Comparison of triple glazed windows based on long-term measurement

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Abstract. This paper deals with measurement of three windows suitable for low-energy or passive houses. Windows are evaluated since 2011 in the laboratory of pavilion type with constant indoor boundary conditions and real outdoor climate. There are three windows, one wooden and two plastic which differ from each other by use of thermo modules inside the frame and center seal. Temperatures and heat fluxes on the glass, sash and frame of the windows are measured continuously. Outdoor climate is measured by the mobile weather station. During the measured period - winter 2017, windows were equipped with more sensors for temperature measuring than before. Sensors were added on the glazing, on the jamb, into the space between frame and sash and also on the montage gap filled with polyurethane foam. Temperatures on the same places of different windows are compared in this paper.

1. Introduction

With the advance in the thermal protection of the buildings and energy performance it is still important to build in better windows. The Slovak standard [1] dealing with thermal protection (STN 73 0540:2012) followed the EC directive about Energy performance of building (EPBD) 2010/31/EU [2]. Valid values for windows are since 2016 $U_w = 1.0$ W/(m²·K) and from 2021 will be on the level 0.6. Current values are suitable for ultra-low energy buildings. The window not only protects the indoor environment against the outdoor climate like a non-transparent part of building envelope, but it has more function. Very important is the insolation of the space, views, contact with outdoor, ventilation, etc. With the more strict requirements of thermal properties it is necessary to increase the thermal properties of used materials, both for glazings (triple, gas fillings, heat mirrors and low emissivity surfaces) and frames (wooden, aluminium, plastic with thermo modules, more chambers etc.). Nonetheless is the advance with incorporating the photovoltaics into the glazing or usage of transparent thermal insulations [3]. Overcome of overheating is also a problem which has to be dealt with in the low-energy buildings [4]. Another problem is the minimizing of thermal loss through the thermal bridges around the windows [5].

The use of triple glazing helps with avoiding the cool radiation from the glass surface and also the vapor condensation at the bottom of the glazing.

The three windows (Figure 1), which are analyzed in this paper are in the laboratory of pavilion type evaluated since 2011 (Figure 2). The windows are back there suitable for low-energy and nearly-zero buildings. Several articles about measurements, analyzing the winter and summer periods, measuring the transmission etc., were published [6-7].
Direct comparison of heat fluxes measured during winter 2017 [7] and 2018 is made in this article. Since December 2017 were also added thermocouples to the new positions, which enable possibility to make deeper analysis of the regime during freezing nights and sunny winter days.

Figure 1. Outside view on the tested windows in laboratory. Visible sensors on surfaces and AC chiller.

Figure 2. Inside view in the room with test windows. Visible positions of sensors and heat flux plates.

2. Laboratory and test setup
The analyzed windows are built into the testing laboratory of the Department since 2011. This is a so-called “laboratory of the pavilion type”, which nowadays consists of three different rooms with aim on the nearly zero building envelopes [8].

The windows are oriented to the south with slight declination to the west (15°). From outside, windows are exposed to the real climate boundary conditions. The outdoor climate is monitored and recorded by the mobile experimental weather station placed on the nearby building’s roof [8]. Exact monitoring of outdoor boundary conditions in-situ enables the possibility for more precise measurement and simulations. The indoor climate is controlled by the AC unit, which is set to maintain the Slovak standard indoor boundary conditions: 20 °C, 50 %. The indoor air temperature is recorded and showed small amplitude about ± 1 °C, during the very cold night about -2 ~ 3 °C, which is taken into the account for calculation of the thermal transmittance coefficient.

Figure 3. Positions of thermocouples and heat flux plates on the windows. View from the interior side.
Sensor used for this measurement consist of NiCR-Ni thermocouples [10] and heat flux plates (HFP) equipped also with thermocouple with correction (standard ones (120 x 120 mm) and half-sized for window sashes and frames.) [11]. Monitoring positions are frame, sash and glazing. Some sensors are also in the cavity between frame and sash. Totally from previous set up were added 21 thermocouples. The pattern of the positions is the same on all three windows to make possibility of direct comparison. Totally are 57 thermocouples used, there are 6 positions on each window on both sides, 4 positions on each window only inside and 2 more position on two windows from inside. Some thermocouples are also on the pillar between the windows and on the joint between pillar and frame, but these were not utilized in this article. Detailed position of the thermocouples and HFP are in Figure 3. The datalogger and both sensor types are from Ahlborn. For this measurements the recording interval was five minutes.

