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2D COMPUTATIONAL ANALYSIS OF A VACUUM GLAZING INSTALLATION IN A WOOD-BASED WINDOW FRAME IN THE CONTEXT OF THE LINEAR THERMAL TRANSMITTANCE Ψ_g

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Abstract

This study investigates the linear thermal transmittance coefficient Ψ_g of vacuum glazing when installed in a wooden window frame. Vacuum glazing is a promising technology for enhancing the energy efficiency of a building by eliminating convective and conductive heat transfer within a vacuum gap. However, thermal losses at the edge seal can significantly impact its overall performance. A 2D computational analysis was conducted to evaluate Ψ_g values for different vacuum glazing configurations and installation positions. Unlike previous studies, this research systematically analyzes the effect of the depth of an installation on Ψ_g and the internal surface temperature at the glazing-frame interface. The findings indicate that vacuum glazing with an indium-based edge seal exhibits Ψ_g values comparable to insulating glazing units with metallic spacers, while vacuum glazing with a glass fusion seal achieves lower Ψ_g values. Furthermore, the study emphasizes that increasing the depth of an installation significantly reduces Ψg and improves the distribution of the surface temperature, thereby mitigating the risk of condensation. These results provide valuable insights into optimizing the integration of vacuum glazing in wooden window frames and offer practical guidelines for enhancing thermal efficiency in building applications.

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Key words

- Vacuum glazing,
- Ψ_g value,
- 2D computational analysis,
- Thermal transmittance,
- Condensation risk.

1 INTRODUCTION

Improving the energy efficiency of a building is crucial for reducing operational energy consumption and greenhouse gas emissions. Windows are a major source of heat loss and drive the need for continuous advancements in thermal insulation technologies. One of the most promising solutions is vacuum glazing, which eliminates conductive and convective heat transfer in the interstitial space between glass panes.

Vacuum glazing works by evacuating air from the space between two glass panes and effectively eliminates gas conduction and convective heat transfer. The absence of air prevents molecular diffusion and circulation, which significantly lower the overall thermal conductivity of the glazing unit. To minimize radiative heat transfer, a low-emissivity (low-e) coating is applied to the internal glass surfaces, thereby effectively limiting infrared radiation exchange between the panes (Pont et al., 2017).

Vacuum glazing technology was first patented by Alfred Zoller in 1913, but its practical implementation remained a challenge for decades. A breakthrough occurred in 1989 when researchers, led by Professors Robinson and Collins, at the University of Sydney (Australia), developed the first functional prototype. The initial prototypes utilized a grid of support pillars to maintain the separation between the glass panes and prevent any collapse under vacuum pressure. Subsequent advancements in vacuum glazing technology focused on low-temperature edge sealing techniques using indium-based alloys, which enabled the application of soft-coat low-emissivity coatings that would otherwise degrade under high processing temperatures (Cuce, Cuce, 2016).

Despite its superior thermal insulation performance, thermal losses through the edge seal remain a critical challenge. The edge seal, particularly when composed of metallic alloys, acts as a thermal bridge and negatively affects the overall thermal efficiency of the glazing system (Fang et al., 2014).

Several recent studies have addressed thermal bridging and edge-zone performance in window systems using numerical simulations and measurements. Gang et al. (2016) investigated surface condensation and thermal behavior at glazing edges by focusing on the role of spacers and temperature distribution. Similarly, Tywoniak et al. (2019) analyzed roof window assemblies with wooden frames using 2D thermal calculations. While these studies provide valuable insights into conventional glazing systems, they do not consider the specific characteristics of vacuum glazing. The present study extends this field by evaluating the thermal performance of vacuum glazing in a wooden window frame, with a particular focus on the effect of the depth of the installation on the linear thermal transmittance Ψg and the interior surface temperature.

