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A REVIEW OF THE FIVA PROJECT: NOVEL WINDOWS EMPLOYING VACUUM GLAZING PRODUCTS

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Abstract. Vacuum glazing products have been in development for the past decades. Such glazing products regularly feature two parallel glass panes that have a small, evacuated gap in their interstitial space. To maintain the vacuum and the form of the glass product, regularly vacuum tight edge seals and a grid of distance pillars are integrated. During the years of development, the major focus was set on the production and durability aspects of the glass products, but relatively few efforts had been conducted towards the integration of such glass products into window constructions. Employing typically used double- and triple glazing windows' frames does not represent a feasible option. This is due to the specification given by vacuum glazing products, such as their small thickness and the requirement for sufficient glass edge coverage due to the major thermal bridge adjacent to the edge seal.

The authors, together with major players from the window producing industry, started a R&D effort that targeted disruptive new concepts for vacuum glass windows. Four different designs were developed that not only integrated vacuum glass products, but also featured unusual opening patterns, the latest generation of electrically driven fitting products, and specific seals. The thermal and acoustical performance of the prototypes was improved during the development via employment of numeric thermal simulation and lab testing. The present contribution illustrates the four prototypes and their performance, which – for instance – pertaining to the U_W-value is down to 0.6–0.7 $W \cdot m^{-2} \cdot K^{-1}$ at a glass thickness of less than 1 cm.

Keywords: Vacuum glazing, windows, thermal performance, functional prototypes, numeric thermal bridge simulation.

1. Introduction

The present contribution reports on the outcome of a recently conducted research project, which focused on the development of highly-insulating windows of contemporary design, which employ vacuum glass products. Such vacuum glass products became available during the past decade, but have been under constant development for over one century, if one accepts the patent of Zoller from 1913 [1] as a first approach for such glazing products. To the knowledge of the authors, Zoller was the first one to suggest an "evacuated space" between two panes of glass. Major challenges in his and all further development efforts included the upkeep of the vacuum in the glass product, which required lots of development effort in view of principal concepts of constituents, industrial production processes, and material science. Currently, different vacuum glass products can be found on the market [2–5], which differ not only in their region of origin, but also majorly in used technologies and glass availability.

Independently of the manufacturer, vacuum glass panels regularly consist of a set of constituents. These are:

(i) (at least) two parallel glass panes,

(ii) a small, interstitial gap between the panes, which is evacuated,

(iii) a set of distance pillars, maintaining the parallel position of the two glass panes against the air pressure load;

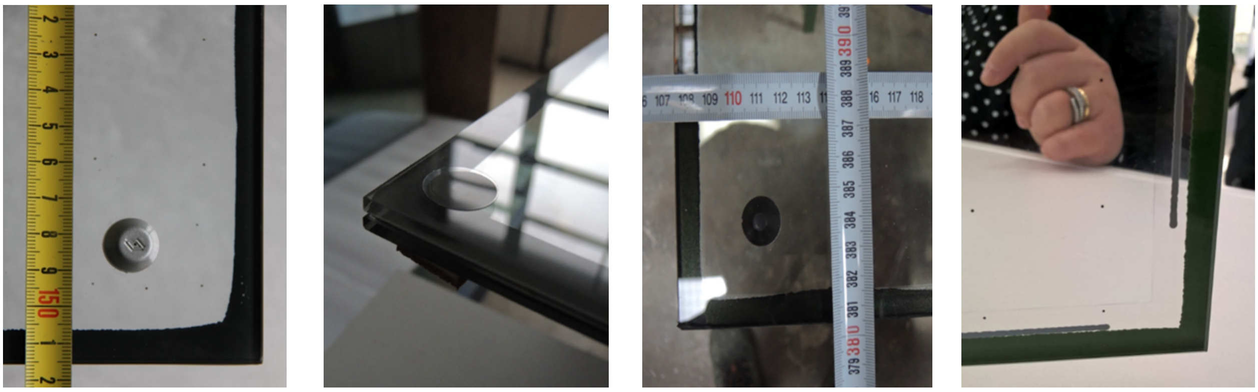
(iv) a gas/vacuum tight edges seal that covers the perimeter of the overall product and is essential for keeping up the vacuum;

(v) a so-called getter unit, which chemically binds left over particles with in the evacuated space;

(vi) an evacuation opening that is used to evacuate the interstitial space and is closed after evacuation with a vacuum tight seal.