Evolution of the laboratory equipment contain: since 2013 the outdoor climate has been monitored more precise by the experimental weather station [9], from autumn 2015 there are also the heat flux plates (HFP) fixed on the inner surfaces, which creates the possibility to measure the heat flux and thermal conductance coefficient of the glass and frame, depending on the position of the plates and since December 2017 were added 21 thermocouples to new positions.

For needs of this article, seven HFP were used. Three of them have a standard dimensions, placed in the center of glazing, three small one placed on the windows sashes and another one on the frame (wooden window C). Positions are marked in Figure 3. Each HFP measures the thermal flow and also the surface temperature.

The windows properties based on the manufacturers data are summarized in Table 1. It is good to mention, that “paper” based values comply nowadays standard values several years ago.

| Window | Material | No. of chambers | Glazing | Gas | Heat gain [%] | Heat calculated [W/(m².K)] |
|--------|----------|----------------|---------|-----|---------------|----------------------------|
| A      | plastic  | 6              | triple  | Ar  | 36            | 0.80                       |
| B      | plastic with thermo modules | 6 | triple | Kr  | 47            | 0.78                       |
| C      | wood     | -              | triple  | Ar  | 48            | 0.79                       |

3. Heat fluxes
The thermal transmittance coefficient (U-value) of a structural element describes the quantity of thermal energy that passes through it from one side to another per second and per square meter surface at a constant difference in ambient temperature of 1 °K. With measured heat flow density using heat flux plates, knowing the outdoor and indoor air temperatures, the thermal transmittance coefficient can be calculated according the equation (1):

$$ U = \frac{q}{\theta_{ai} - \theta_{ae}} $$  \hspace{1cm} (1)

$U$ – thermal transmittance coefficient [W/(m².K)]
$q$ – heat flow density [W/(m².K)]
$\theta_{ai}$ – temperature of indoor air [°C]
$\theta_{ae}$ – temperature of outdoor air [°C]

Thermal surface transfer coefficient can be calculated according to Equation 2 and 3:

$$ h_i = \frac{q}{\theta_{si} - \theta_{ai}} $$  \hspace{1cm} (2)
$$ h_e = \frac{q}{\theta_{se} - \theta_{ae}} $$  \hspace{1cm} (3)
$h_i$ – surface coefficient of heat transfer, inside [W/(m$^2$.K)]

$h_e$ – surface coefficient of heat transfer, outside [W/(m$^2$.K)]

$\theta_{si}$ – temperature of inner surface [°C]

$\theta_{se}$ – temperature of outer surface [°C]

**Figure 4.** Illustration of heat flow from warmer indoor side to outdoor and the coefficients and physical properties which influence it.

Calculated heat fluxes represented in form of thermal conductance coefficients are summarized in Table 2. There is also the comparison with measured values from January 2017 [7]. The measured differences are accounted to the uncertainty during the measurement period, air flow in the room, not perfectly contact between windows and HFP. There was also different average outdoor air temperature during the measurement period. It was selected five days and the time periods from 20:00 to 5:00, with 5 minutes interval, which creates enough measured values.

The differences can be also accounted on the fact that the thermal conductance coefficient is not constant, but slightly varies depending on the temperature differences (outdoor air temperature). This is showed in the Figures 5 and 6. The influence of temperature on the thermal conductance and quantification cannot be determined in this case. The measured values are very different from the manufacturers’ values, but it has to be taken the difference compared to the laboratory measurement. The glazing values for window A and B are significantly higher than window C.

**Table 2.** Measured heat fluxes represented in form of thermal conductance coefficient [W/(m$^2$.K)]. Values from January 2017[7] - 300 values, average $\theta_{ae} = -11.0$ °C, February 2018 - 682 values, $\theta_{ae} = -12.5$ °C

| Window | Frame  | Glazing |
|--------|--------|---------|
|        | January 2017 | February 2018 | January 2017 | February 2018 |
| A      | 0.76    | 0.78    | 0.90    | 0.92    |
| B      | 0.73    | 0.80    | 1.05    | 1.01    |
| C      | 0.65    | 0.67    | 0.67    | 0.69    |

**Figure 5.** Dependence between temperature of outdoor air and thermal conductance for the window sash.

**Figure 6.** Dependence between temperature of outdoor air and thermal conductance for the glazing.
The surface temperatures are influenced by the surface coefficient of heat transfer. These coefficients are stated in the Slovak Standard [1] for various surfaces and indoor and outdoor surfaces. For the windows are valid different values than for walls, or non-transparent structures. It differs also by the heat flow orientation. Calculated values for glazing and window’s sash are in Table 3. For calculations were used equations (2 and 3). For \( h_i \) were used surface temperatures measured with the sensors integrated into the heat flux plates.

