In situ $U_g$-value measurement on three different glazing types

F Paschke$^1$, N Bishara$^1$, I Schulz$^1$, C Kocer$^2$, J Schneider$^1$ and A Maier$^1$

$^1$ Institute of Structural Mechanics and Design, Franziska-Braun-Straße 3, 64285 Darmstadt, Germany
$^2$ School of Physics, The University of Sydney, N.S.W., 2006, Australia
E-mail: paschke@ismd.tu-darmstadt.de

Abstract. This study presents in situ monitoring data of three different glazing systems over a period of one year. An insulated glass unit (IGU), a Vacuum Insulated Glass hybrid unit (VIG-hybrid) and an opaque architectural insulation module (AIM) were monitored under the equivalent environmental condition in this study. Different issues were observed and analyzed. It was found that the $U_g$-value cited by the manufacturers agrees with the $U_g$-values derived from the measured data, to within less than 5% for the IGU and the VIG-hybrid. The consistency of the $U_g$-value of each glazing types one year after the start of monitoring was validated for similar environmental conditions. Depending on the magnitude of the resistance to heat flow, an increasing $U_g$-value was observed for a higher temperature difference between the inside and outside environments. The effect is much more significant for the glazing type with the largest $U_g$-value (IGU) and less significant for the glazing types with a high thermal resistance (VIG-hybrid, AIM).

1. Introduction

New regulations introduced by the European governments [1] force the building sector to minimize energy consumption, e.g. by increasing the resistance to heat flow through the building facade. A modern facade consists often of glass elements, the glazing systems which are integrated into the frame elements. The main part of a modern facade can therefore be represented by the glazing system and may play the most important role in the reduction of energy loss of a building facade. In this research, three different types of glazing were monitored under the same measuring conditions over a period of one year to evaluate their thermal performance and compare the results to the manufacturers’ claims.

In-situ measurements of facade elements have been carried out among others by Ficco et al [2], Cesaratto et al [3] and Feng et al [4]. They investigated influences on the in situ $U$-value measurement for different facade elements under various measuring conditions with diverse heat flux meters. However, a comparative analysis of different glazing types under the same boundary conditions have not been performed so far.

The three glazing types investigated in this research are integrated in the north facade of the ETA-Factory [5, 6] (see figure 1), which is located at the Technical University in Darmstadt, Campus Lichtwiese. The thermal performance or rather the $U_g$-value of each glazing was monitored over a period of one year. The first glazing type under investigation is a double
insulated glass unit (IGU). The resistance to heat flow of an IGU is influenced by the cavity between the two glass panes, the conductivity of the gas in this cavity and the low emittance surface coatings. The thermal processes which occur in an IGU are direct heat transfer through the edge seal, convection in the cavity between the glass panes and thermal radiation between the glass panes. The heat flow perpendicular to the glass surface is assumed to be uniform over the surface. The second glazing type is a vacuum insulated glass hybrid unit (VIG-hybrid) which is a combination of an insulated glass unit and a VIG unit. It is a new type of glazing for the European market but already used on the Asian market. The design as compared to an IGU differs mostly in one aspect, the resistance to heat flow of a VIG unit is achieved by evacuating the cavity between two glass panes not by filling the gap with low conductive gas. At a vacuum pressure at or less than 0.1 Pa the convection and conduction of heat through the residual gas can be neglected [7]. To maintain the separation of the glass panes under the load of atmospheric pressure a regular array of support pillars is placed between the two glass panes. Hence, the main heat flow pathways in a VIG are direct heat transfer through the edge seal and the pillars, and surface-to-surface radiation between the glass panes. The pillars which are spread evenly between the two glass panes of the VIG represent point contact thermal bridges [8] between the glass surfaces. Therefore the surface temperature varies periodically and the heat flow rate over a pillar is higher than in the regions surrounding the pillars [8]. The third glazing type is an Architectural Insulation Module (AIM) which is a vacuum panel that is constructed as a pyrogenic silica technology en wrapped in black fleece layers which makes the panel opaque.