Figure 2 illustrates the major constituents of a vacuum glass product schematically. Figure 1 illustrates different vacuum glass products from different commercial providers, and some key data about them.

In view of thermal building performance aspects, vacuum glass products feature very low thermal transmittance values (U_g-values), which is due to the widely eliminated conductive and convective heat transfer processes. These values can be reached at very thin system thicknesses of 1 cm or less. While the overall thermal insulation of vacuum glass products show convenient performance indicators, it has to be con-



(a). SYNERGY / China
Distance of pillars: 40 mm
Seal thickness: 10 mm
Getterpoint diameter: 14 mm
U_g: 0.58 $W \cdot m^{-2} \cdot K^{-1}$

(b). EAGON / Korea
Distance of pillars: 40 mm
Seal thickness: 10 mm
Getterpoint diameter: 18 mm
U_g: 0.48 $W \cdot m^{-2} \cdot K^{-1}$

(c). GUARDIAN / USA
Distance of pillars: 40 mm
Seal thickness: 10 mm
Getterpoint diameter: 16 mm
U_g: 0.47 $W \cdot m^{-2} \cdot K^{-1}$

(d). AGC INTERPANE / Belgium
Distance of pillars: 20 mm
Seal thickness: 5 mm
Getterline: 2 mm
U_g: 0.7 $W \cdot m^{-2} \cdot K^{-1}$

Figure 1. From left to right: Different vacuum glazing products (partly [2–5], partly own illustrations).

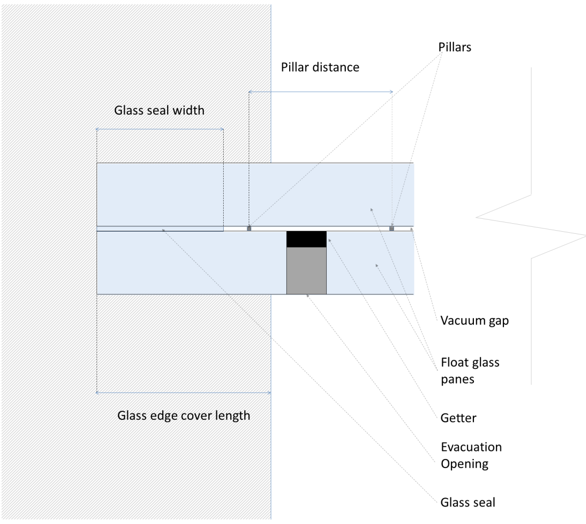


Figure 2. Terminology of the major constituents of vacuum glass products.

sidered that both distance pillars and the tight edge seal pose thermal bridges. It has been proven that the distance pillars – as punctual thermal bridges – do not significantly affect the performance of the vacuum glass panes [6], due to their small dimension and used material. This means that neither condensation risk nor large heat losses can be expected based on the distance pillars. However the tight edge seals are linear thermal bridges of significant contact area with both glass panes, and thus require consideration in window constructions. Given these aspects, it seems clear that both in the case of new windows and in the case of existing window constructions require in-depth analysis and adaptation to the characteristics of vacuum glass: In the **case of the new windows** the overall window construction (including window wing, frame, and wall-connector detailing) should be adapted to the specifications of the vacuum glass. Consequently, the overall operation and construction principles of such new windows should be overthought. Aspects to be optimized should be building physics aspects (overall thermal performance, mitigation of thermal bridges, acoustical performance, etc.), aesthetics, integration in fast and clean mounting processes, and – last but not least – user comfort and usability. In the **case of existing windows** the improvement of the thermal performance at major upkeep of the overall appearance of the window might be focal. The authors conducted a set of projects that focused on new and existing windows equipped with vacuum glass. Figure 3 illustrates the relation of these projects in view of new and existing windows and technical development and monitoring. Note that the cooperative R&D projects included contributions by the industry and domain experts.

The present contribution wants to highlight the method and results of the project FIVA. In this project four different, innovative, vacuum-glass equipped windows have been developed. The starting point for this research and development project was to reconsider classic window constructions in view of technical innovations such as vacuum glass but also beyond: The four different window constructions have been designed, virtually constructed and subjected to different assessment methods based on numeric thermal simulation. Moreover, mock-ups were constructed and evaluated by laymen and domain experts of the window construction industry.