The primary objective is to analyze the effect of different installation positions on the frame's thermal transmittance U_f, the linear thermal transmittance at the glazing-frame interface Ψ_g, and the internal surface temperature at the contact area. Optimizing these parameters can significantly reduce the risk of condensation and enhance the long-term thermal performance of window systems.

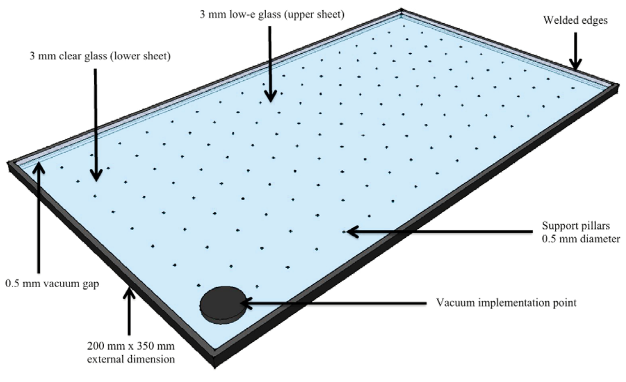

***Fig. 1** The 3D schematic of vacuum glazing (Cuce, Cuce, 2016).*

2 METHODS

Fenestration systems, including windows, doors, and glazed walls, play a crucial role in the energy balance of buildings. From the perspective of a building's physics, they require special attention, as they exhibit higher heat transfer rates compared to opaque building elements such as walls, roofs, and floors. This is primarily due to their heterogeneous structure, which is characterized by the differing material and thermal insulation properties of the frame and glazing components.

According to STN 73 0540-2 + Z1 + Z2: 2019, two key parameters define the thermal performance of fenestration systems:

- The internal surface temperature of the window construction $\Theta_{si,w}$ [°C],
- The thermal transmittance coefficient U_w [W/(m²·K)], which quantifies the amount of heat transferred through the window per difference in the unit temperature between the interior and exterior environments.

The thermal transmittance of external windows and doors must comply with the following requirement:

$$U_w \leq U_{w,r^2}$$

where:

U_w represents the calculated value, which is either obtained from direct measurement or derived from the measured values of the glazing and frame in accordance with STN EN ISO 10077-1. The value of U_{wr^2} is equal to 0.85 W/(m²·K).

Heat transfer in the glazing edge zone affects U_w, making it dependent on the window's geometry and dimensions rather than a fixed value. European standards (e.g., STN EN ISO 10077-1) offer standardized methodologies for calculating Uw based on predefined frame and glazing parameters. This methodology accounts for:

- The frame's thermal transmittance coefficient U_f,
- The glazing's thermal transmittance coefficient U_g,
- The interaction between the frame and glazing, as expressed by the linear thermal transmittance coefficient Ψ_g,
- The thermal transmittance coefficient U_w is determined using the following equation:

$$U_w = \frac{U_f.A_f + U_g.A_g + \Psi_g.l_g}{A_f + A_g}\ [W/(m^2.K)] \quad (1)$$

where:

- U_f – Frame's thermal transmittance coefficient [W/(m²·K)],
- U_g – Glazing's thermal transmittance coefficient [W/(m²·K)],
- Ψ_g – Linear thermal transmittance coefficient [W/(m·K)],
- l_g – Perimeter length of the glazing in the window sash [m].

The U_g value for a given insulating glazing system is determined without considering the effect of the edge, while U_f is evaluated for the frame independently of the glazing. The linear thermal transmittance coefficient Ψ_g represents the additional heat transfer occurring at the glazing-frame interface, which depends on the type of glazing, frame material, and spacer system.

