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# In-situ performance evaluation of historic box-type windows with vacuum glazing

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**Abstract.** Climate protection objectives and energy efficiency targets imply stricter performance expectations from both new and retrofit building projects. Given the related important role of the building envelope, there is a need for a holistic approach to the design, construction, as well as laboratory and field testing of buildings' window and wall systems. In this context, the present contribution reports on recent efforts regarding the thermal retrofit of box-type windows. In the course of an actual research project, vacuum insulated glass (VIG) elements were integrated with ten existing box-type windows at six locations in Austria. To facilitate empirical testing and evaluation of these windows, a detailed concept for a continuous in-situ performance monitoring concept was designed and implemented together with the required monitoring infrastructure. This infrastructure involves the deployment of regular state-of-the-art IoT (Internet of Things) technology and enables the continuous monitoring of the salient performance indicators (including temperature, relative humidity, and heat flow). The derived values of performance indicators (such as the  $f_{Rsi}$ -value) can facilitate, among other things, the assessment of water vapor surface condensation risk. Collected data since mid-2020 cover both hot and cold weather periods have been analysed to capture performance differences between alternative vacuum glass settings at the testing locations. The alternative implementations pertain to different positions of the glazing layer (inside versus outside), different opening directions of the casements, and different positions of box-type within the opaque wall. Moreover, for comparison purposes, monitoring equipment was integrated into a comparable regular box-type window (with float glass or insulation glass) at each of the demonstration sites. Occurrences of potential visible or functional defects (including surface condensation) have been documented as well. The paper presents, analyses, and discusses the preliminary findings of this effort in detail.

**Keywords:** Vacuum insulated glass, historic box-type windows, performance monitoring

## 1. Introduction

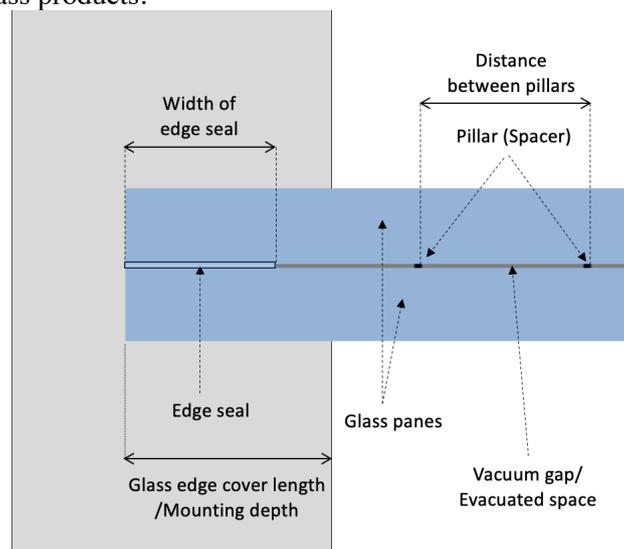
The thermal and energy performance of windows is influenced by the thermal performance of the used glass products as well as by the overall window construction including material, geometry and setup of frames [1]. In past decades, linear optimization of windows via multi-pane insulation glass including gas filling of the interstitial spaces and implementing of low-emissivity foils as well as development of corresponding frame constructions have been considered the major steps toward highly-insulating windows [2]. While such technologies can easily be integrated in new windows, which are regularly



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constructed and developed from scratch, especially heavy multi-pane glass products are often no option for existing window constructions, as for instance box-type windows (often also referred to as double casement windows). The façades of historic buildings often are strongly characterized by such windows, thus a replacement with insulation windows featuring multi-pane glass cannot be considered as a valid option. As such, other concepts for the thermal retrofit of such windows are required. One potential option is the replacement of the float glass of such windows with vacuum glass products [3].