2. Methodology

Figure 4 illustrates the general methodological approaches of the research project FIVA as work packages. Based on the findings of the previous projects [7, 8], a convenient requirement analysis was conducted in WP2. Moreover four design principles which had been envisioned during the previous project

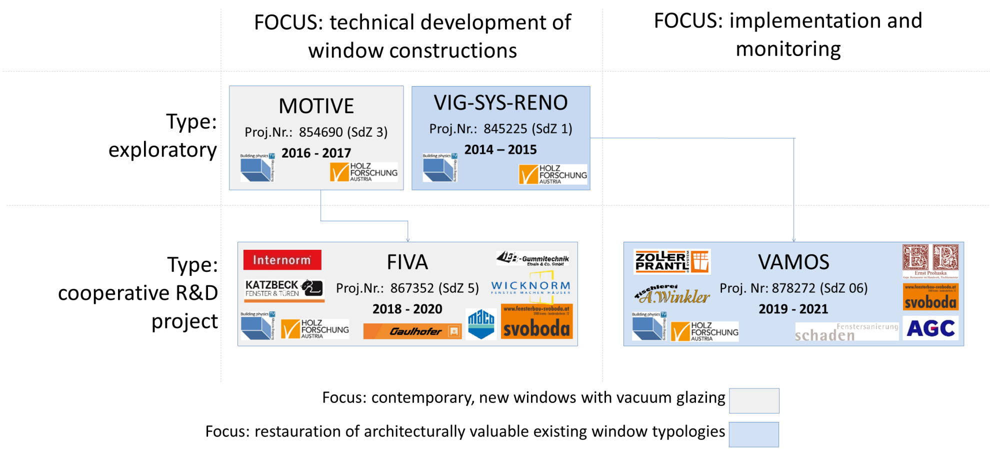


Figure 3. Landscape of R&D projects pertaining to vacuum glass integration into new and existing windows.

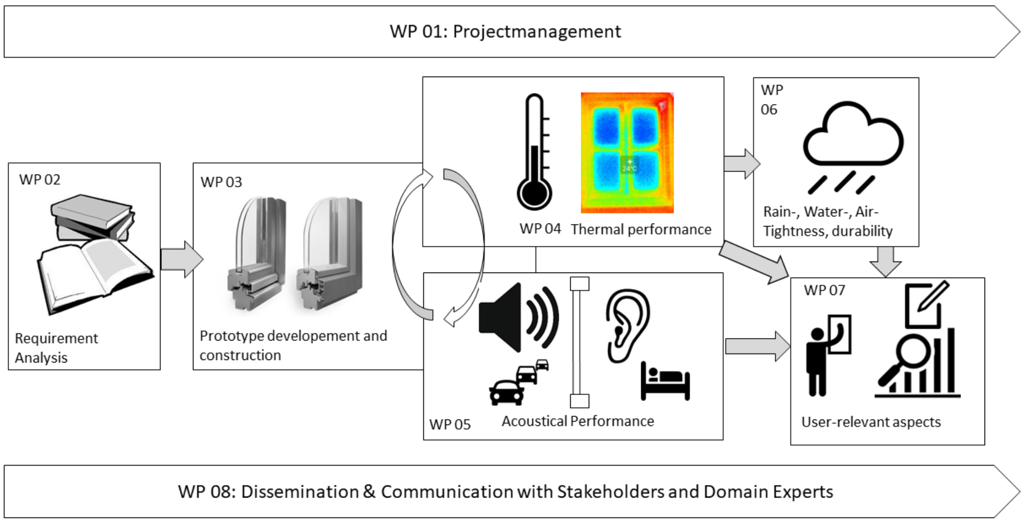


Figure 4. Work packages (WPs) of the project FIVA.

MOTIVE as drawings and small-scale models were selected for further development in FIVA. These were a turn window opening to the inside (I), a turn window opening to the outside (A), a swing window (K), and a sliding window (S). These principles are illustrated in Figure 5.

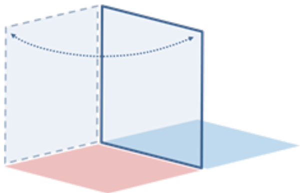
The work packages 3, 4, and 5 were conducted in parallel and under iterative information exchange. This was necessary due to the strong interdependencies between these domains. Tools and instruments used in these work packages included numeric thermal simulation for work package 4, conducted with a state of the art tool [9], small physical construction models and comprehensive testing on normative test beds. Figure 6 illustrates some early stage construction physical function-models.