The monitored IGU and the AIM are installed next to each other on the first floor and the VIG-hybrid on the second floor (see figure 1). Each of the three glazing types has a different heat flow resistance or rather $U_g$-value. The specified $U_g$-values and the construction of each glazing type are shown in table 1.

![Figure 1. North facade of the ETA-factory with the glazing systems of interest.](image)

| Glazing type | IGU | VIG-hybrid | AIM |
|--------------|-----|------------|-----|
| $U_g$-value  | 1.10| 0.65       | 0.23|

Table 1. Constructions and $U_g$-values of the glazing types.
2. Method

The $U_g$-value describes the inverse of heat flow resistance in the center region of a glazing. The $U_g$-value is equivalent to the thermal transmittance $\Lambda$ which is defined in ISO 9869 [9] as

$$\Lambda = \frac{\sum_{j=1}^{n} q_j}{\sum_{j=1}^{n} (T_{ij} - T_{ej})}$$

(1)

where $q$ is the heat flux density and $T_i$ and $T_e$ are the inside and outside environmental temperatures respectively. But equation 1 delivers only the actual $U_g$-value for the defined condition given in ISO 9869, which will be described and discussed in detail in chapter 3. Most important is that the heat flow over the analyzed time period is constant. Otherwise, if the heat flow varies too much or even changes direction during the period of interest, it is not possible to determine the actual $U_g$-value accurately. As the average method was used for the evaluation of the $U_g$-value the temperature difference between the inside and outside environment should be higher than 3 K to ensure the accuracy of the evaluated data [10].

2.1. Monitoring concept

Each glazing type was equipped with an U-value measurement kit. The measurement instruments use one air temperature sensor on each side of the glazing and one heat flux meter which is installed at the internal surface of the glazing, as can be seen in figure 2. The heat flux meter was applied on a 0.75 mm thick tape which was glued on the glass surface. The tape is part of the U-value measurement kit and is therefore tuned to the sensor. The properties of the U-value kit are shown in table 2.

![Figure 2. Sensor arrangement (exemplary for VIG).](image)

![Figure 3. Heat flux sensor placement on VIG-hybrid surface.](image)

The measurement frequency was set to 10 minutes, which provides reasonable accuracy and small effects like environmental conditions or user behavior can be tracked. The $U_g$-value was calculated based on the temperature and heat flux measurement, using the average method according to ISO 9869. The $U_g$-value describes the thermal conductance through the center of a glazing from the hot to the cold environment. Therefore, the heat flux and temperature sensors are attached at a distance of at least 25 cm to the frame edge, where the edge conduction has no influence on the measurement [11]. Furthermore, the heat flux sensor should be attached in an area with a constant heat flow over the surface, avoiding thermal bridges next to the sensors. For the IGU and the AIM the heat flow in the center region of the glazing is considered to be constant. But, as it is shown in figure 2, the pillars of the VIG, which are thermal bridge contacts may influence the measurement. The pillars have a separation distance of 20 mm from each other which is smaller than the size of the heat flux sensor (30 mm x 30 mm x 3.3 mm).

The heat flow meter is placed in the center of 4 pillars, as one can see from figure 3. As the $U_g$-value with units of W m$^{-2}$K$^{-1}$ is investigated in this study, the size of the glazing system has no influence on the results, presented in section 3.2.
Table 2. Properties of the measurement instrument. [12][13]

| Properties                  | Range                  |
|-----------------------------|------------------------|
| Heat flux measuring         | -300 W m⁻² to +300 W m⁻² |
| Heat flux resolution        | < 0.22 W m⁻²           |
| Heat flux sensitivity       | > 7 µV                 |
| Temperature sensors         | -20 °C to 65 °C        |
| Temperature accuracy        | ± 0.5 °C               |
| Minimal temperature difference | ± 5 K                 |