The term vacuum insulated or vacuum glass regularly refers to glazing products [4, 5] that are characterized by the following aspects: (i) two thin glass panes (each about 3 to 4 mm thick) are positioned parallel with a small (less than a millimetre) interstitial space between them. This interstitial space is evacuated; (ii) a grid of so called pillars is integrated in the interstitial space, which maintain the form and position of the glass panes to each other; (iii) the glass edge seal is a gas tight layer either made of glass or metal; (iv) an evacuation opening can be found in one of the glass panes. This opening is later sealed; (v) a so-called getter substance/surface is integrated, which is intended to chemically extract remaining particles in the vacuum space. Figure 1 illustrates constituting parts and terminology connected to vacuum glass products.



**Figure 1.** Constituting parts and terminology of vacuum glass

By widely eliminating the heat transfer by minimizing conduction and convection, such glasses boast a very low  $U_g$ -value (typical products feature  $U_g$ -values of  $0.4$  to  $0.7 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ ) at a thickness of less than a centimetre. As such, the glasses might offer a potential alternative to float glass panes in box-type windows. However, increased heat flow through such glass products can be found in the area of the glass edge seal and around the pillars. While the latter is considered as uncritical, the sooner requires consideration in the frame design, to provide a glass edge cover as long as possible by framing materials.

## 2. Retrofitting of box-type windows with vacuum glazing

While the development of the aforementioned vacuum glass products was explored in the scope of different R&D groups of academic and industrial background [6], surprisingly few efforts could be identified that focussed on the integration of vacuum glass products in new and existing window constructions [7]. As such, the authors started extensive research about possibilities, limits, and recommendations pertaining to the integration of vacuum glass products already back in 2014.

Basic research efforts (exploratory projects) were conducted to estimate the impact of vacuum glass application in both existing and new windows: In the project VIG-SYS-RENO [8], principle tests with glass specimen of different vacuum glass producers were subjected to performance tests (thermal

performance, acoustical performance). Moreover, a simulation-based study explored the impact of implementing the vacuum glass into different positions of casement windows (inner layer, outer layer, both layers), both on a building energy performance assessment and thermal bridge assessment level of detail. Thereby, the positioning of the vacuum glass on the outer layer of the box-type window was considered favourably.

In contrast to new windows, the implementation of vacuum glass into existing window structures and formats have to follow existing design paradigms. Moreover, aspects of heritage protection and corresponding requirements often have to be considered. The present contribution demonstrates such application efforts in a number of six existing buildings with box-type windows. Vacuum glass panes have been integrated into a number of test-windows at each of the sites. Thereby, the surrounding setting of the opaque wall was different, as were the layer where the vacuum glass was implemented. Based on the behaviour of these windows during a 6-month observation period, recommendations for future implementation of vacuum glass into existing, culturally relevant constructions can be derived.

### 3. Continuous in-situ performance monitoring

A detailed evaluation of the real in-situ performance of different typical thermal improved box-type windows with a vacuum glazing was one of the major topics of the associated research project. A set of different original historical and refurbished box-type windows were selected in consideration to realization possibilities and acceptance of owners and stakeholders. The test sites are located in five different (climatic) regions (Wien, Wilhering/Linz, Puchberg/Wels, Salzburg and Innsbruck) of Austria. For a continuous data collection, a web-based monitoring concept was designed and implemented. Due to the COVID19 related restrictions and the resulting reduced travel possibilities it was necessary to switch from an offline data monitoring solution with stand-alone loggers to a live remote monitoring concept. Therefore, two IoT (Internet of Things) related installation settings were designed. The first one uses a very accurate data logger and sensor setting that is normally used for laboratory measurements. A minicomputer (Arduino Yun) and UMTS-modem further transfers the live data via a restful-service to the monitoring server at TU Wien. The second monitoring setting is a low-cost solution which combines of the shelf LoraWan (Dragino LHT65 [9]) sensor nodes, a standard LoraWan-Gateway (Dragino LPS8 [10]) and the same microcomputer with UMTS-modem for the data upload as the concept presented before. Table 1 presents the details of the used devices, the measured physical variables and ranges, together with the accuracy of the resulting measurements. Additional to the standard factory testing a validation of temperature sensors was performed in a climatic exposure test cabinet at typical temperatures (0, 10, 20 °C). The distribution of recorded values, except the external temperature sensors of the standard (low cost concept), was not exceeding a 0.1 K range around the average of the recordings. The distribution of the validation measurements from the external temperature sensors (Dallas DS18B20) showed with 0.4 °C a bigger but acceptable variation.