The work package dealing with aspects of non-thermal and non-acoustical technical aspects such as air- and water-tightness, resistance against wind-driven rain and durability, were conducted via functional mock-ups on test beds. The user-relevant aspects included an evaluation of the window operation and aspects such as universal design. Fully functional mock-ups were constructed and presented and exhibited at the annual convention of window and door constructing companies in Austria in 2020. Thereby, peers of the relevant domain were asked to fill a questionnaire about the different prototypes. Likewise, non-domain experts were confronted with the prototypes at a later stage to also harvest laymen opinion.

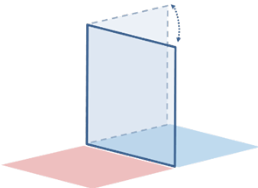
3. Results and Discussion

3.1. Window prototypes I, A, K and S

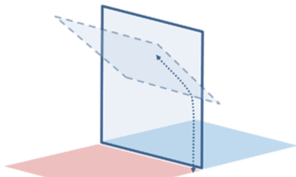
In an early stage of the development the decision was made to not only generate highly-insulating windows with low thermal transmittance, but also to motorize the window operation at least in part. The idea behind was to integrate a ventilation position in each of the prototypes that allows user-independent operation and automation. Thereby, a basic requirement was defined as a fully automated change from locked and closed position to the ventilation position. The further opening (that is from ventilation position to fully opened position) was foreseen as manual operation in



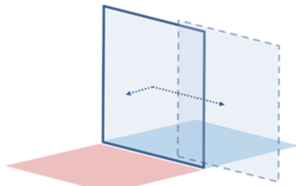
(a). Turn window opening to the inside (I).



(b). Turn window opening to the outside (A).



(c). Swing window (K).



(d). Sliding window (S).

Figure 5. Selected operational window concepts elaborated in the FIVA project.

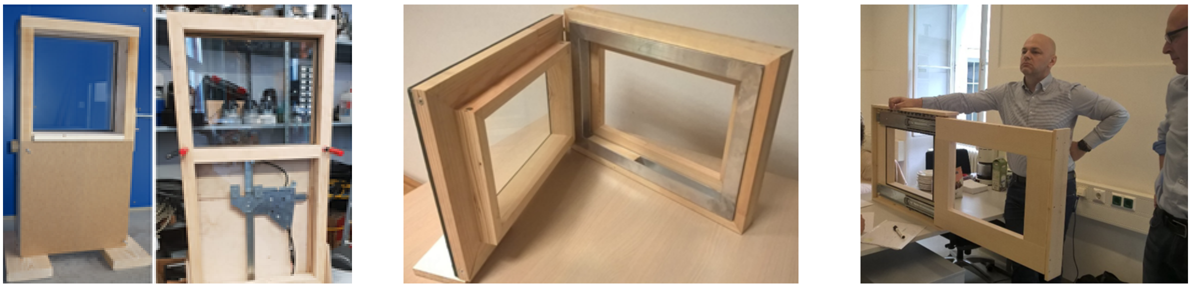


Figure 6. Early functional prototypes for sliding windows and turn windows.

all but one of the prototypes. In the following subsections, the different prototypes are briefly presented and illustrated.

3.1.1. Window prototypes I: Turn window opening to the inside

Turn windows that open to the inside are a well-established operation scheme in Central Europe, and thus come with high level of user acceptance. This well-established operation concept was adapted to the necessities of the vacuum glass. In the design, the glass surface was intended to be in line with surrounding inner wall surfaces. This was reached by situating the wing-frame of the window on the outer side of the vacuum glass pane via structural sealing. Thereby, the required glass edge cover necessary to mitigate thermal bridge effects of the glass seal is exceeded. The operation works as follows: The wing is de-locked and moved to the ventilation position (about 10 cm offset) via the integrated electromotor. From this position the window can be opened to a full 90° opening angle. Due to the turn movement to the inside, a moveable shading device can be deployed in the outer perimeter of the window aperture. Another aspect of this window design is the positioning of all motors and moving fitting parts in the fixed part of the window frame. Figure 7 illustrates the window prototype I.

3.1.2. Window prototypes A: Turn window opening to the outside

Turn windows that open to the outside are not a well-established concept in central Europe in contemporary building construction despite the fact that this has been part of the architectural portfolio in past epochs and the undeniable advantages regarding space utilization of the adjacent interior space. However, many buildings in northern Europe are equipped with windows that wings that can be turned to the outside. The window prototype A was designed to feature a rather homogeneous appearance by keeping the window clearance and glass clearance in the same dimension. The window has a motor-driven ventilation position, which is a 60 mm offset to the closed position. This still allows the usage of an external moveable shading device that can be lowered before the offset window wing. The window can be unlocked in the offset position to allow a 90 degree turn to the outside. Figure 8 illustrates the prototype of window A.