Values for glazing for interior were above the Standard value, for sash lower. If averaged, there will be a good match. For exterior is the trend opposite, glazing has lower values than sash. These surface heat transfer coefficients are probably influenced by the night sky cool radiation. This is planned to be compared to the laboratory measurement in the climate chamber in the future.

| Table 3. Calculated surface coefficient of heat transfer based on the measured heat fluxed with Equation (2 and 3) and defined values in Slovak Standard [1] |
|---------------------------------|--|--|--|--|--|--|
| Surface coefficient of heat transfer [W/(m².K)] | STN 73 0540 | A glazing | B glazing | C glazing | A sash | B sash | C sash |
| \( h_i \) (HFP) | 7.62 | 10.5 | 9.53 | 13.2 | 5.1 | 5.2 | 6.3 |
| \( h_e \) | 25 | 10.3 | 8.1 | 10.3 | 12.7 | 18.4 | 11.7 |

4. Temperatures

All measured courses are for the time period 25th of February - 1st of March 2018. Analyzed were positions in the cavity between frame and sash (Figure 7 and 8), on the frame (Figure 9), on the glazing with position on the bottom (Figure 10) and on the top (Figure 11). The window B has additional sensor on the contact between glazing and sash. Standardly, the thermocouple is about 2 cm above this position. Difference between this two temperatures are in Figure 12. Because of the amplitude of the indoor air temperature during the night, there is also added required surface temperature from Slovak standard for 18 °C. Temperatures for the glazing of Window C for all five positions are presented in Figure 13.
5. Discussion
Temperatures in the cavity were compared for the position at the bottom (all three windows) and on the right side (two windows). There are big differences between this positions for the windows B (Figure 7 and 8). Differences between Window A and B is not only in use of thermomodules but also Window B
has additional sealing in the middle. At the bottom there could be problem with the contact, because there is a minimal difference. On the other hand, there is a significant difference up to 5 °C in the cavity between windows A and B. Window C has no thermocouple in this position.

**Figure 12.** Temperature courses on the Window B glazing with lowest temperatures - bottom of the glazing (about 20 mm from the bottom) and direct contact between sash and glazing at the bottom.

**Figure 13.** Temperature courses on the window C for all position on the glazing - during night.

Differences on the position at the bottom and top of the glazing are shown in Figures 10 and 11. During the night, temperatures on all windows are about 5 °C higher than at the bottom. Interesting are the daily peaks, which are lower on the top, so the daily amplitude is lower.

According to the previous results [6, 7] and also this, the critical position on the glazing is not the corner but the bottom of the glazing. The thermocouples are fixed on the windows approximately 20
mm from the bottom. For the window B was added thermocouple on the direct joint of glazing and sash. These courses are in Figure 12. The graph showed that the difference between these two positions is up to 2 °C. For comparison are stated two surface temperatures from the Slovak standard, one for 20 °C and second for 18 °C. This is because the indoor air temperature during the night was about 18 °C. The measured temperature on the contact was lower than both required values, bottom of the glazing was above the required temperature for 18 °C. Critical temperature for the outdoor air temperature is the same as for the frame (Figure 9).

From the comparison it is visible that the wooden Window C has the best results. Comparison of surface temperatures on the glazing for all five positions is on the Figure 13. This is only for the night representative because of the solar insolation on the additional sensors. Bottom and corner values are much lower than the middle or center of glazing, the top and right side courses are similar to the middle position.

6. Conclusion
Three windows in the pavilion type laboratory are constantly measured with the real outdoor climate. In this paper were monitored temperatures with additional thermocouples mounted in December 2017. This deals with the temperature courses in the frame/sash cavity, more detailed temperature distribution on the glazing and comparison between sash and frame. Detailed analysis confirms that the best window is with wooden frame, which complies the Standard requirements and based on the heat flux measurements has stable values over the years.

The window C has also the best measured values from the heat flux measurement compared to the other two windows. Comparison with the laboratory measurements cannot be made in this type of measurement because of the use of real windows, changing outdoor climate and other uncertainties such as air conditioning unit working interval etc

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