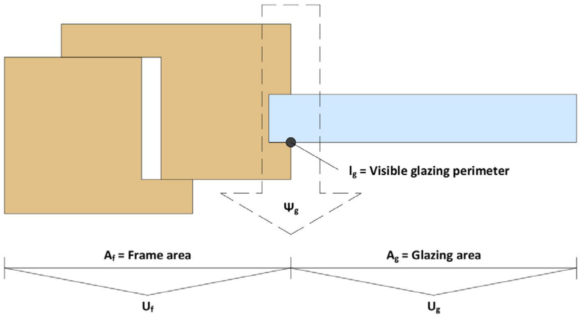

Fig. 2 Scheme for determining the glazing, frame, and sash areas

Since Ψ_g is not an intrinsic material property, its value depends on the specific configuration of the glazing-frame interface. The same spacer material may induce varying levels of additional heat loss when applied to different frame types (wood, plastic, aluminum), which may ultimately influence the overall thermal transmittance of the window system. Standards such as STN EN ISO 10077-2: 2019 define a numerical method for calculating Ψ_g and provide a more precise evaluation of the thermal performance of frame profiles.

Tab. 1 Ψ_g values for aluminium, steel spacer bars, and thermally improved plastic-based spacer bars

Frame material Glazing infill	Double or triple glazing, Uncoated glazing, Air- or gas-filled gap Ψ_g [W/(m·K)]		Low- emissivity double glazing, Triple glazing with double low-emissivity coating, Air- or gas-filled gap Ψ_g [W/(m·K)]	
	Thermally improved spacer bar	Aluminium spacer bar, Steel spacer bar	Thermally improved spacer bar	Aluminium spacer bar, Steel spacer bar
Wood frame, PVC frame	0.05	0.06	0.06	0.08
Metal frame with thermal break	0.06	0.08	0.08	0.11
Metal frame without thermal break	0.01	0.02	0.04	0.05

The methodology is specified in STN EN ISO 10077-2: 2019: Thermal Performance of Windows, Doors, and Shutters; Calculation of Thermal Transmittance; Part 2: Numerical Method for Frames. It defines and provides, the reference input data for the calculation of the thermal transmittance coefficient of frame profiles U_f and the linear thermal transmittance coefficient at the glazing interface Ψ_g.

Boundary conditions for a 2D analysis:

Exterior:
- Reference temperature conditions: $\Theta_e = 0$ °C
- External surface heat transfer resistance: $R_{se} = 0.04$ (m²·K)/W
- External surface heat transfer coefficient: $h_{se} = 25.00$ W/(m²·K)

Interior:
- Reference temperature conditions: $\Theta_i = 20$ °C
- Internal surface heat transfer resistance: $R_{si} = 0.13$ (m²·K)/W
- Increased internal surface heat transfer resistance: $R_{si} = 0.20$ (m²·K)/W
- Internal surface heat transfer coefficient: $h_{si} = 7.69$ W/(m²·K)
- Increased internal surface heat transfer coefficient: $h_{si} = 5.00$ W/(m²·K)

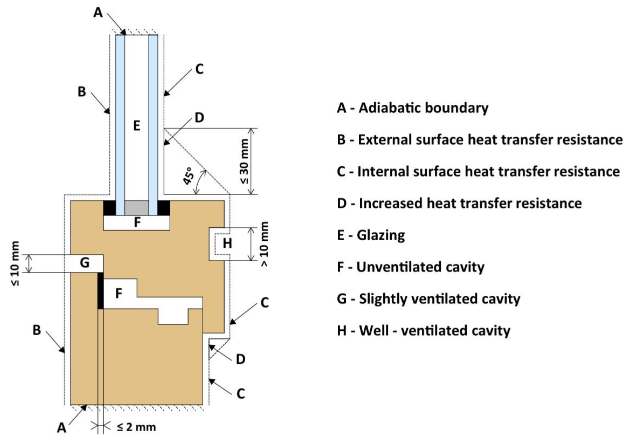

Fig. 3 Schematic section of the glazing-frame interface used for defining boundary conditions. This is a simplified illustration; the actual frame geometry used in computional analysis is shown in Figs. 12 and 13