3.1.3. Window prototypes K: Swing window

In contrast to the previous two window prototypes, the swing window features the movement of 1960s and ’70s car port doors. Two parallel, fixed rotation points allow a motor-driven swing-movement until the fully open position that stores the window wind closely under the room ceiling. The kinematics of the window can be considered as complex, but allows for very large windows. Challenges connected with this window typology encompass the potential lack of user acceptance, the complex sealing detailing around the rotation points, and the difficult implementation of external shading devices. Nonetheless, the window offers a set of advantages, such as large opening apertures, full motorization that allows to fix the wing in any opening position and the space-saving handling of the wing. Figure 9 illustrates the prototype of window K.

3.1.4. Window prototypes S: Sliding window

This window prototype combines offset and sliding movement. After being offset by motorized actuators, the window can be slid open manually. Assets of the window include the aesthetics, as no sliding rails

(a). View from inside. (b). View from inside. (c). View from outside including moveable shading membrane. (d). Simulation model and false-color temperature distribution.

Figure 7. Window prototype I.

Figure 8. Window prototype A. Different views and perspectives of prototype A.

Figure 9. Window prototype K. Different photographs of the prototype illustrating appearance in closed and open states as well as details.

FIGURE 10. Window prototype S. From left to right: Thumb cinema of the opening process, window and fitting detailing.

Prototype	Average grade (subjective evaluation)	U_W-value $[W \cdot m^{-2} \cdot K^{-1}]$ (U_g-value = $0.7\,W \cdot m^{-2} \cdot K^{-1}$)	U_W-value $[W \cdot m^{-2} \cdot K^{-1}]$ (U_g-value = $0.4\,W \cdot m^{-2} \cdot K^{-1}$)	f_{Rsi} [-]
I	1.8	0.91	0.71	0.74
A	2.3	0.85	0.66	0.77
K	2.5	0.76	0.58	0.75
S	1.7	0.75	0.55	0.87

TABLE 1. Evaluation results (average grade), U_w-values, and f_{Rsi}-values of the different prototypes.

or other hints unravel the operation, and the easy integration in any opaque wall system. Equipped with vacuum glass, the window performs fine in view of thermal bridge aspects and overall heat transfer reduction. Moreover, the offset movement allows for the use of rather noncomplex rubber seals. Challenges include the uncommon and thus non- user-proven operation, the cleaning of the transparent parts of the windows, and the size limitations of apertures by the telescope rails used in this prototype. Never the less, we believe that this window prototype possess a high degree of innovation that might have disruptive effects for the window building industry. Figure 10 shows prototype S.

3.2. Evaluation by domain experts and thermal performance of the shown window prototypes

We asked domain experts to evaluate the window mock-ups in an exhibition during the Fenster-Türen-Treff 2020 in Salzburg, Austria. Evaluation criteria included aesthetics, innovation, technical aspects, mounting, and usability comfort and user acceptance. The results of this evaluation (conducted by nearly 50 experts) can be found in Table 1 (Austrian school grade system: 1 = excellent, 5 = insufficient). Moreover, Table 1 illustrates the U_W-values and f_{Rsi}-values that could be reached with two different vacuum glass products (Glass I: $U_g = 0.7\,W \cdot m^{-2} \cdot K^{-1}$, Glass II: $U_g = 0.4\,W \cdot m^{-2} \cdot K^{-1}$). A full discussion of the thermal performance of the presented window prototypes can be found in [10, 11]. All prototypes show excellent U-values (given the glass pane size of less than 1 cm) and fulfil the condensation and mold-growth criteria ($f_{Rsi} \geq 0.71$, following EN ISO 10211 and ÖNORM B 8110-2) [12, 13].

4. Conclusion & Future Research

The present contribution highlighted the main outcome of the project FIVA, which focused on generation of new, highly-insulating window prototypes that employ vacuum glazing products. Both the construction generation process and insights in the performance analysis were provided. All four developed window prototypes can be considered to be in a rather high level of technology readiness. However, until such windows will emerge on the market, still a long way has to be gone, including further assessment and improvement of industrial construction processes, availability of vacuum glass on the European market, finalizing of the technology development regarding frames and glass pane integration, as well as supplementary parts (fittings and sealing). Nonetheless, the project did prove the high potential of vacuum glass for innovative window products.

Acknowledgements

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