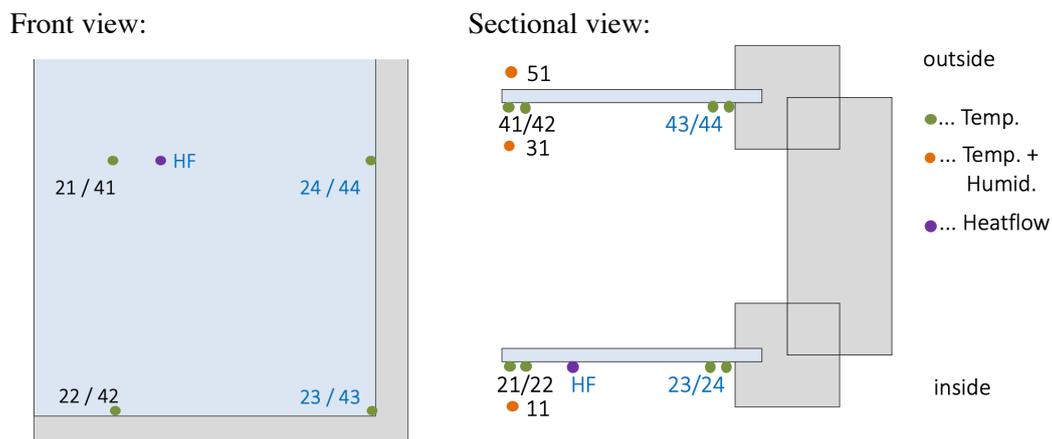
A similar setting for the sensor positioning was applied at all locations. Figure 2 illustrates that in general with a front view and the related section view of the box-type window. Locations of surface temperature installed at representative points in the centre (20 cm from the bottom and side edge) and the bottom edge (20 cm from the corner) of the glazing are illustrated with green dots. In two of the location the “detailed” sensing installation was applied and records also two additional temperatures at the glazing edges as illustrated with green dots and blue label. As visible in the section view glass temperature sensors are installed on the inner (locations 21 to 24) as well on the outer window layer (locations 41 to 44). Air temperature and humidity is captured at positions with 20 cm distance from the bottom and 4.5 cm in front of the inner glazing (location 11), the outer glazing (location 31), and in front of the outer glazing (location 51). The “detailed” sensing installation measures also the heat flow at the inner glazing level near to the centre surface temperature measurement of the inner glazing layer.

The presented measurement concept was designed to collect the necessary data to evaluate the thermal performance. Thereby, the focus was on heat transfer and condensation risk of various settings with vacuum glazing ( $U_g=0.7 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ ). Different configurations have been evaluated: on the inner or exterior layer, classical thermal retrofitted or new box-type windows with double-layer insulation glass

( $U_g=1.1 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ ) on the inside or the original setting with float glazing on both layers. Table 2 provides an overview of the 15 different monitored test windows as well as details about the location, setting of glazing types and configuration (vacuum glazing application location and reference window for comparison).