2.1 Determination of the frame thermal transmittance coefficient - U_f

In the computational model, the glazing or opaque panel is substituted by a thermal insulation panel (λ = 0.035 W/(m·K)). The separation distance b_1 must be at least 5 mm (see Fig. 4), while the overlap b_2 corresponds to the portion of the glazing replaced by the insulation panel. The length of the panel must be at least 190 mm. For protruding seals, this means that the visible length of the panel may be less than 190 mm. The frame model must include all materials used by the window manufacturer, except for the glazing or opaque panel, which is substituted by the thermal insulation panel. If the frame is designed for a specific glazing or panel thickness, it must be replaced with the corresponding thickness.

$$U_f = \frac{L_f^{2D} - U_p \,.\, b_p}{b_f} \; [W/(m^2.K)] \qquad (2)$$

where:

- U_f – Frame's thermal transmittance coefficient [W/ (m²·K)],
- Lf^{2D} – Thermal conductance of the section [W/ (m·K)],
- U_p – Thermal transmittance coefficient at the central part of the panel [W/(m²·K)],
- b_f – Projected frame width [m],
- b_p – Visible panel width [m].

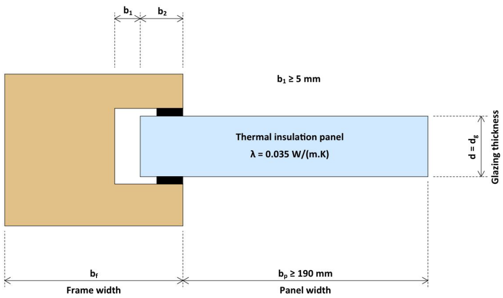

Fig. 4 *Profile with installed thermal insulation panel*

2.2 Determination of the linear thermal transmittance coefficient at the glazing interface -ψ_g

The glazing thermal transmittance coefficient U_g represents the heat transfer at the center of the glazing, which is unaffected by the glazing-frame interface. The frame thermal transmittance coefficient U_f characterizes the heat transfer through the frame structure, independent of the glazing. The linear thermal transmittance coefficient Ψ_g quantifies the additional heat flow at the glazing-frame interface, which is influenced by the spacer profile. This thermal bridge effect is defined by Ψ_g and the glazing perimeter length l_g, which accounts for the multidimensional heat transfer at the interface. Metal spacers, particularly aluminum and steel, have the greatest impact on Ψ_g. For non-standard spacer profiles, Ψ_g values can be calculated using STN EN ISO 10077-2: 2019. For 2D thermal conductivity calculations, the frame segment bf, Uf is combined with the glazing segment U_g, b_g (Fig. 5). The linear thermal transmittance coefficient Ψ_g is determined by the following equation:

$$\Psi_g = L_\Psi^{2D} - U_f \,.\, b_f - U_g \,.\, b_g \;\; [W/(m.K)] \qquad (3)$$

where:

- Ψ_g – Linear thermal transmittance coefficient [W/ (m·K)],
- L_Ψ^{2D} – Thermal conductance of the section [W/(m·K)],
- U_f – Frame's thermal transmittance coefficient [W/ (m²·K)],
- U_g – Thermal transmittance coefficient of the central part of the glazing [W/(m²·K)],
- b_f – Projected frame width [m],
- b_g – Visible glazing width [m].

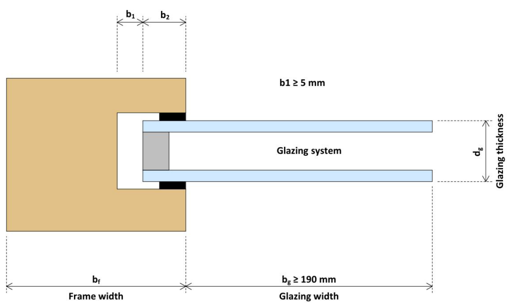

Fig. 5 *Profile with installed glazing*

2.3 Verification of the methodology for determining the frame's thermal transmittance coefficient – U_f

Based on the above methodology, the verification of the computational procedure was carried out. Since this article also focuses on the optimization of the shape and geometry of a wooden window frame, a wooden profile was selected from the referenced STN EN ISO 10077-2: 2019 – Annex H (Normative) – Example Window Frames for Verification of Calculation Programs. To validate the methodology, a specific profile was selected from the standard (Figure H.5, p. 55) to represent a wooden frame with a thermal insulation panel.

