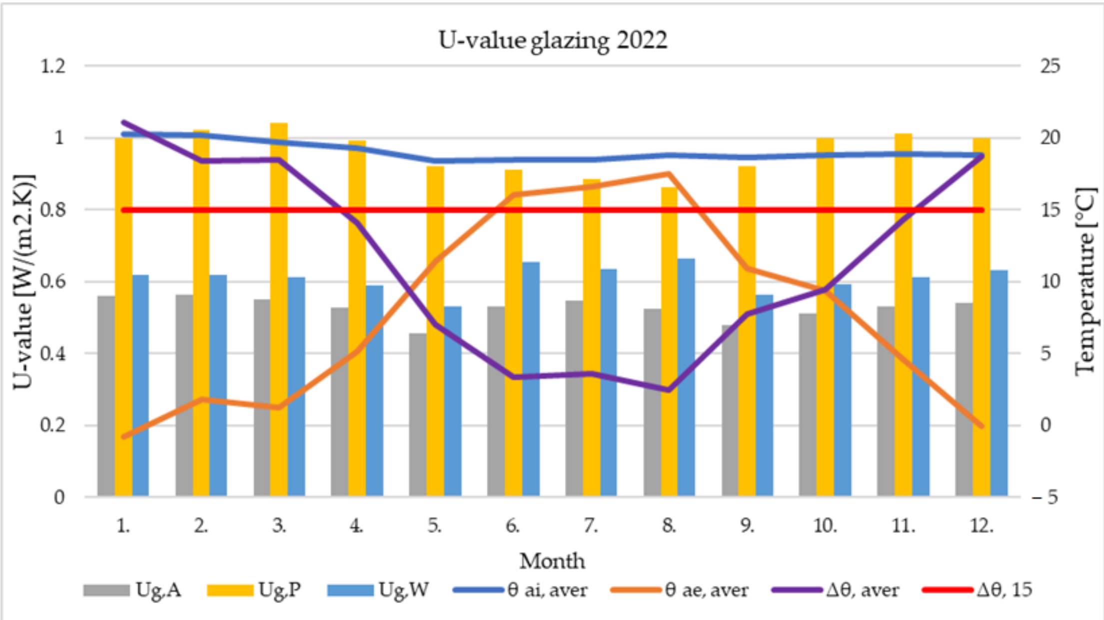


Figure 11. Average monthly U-values in 2022.

By analyzing the data, which represent the average monthly values of the heat transfer coefficient through the glazing, we concluded that the heat flux density measurement method presents logically more optimal results in winter than in summer. The relative difference between the values in winter and summer is about 12 to 14%, which therefore increases the risk of the inaccuracy of the data measured in summer. This is mainly due to the higher air temperatures in summer and thus a smaller temperature difference between indoor and outdoor air temperature and of course also due to excessive solar radiation. Figures 10 and 11 also show the average temperature difference between indoor and outdoor air temperature during the measurements compared to the recommended temperature difference of ≥15 °C. Based on this information, it is evident that the ideal period for using this method is in the spring and winter months.

4. Conclusions

The heat loss of the building envelope, characterized by the heat transfer coefficient, is an essential element in the calculation of the energy performance of buildings. Window constructions are complex structural systems of building façades. The value of their heat transfer coefficient is normally determined by measurements under laboratory control conditions or estimated by numerical calculations. However, neither of these methods allows an assessment of the actual behavior of the heat transfer coefficient in real conditions after installation. In this study, the glazing of three window constructions were investigated for which the heat transfer coefficient was investigated by in situ measurement using the heat flux measurement (HFM) method. Some studies, such as Kim S. et al. [9], state that a difference between outdoor and indoor air temperature ≥15 °C during the measurement is required for the results to be correct. In our case, the data recording took place throughout the year and thus this temperature difference was not fully observed in the summer period. Bienvenido-Huertas D. et al. [10] in their study state that the principle of such measurements can be implemented even with a temperature difference of about 5 °C but with a higher risk of data inaccuracy. It should be emphasized that few studies have been devoted to the use of this method throughout the year.

Comparisons made based on in situ measurements and values obtained from calculations show identical patterns. The average annual measured values are slightly smaller than the calculated values. Except in the case of the PVC window glazing, where the measured value differs significantly from the calculated one. In all three cases, however, the measured and calculated values differ from the values declared by the manufacturers and thus the values presented by them are overestimated. The differences between these values could be explained by the following factors:

- The parameters of the window constructions set by the manufacturers may be overestimated from a marketing point of view,
- Measurements of the thermal properties of materials are carried out in laboratories with controlled boundary conditions,
- The influence of the external environment (rain, wind, solar radiation) on the window construction after installation in the structure,
- The implementation of the individual construction details of the contacts with the full parts of the envelope.
- From the results shown in Tables 3 and 4, the following conclusions are drawn:
- The heat flux measurement method is a suitable way to verify the U-value over an annual cycle,
- The analyzed glazing of wooden and aluminum windows are suitable for use and meets the recommended values for use in buildings with almost zero-energy demands,
- The PVC window glazing analyzed is not suitable for use since it does not meet the recommended values for use in almost zero-energy buildings.

In the case of installing a PVC window with such defective glazing, its economic efficiency is lost. PVC windows are among the best-selling windows on the market with excellent affordability. However, if a window with such glazing is installed during construction, its total cost will be much higher. As remediation interventions will be needed to solve the problem, in this case this means replacing the entire glazing system with a new one.

It follows from the above that, especially for major buildings with high energy performance requirements, it is necessary to apply in situ assessment of the heat transfer coefficient, as inaccurate or overestimated data from manufacturers can have a negative impact on the budgetary analysis of the building or its overall life-cycle performance. This is particularly important when using and verifying the results in computational simulations.

In a future study, we would like to build on the results presented in this paper and compare the values measured in situ with those that will be measured in the experimental chamber and analyze the difference between long and short-term measurements on specific window constructions.

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Data Availability Statement: Data sharing not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

U	Heat transfer coefficient [W/(m^2.K)].
U_w	Heat transfer coefficient of the window [W/(m^2.K)].
U_f	Heat transfer coefficient of the frame [W/(m^2.K)].
U_g	Heat transfer coefficient of glazing [W/(m^2.K)].
Λ	Thermal conductance [W/(m^2.K)].
Q	Heat flow density [W/m^2].
h_i	Heat transfer coefficient at internal surface [W/(m^2.K)].
h_e	Heat transfer coefficient at external surface [W/(m^2.K)].
R_0	Heat transfer resistance of the structure [(m^2.K)/W].
R	Thermal resistance [(m^2.K)/W].
R_{si}	Internal surface resistance [(m^2.K)/W].
R_{se}	External surface resistance [(m^2.K)/W].
$R_{g,j}$	Thermal resistance of the layer filled with inert gas [(m^2.K)/W].
d_j	Thickness of the glass layer [mm].
λ_j	Thermal conductivity coefficient of the glass layer [W/(m.K)].
θ_{ai}	Indoor air temperature [°C].
θ_{ae}	Outdoor air temperature [°C].
θ_{si}	Internal surface temperature [°C].
θ_{se}	External surface temperature [°C].
$\Delta\theta$	Temperature difference [°C].

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