**Table 1.** Overview of the used monitoring equipment.

	Device	Measured variable Sensor	Range	Accuracy
Detailed	Microcomputer Arduino YUN +	Air temperature and relative humidity Ahlborn FHAD46C0	-20 ... 80 °C 5 ... 98 % rH	typ. $\pm 0.3 \text{ K}$ at 25 °C $\pm 0.4 \text{ K}$ at 10 ... 40 °C $\pm 1.8 \text{ % rH}$ at 10 ... 90 % rH
	USB UMTS Modem +	NTC temperature sensor with Ahlborn ZA9040FS2	-50 to 125 °C	$\pm 0.1 \text{ K}$ at 0 ... 30 °C
	Datalogger Ahlborn ALMEMO® MA2890-9	Heat flow plate Ahlborn FQA017C	0 to 5200 W/m <sup>2</sup>	C: 5% at 23 °C
	Microcomputer Arduino YUN +	LoraWan Air temperature and relative humidity node Dragino LHT65 (Sensiron SHT20 sensor)	-40 ... 80 °C 0 ... % rH	typ. $\pm 0.3 \text{ K}$ at 5...60 °C $\pm 0.8 \text{ K}$ at -40 ... 80 °C typ. $\pm 3 \text{ % rH}$ at 20 ... 80 % rH
Standard	USB UMTS Modem +	External temperature sensor (Dallas DS18B20) for LoraWan node Dragino LPS8	-55 to 125 °C	$\pm 0.5 \text{ K}$ at -10 ... 85 °C $\pm 2 \text{ K}$ at -55... 125 °C



**Figure 2.** Overview of sensor locations with window front (left) and horizontal section view (right).

**Table 2.** Overview of monitored test window and specific details.

	Location					
	P1	P2	P3	P4	P5	P6
	Puchberg Wels	Wien Grinzing	Wien TU	Wilhering	Salzburg	Innsbruck
						
Retrofit action	Glass replacement	Refurbishment with new outer wings	Outer or inner wing replacement with VIG	New with Box-type windows VIG or IG	New with Box-type windows VIG or IG	New with Box-type windows VIG or IG
Monitoring setting	standard	standard	detailed	standard	standard	Detailed
F1: VIG inside	✓	-	✓	✓	✓	✓
F2: VIG outside	✓	✓	✓	-	✓	✓
F3: reference	Original float/float	-	Original float/float	✓	IG inside	IG inside

#### 4. First in-situ performance results

Data from the winter period 2020/2021 was examined. The performance of the window widely followed expected trends. For this contribution it was necessary to reduce the observation on a single topic and we present first results with focus on cold day performance only. Typical cold winter days from 10. to 13. February 2021 were selected for a critical evaluation of the condensation risk. To avoid influences of solar radiation, only data from unoccupied night time hours was used to illustrate the distribution of recorded temperatures and to calculate the related  $f$ -values according to Eq. 1.

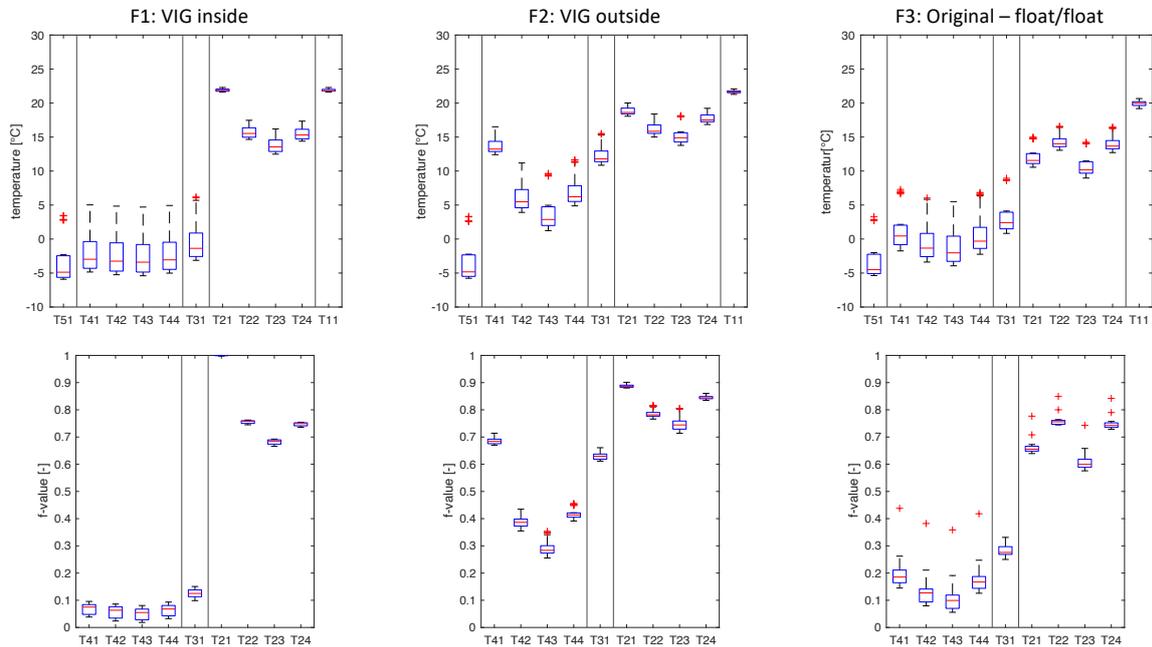
$$f_{TMP} = \frac{T_{TMP} - T_e}{T_i - T_e} \quad \text{Eq. 1}$$