2.2. Heat flux density measurement

With the two temperature sensors and the heat flux sensor positioned, the $U_g$-value of the three glazing systems was evaluated and monitored from November 2018 until November 2019. The heat flux progression over the year for the three glazing types is shown in figures 4 to 6. As long as the inside room temperature $T_i$ is higher than the outside environmental temperature $T_e$, the heat flux density is directed from the room-side to the outside environment and is therefore measured as a positive value. This is the case for most of the time as it can be seen in figures 4 to 6. Figure 4 shows the measured heat flux for the IGU. The two linear progressions in figure 4 are due to a sensor failure. From November to March the heat flux is mostly positive due to the cold outside and warm inside temperatures. Some high negative heat flux values occur due to specific effects which will be discussed in section 3.1. From May to August 2019 the heat flux value becomes negative more often due to the hot outside temperatures. As of October 2019, the heat flux follows a similar course as at the beginning of the measurement.

![Figure 4. Heat flux density over one year for the IGU.](image)

The measurement data of the heat flux for the VIG-hybrid (figure 5) gives similar results. It is significant that the negative peaks of the heat flux values are highest in magnitude for the VIG-hybrid.

![Figure 5. Heat flux density over one year for the VIG-hybrid.](image)

The heat flux data of the AIM, which shows the lowest $U_g$-value, fluctuates much more compared to the other glazing types. However, the tendency of the heat flux curve over the year
is similar to the heat flux curves of the IGU and the VIG-hybrid. Due to a sensor failure, the heat flux data is available only until September 2019. Since all three glazing types are installed on the same facade, the environmental conditions for all three glazing types were similar, as one can see from table 3 below.

Table 3. Averages of the measured data point for each glazing type.

| Glazing type | Heat flux $[W \text{ m}^{-2}]$ | $T_i$ $[^\circ \text{C}]$ | $T_e$ $[^\circ \text{C}]$ |
|--------------|-------------------------------|--------------------------|--------------------------|
| IGU          | 11.35                         | 21.75                    | 10.17                    |
| VIG-hybrid   | 1.37                          | 21.51                    | 11.41                    |
| AIM          | 1.08                          | 21.71                    | 10.86                    |

3. Results and discussion

From figure 4 to 6 one can see, that frequency of fluctuation of the heat flux course increases with the magnitude in resistance to heat flow. The IGU has the lowest resistance to heat flow and the smallest relative change of the heat flux. Even though the resistance of the AIM is about triple in magnitude of the VIG-hybrid, the average measured heat flux density on the VIG-hybrid is only 26 % higher than that compared to the AIM due to the high variation of the heat flux measurement of the VIG-hybrid. This could be attributed to the small pillars in the VIG which act as small thermal bridges [8] and could lead to quick changes in the direction of the measured heat flux.

3.1. Specific effects

Since the facade is facing north, it can be assumed that the influence of direct solar radiation on the measurement results is small. Especially during the winter period (December to February) sun-light exposure does not influence the sensor output.

However, the measurement is not only influenced by the external environmental conditions, but also by the behavior of the room users. One specific effect could be identified clearly. The manual ventilation processes during the winter period by opening and closing the window have a great influence on the measured values. If one opens a window, the cold air floats over the heat flux sensor and creates a colder environment at the internal surface of the sensor. The glazing is still heated up and therefore the heat flux is directed from the glazing towards the inside of the room and the heat flux density sensor delivers a negative value. In figure 7, the heat flux density for the IGU is shown during a typical working week. From Monday to Friday, one can identify recurring peaks (marked with red numbers) of the measured heat flux values. They all occur during the day while the office is occupied. Over the weekend when the office is
empty these effects cannot be observed. Furthermore, the effect could not be observed during winter break (22nd of December 2018 to 7th of January) when the offices were empty. This effect explains the high negative measured heat flux values over the year for all glazing types.

Figure 7. Heat flux density over one week for the IGU showing the influence of opening a window.