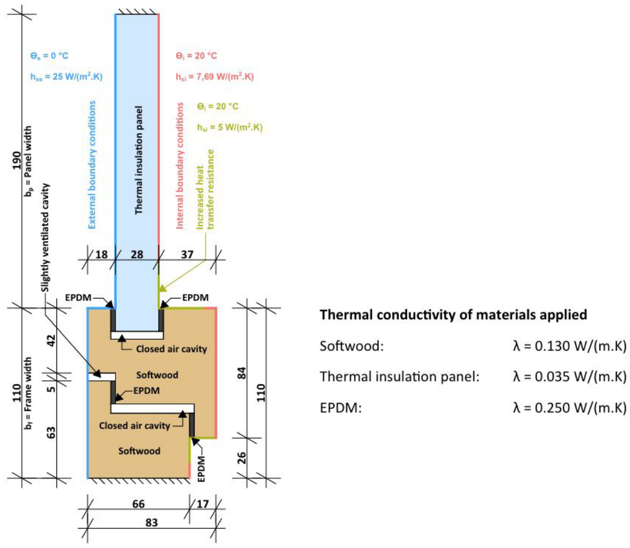

Fig. 6 *Wooden frame "H.5" with thermal conductivity of materials applied*

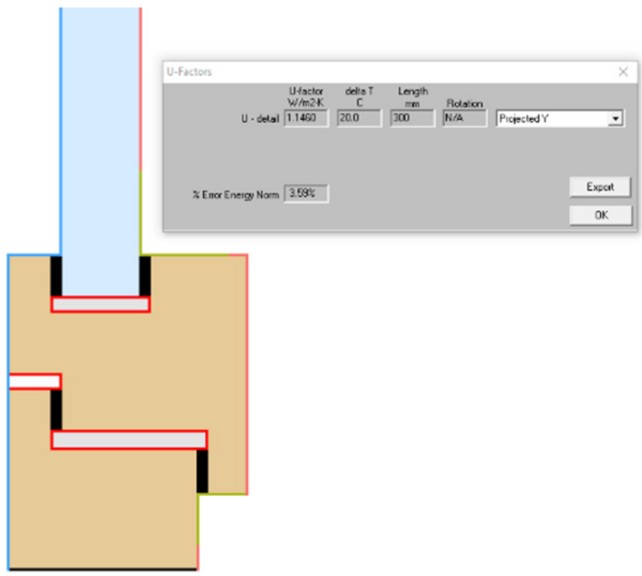

Fig. 7 *Wooden frame "H.5" in Therm software and the U_{detail} value*

Based on the computational analysis in the Therm software, the U_{detail} value was obtained. The thermal conductance Lf_{2D} was determined by multiplying the U_{detail} value by the total projected width of the window profile model, including the projected width of the insulation panel, i.e., $b_f + b_p$.

$$L_f^{2D} = U_{detail} \cdot (b_f + b_p)\ [W/(m.K)] \qquad (4)$$

where:

- L_f^{2D} – Thermal conductance of the section [W/ (m·K)],
- U_{detail} – Thermal transmittance coefficient of the construction analyzed [W/(m²·K)], (note: author's working designation),
- b_f – Projected frame width [m],
- b_p – Visible panel width [m].

In the equation for determining the frame's thermal transmittance coefficient U_f, it is necessary to express the thermal transmittance coefficient at the central part of the thermal insulation panel U_p.

$$U_p = \frac{1}{R_{si} + R_p + R_{se}}\ [W/(m^2.K)] \qquad (5)$$

- R_{si} – Thermal resistance of the internal surface heat transfer [(m²·K)/W],
- R_{se} – Thermal resistance of the external surface heat transfer [(m²·K)/W],
- R_p – Thermal resistance of the thermal insulation panel [(m²·K)/W].