$f_{TMP}$  ... temperature factor at measurement point;  $T_{TMP}$  ... surface temperature at the measurement Point;  
 $T_e$  ... external (outside) air temperature;  $T_i$  ... internal (inside) air temperature

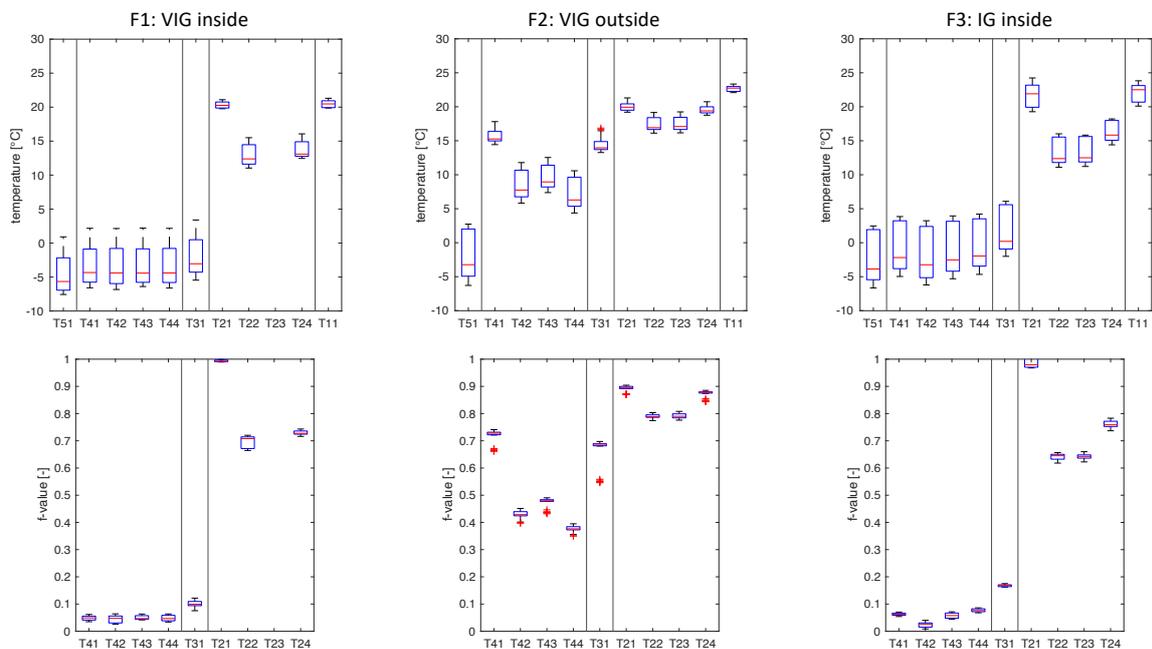
Figure 3 and 4 show boxplots for the locations with “detailed” quality setting at TU Wien and Innsbruck. It is visible that both VIG test windows are performing well with good  $f$ -values at the inner layer. The VIG outside seems to be slightly better than VIG inside because of higher  $f$ -values, especially on the critical edge point (23). But we have to mention that this case with VIG outside can be also problematic if a huge air exchange between inside and the air space happens which will end in a critical condensation situation on the edge associated with the outer wing vacuum glazing. All of the  $f$ -values for the VIG outside are below 0.7 (condensation risk criteria threshold). VIG test windows at the location Innsbruck are performing very similar. Due to sensor problems no data for the location T23 could be recorded for the test window F1 (VIG inside). Figure 5 shows the boxplots of calculated  $f$ -values for the locations with “standard” quality setting at Puchberg, Vienna (Grinzing), Wihlering and Salzburg and provides similar performance results as the cases before.