During the summer period, the heat flux density varies greatly, as can be seen in figure 8. The periodic change of the heat flux density during the day and night cycle, with respect to the inside and outside temperatures, $T_i$ and $T_e$ is representative for the summer period. At night, when $T_i > T_e$, the heat flux is positive. As soon as the outside temperature $T_e$ exceeds $T_i$, the heat flux direction changes and the heat flux becomes negative. The heat flux density gradient increases with the convergence of $T_i$ and $T_e$. The peaks due to manual ventilation can not be identified as simply for the summer period as they were for the winter period.

Figure 8. Heat flux density during one week in the summer period for the IGU.

These effects show why it is important to evaluate suitable time periods with constant environmental conditions which leads to a constant heat flux density. In compliance with the standard ISO 9869, the $U_g$-value could be evaluated for each glazing type and is presented in the next section.

3.2. $U_g$-value analyses
The primary objective of this study is to confirm that the $U_g$-value as given by the manufacturers as a glazing specification is consistent with the measured in situ data under varying environmental conditions. The number of time periods which could be analyzed depended on the consistency of the measured heat flux density. Therefore, it was possible to evaluate more time periods for the IGU and the VIG-hybrid than for the AIM. In figure 9, all the measured and analyzed $U_g$-values in accordance to ISO 9869 and calculated from eq. 1 for the three glazing types are presented.
Figure 9. Measured $U_g$-values for the three different glazing types.

For the IGU and the VIG-hybrid, most of the evaluated $U_g$-values are within 5 % of the $U_g$-value specified by the manufacturer. Only a few measurements of the AIM could be evaluated, therefore the accordance between the measured $U_g$-value and the $U_g$-value stated by the manufacturer is not well and has to be investigated in future work. The variation of the evaluated $U_g$-values is higher for the IGU than for the VIG-hybrid. This could be attributed to the temperature-dependent convective heat transfer in the IGU, which has a greater influence on the $U_g$-value of the IGU. Another influence on the evaluated $U_g$-value due to convection is shown in figure 10. The $U_g$-value rises with an increase of the temperature difference $\Delta T$ between the inside and outside environment since a rise in temperature difference promotes an increase in the convective heat transfer.

Figure 10. Correlation between temperature difference and $U_g$-value.

The measured average $U_g$-value of the IGU and the VIG-hybrid are in good agreement with the manufacturer’s information, as it can be seen from table 4. The measured data for the AIM differs 27.8% from the manufacturer’s specification. Discrepancies over 20 % could be attributed, among other effects to the heat flow lines which were not straight and perpendicular to the glass element [9]. This might be the case as the frame is a significant thermal bridge to a glazing type with such a low $U_g$-value.

Table 4. Comparison of measurement and manufacturer’s information.

| Glazing type | Manufacturer’s information [W m$^{-2}$K$^{-1}$] | Average measured $U_g$-value [W m$^{-2}$K$^{-1}$] | Deviation absolute | Deviation rel.[%]
|--------------|-----------------------------------------------|-----------------------------------------------|-------------------|----------------
| IGU          | 1.10 [14]                                    | 1.12                                          | +0.02             | +1.8           |
| VIG-hybrid   | 0.65 [15]                                    | 0.63                                          | -0.02             | -3.2           |
| AIM          | 0.23 [14]                                    | 0.18                                          | -0.05             | -27.8          |
4. Conclusion

In situ monitoring of three glazing types with the same environmental and structural boundaries was carried out over a period of one year. Depending on the magnitude of the resistance to heat flow, it turned out that the data collection in compliance with ISO 9869 for high insulating glazing types is more difficult than for glazing types with a low resistance to heat flow. During the monitoring period two major effects influenced the measurements significantly: The manual ventilation effect. And the change of the heat flux direction and amplitude. The heat flux measurement for a VIG-hybrid unit delivers accurate values despite the small thermal bridges (pillars) if the measurement boundary conditions and the data evaluation are complied within the ISO 9869 standard. The analyzed $U_g$-value for all three glazing types is consistent over the monitoring period of one year. Further investigations will include the assessment of the solar radiation in the office rooms and the thermal transmittance through the frame.

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