The thermal resistance of the thermal insulation panel R_p is determined as the ratio of the panel thickness dp to the thermal conductivity of the panel λ_p. According to the standard, the thermal insulation panel has a thermal conductivity of λ_p = 0.035 W/(m·K).

$$R_p = \frac{d}{\lambda}\ [(m^2.K)/W] \qquad (6)$$

All the values expressed were entered into the overall equation (2) to determine the frame's thermal transmittance coefficient U_f.

2.4 Verification of the methodology for determining the linear thermal transmittance coefficient at the glazing interface – ψ_g

Subsequently, the methodology for determining the linear thermal transmittance coefficient Ψg at the glazing-frame interface was validated for the wooden frame H.5 (as specified in the referenced standard – Figure H.11 on page 60) with an installed double insulating glazing unit (configuration 4/20/4), which has a glazing thermal transmittance coefficient of Ug = 1.30 W/(m²·K).

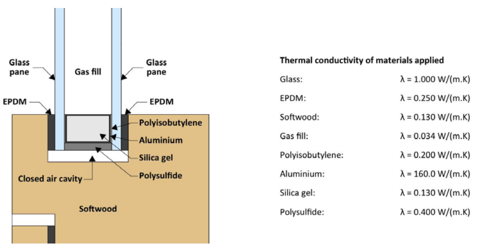

Fig. 8 *Detail of insulating double glazing installation in wooden frame "H.5" as a basis for determining the linear thermal transmittance at the glazing-frame interface Ψg [W/(m·K)]*

Similarly to the previous subsection, which is based on the computational analysis in the Therm software, the Udetail value was obtained. The thermal conductance L_ψ^{2D} is determined by multiplying the Udetail value by the total projected width of the window profile model, including the projected width of the insulated double glazing, i.e., $b_f + b_g$.

$$L_\Psi^{2D} = U_{detail} \cdot (b_f + b_g)\ [W/(m.K)] \qquad (7)$$

- L_ψ^{2D} – Thermal conductance of the section [W/ (m·K)],
- U_{detail} – Thermal transmittance coefficient of the construction analyzed [W/(m2·K)], (note: author's working designation),
- b_f – Projected frame width [m],
- b_g – Visible glazing width [m].

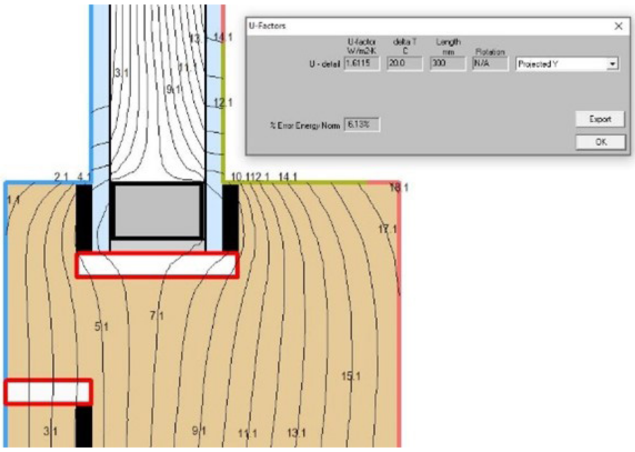

Fig. 9 *Detail of insulated double glazing installation in wooden frame "H.5" in Therm software and the U_{detail} value*

Based on the derivation of the thermal conductance of the section, the linear thermal transmittance coefficient at the glazing interface can be determined. Furthermore, based on the 2D computational analysis, the values from the standard were compared with those obtained from the Therm simulation software. The parameters compared were the thermal conductance Lf^{2D} and the frame thermal transmittance coefficient U_f.