In-situ  $U$ -values (see Figure 6) were calculated according to ISO 9869 [11] for installations with heat flux plates (“detailed”). Only recorded data from nights with minimum outside air temperatures below 5°C and in timeframes of 3 hours around the minimum were considered to ensure that the situation is similar to a stationary situation. Note that the measured in-situ  $U$ -values more likely represent the classic

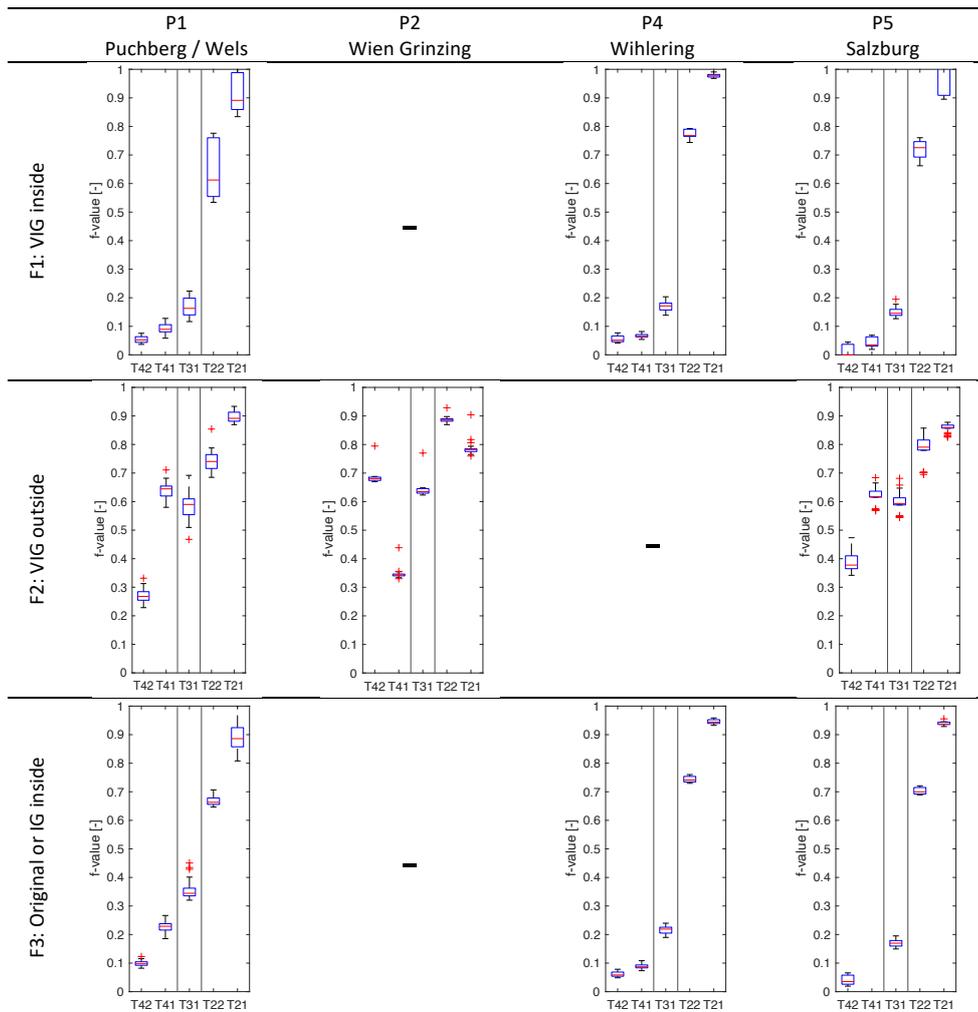
theoretical  $U_g$  because of the used glass temperature and heat flow. In this context the values have to be compared to theoretical values for the different combinations: 1) 3 mm float – 3 mm float with  $2.8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ ; 2) 3 mm float and double-layer insulation with  $0.91 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ ; 3) 3 mm float and VIG with  $0.62 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ . Especially the versions with VIG inside are performing very well in terms of thermal insulation quality with  $U$ -values around  $0.6 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ . Settings with VIG outside performed much lower with  $1.4 / 1.6 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$  in comparison to the theoretical values. This was most likely caused by high air changes of the interstitial space to the outside.



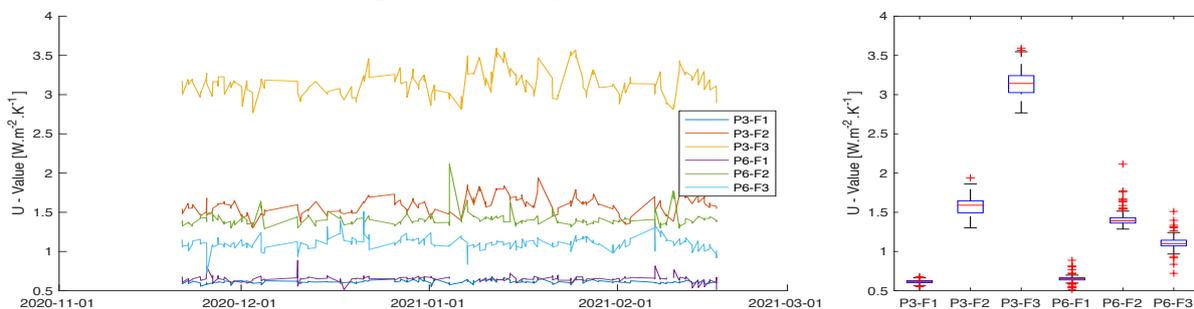
**Figure 3.** Distribution of measured temperatures (top) and calculated f-values (bottom) for location Wien TU-Wien during very cold nights in February 2021 (10., 11., &12.02.2021).



**Figure 4.** Distribution of measured temperatures (left) and calculated f-values (right) for location Innsbruck during very cold nights in February 2021 (10., 11., &12.02.2021).



**Figure 5.** Distribution of calculated f-values for location with standard monitoring setting during very cold nights in February 2021 (10., 11., & 12.02.2021).



**Figure 6.** Calculated U-values location TU Wien (P3) and Innsbruck (P6) during nights with outside temperatures below 5°C.

**5. Conclusion**

The first evaluation of recorded data from winter 2020/2021 are indicating a good in-situ performance of vacuum glazing in box-type windows. Condensation risk can be considered rather low for application of VIG and IG on the room side with calculated f-values higher than 0.7. Needless to say, the higher thermal insulation of the inner wing results in rather low temperatures in the interstitial space. VIG applied on the external layer without additionally window seal on the inner layer showed acceptable

conditions at the glazing center, but considerable condensation risk at the edge with f-values around 0.3. This does not match with expectations based on previous simulation results and yet has to be analysed in detail. The related measurements are showing lower temperatures in the interstitial air space and on the VIG. The measurements indicate an additional heat losses within the air space potentially caused by uncontrolled ventilation effects and/or high heat losses through the perimeter of the box-type window. The application of VIG on the inner layer resulted in a very good thermal insulation performance as visible in the calculated in-situ U-values around  $0.6 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ .

However, the results presented in this paper need to be understood as preliminary, as detailed analysis of the building constructions are ongoing, bases on measurements, empiric analysis, and simulation.

## 6. Acknowledgment

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