Tab. 2 *Comparison of Uf and Ψg values from the 2D analysis and the standard*

	2D analysis	Standard
Thermal conductance of the section L_{f2D}	0.3438 W/(m·K)	0.3440 W/(m·K)
Frame thermal transmittance coefficient U_f	1.3448 W/(m²·K)	1.3400 W/(m²·K)
Thermal conductance of the section $L_{\Psi 2D}$	0.4835 W/(m·K)	0.4780 W/(m·K)
Linear thermal transmittance coefficient Ψ_g	0.0885 W/(m·K)	0.0830 W/(m·K)

The values from the standard and the 2D computational analysis are similar, which confirms that the methodology applied is correct.

2.5 2D Computational analysis of the vacuum glazing application in a wood-based frame

The 2D computational analysis follows the previously described methodology and examines the integration of vacuum glazing into a softwood window frame. The glazing unit has a total thickness of 10 mm and comprises two 4.9 mm glass panes separated by a 0.2 mm vacuum gap. The wooden window profile is based on the "H.5" profile, which represents a simplified geometry of a wooden window frame with an operable sash. In this analysis, the edge seal of the vacuum glazing is considered to be made of indium-based alloys. Since it is a metallic alloy with high thermal conductivity, it is assumed that this glazing configuration represents the worst-case scenario. For the analysis presented in this chapter, integrating this type of glazing ensures that the results are conservative, as modern vacuum glazing typically utilizes a glass fusion edge seal, which exhibits better thermal performance due to its lower thermal conductivity coefficient λ. In the 2D computational model, the height of the edge seal is 12 mm. The vacuum glazing analyzed corresponds to a product manufactured by Beijing Synergy Vacuum Glazing Technology Co., Ltd., which was tested in the Laboratory of Building Structures at the Faculty of Civil Engineering, STU, in Bratislava in 2018. The following data is provided directly by the manufacturer (Chmurny, 2019).

The vacuum glazing structure consisted of T5 + V + TL5, where:

"T" represents a 5 mm thick thermally-treated glass,
"V" denotes the vacuum gap, with a thickness ranging from 0.15 to 0.2 mm,
"TL" describes a thermally-treated glass pane with a low-emissivity coating.

The height of the edge seal, which is made from indium-based metal alloys, is 10 mm. The declared thermal transmittance coefficient of the glazing is U_g = 0.58 W/(m².K). All the parameters provided by the manufacturer are declared based on calculations performed in the "Window 7" software, following the Canadian standard NFRC 100-2010 (Chmurny, 2019).

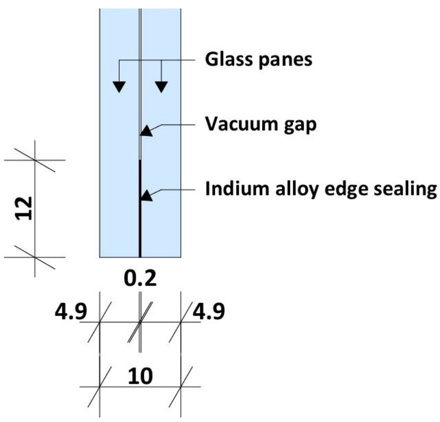

Fig. 10 Schematic of the edge fragment of the vacuum glazing applied in the 2D analysis

As part of the 2D computational analysis, the following calculated values were monitored:
the frame thermal transmittance coefficient U_f and the linear thermal transmittance coefficient at the glazing-frame interface Ψ_g. Additionally, the internal surface temperatures at the glazing-frame interface were compared in the 2D computational analysis. The temperature in this region must not drop below the dew point temperature (Θ_{dp} = 9.26 °C) at an indoor relative humidity of 50%. When performing the calculations, it is necessary to consider various boundary conditions, particularly different reference temperature conditions.

However, in this case, the reference temperatures were maintained in compliance with STN EN ISO 10077-2: 2019, which defines the thermal performance assessment of windows, doors, and shutters through numerical methods. The resulting internal surface temperature values were used for the comparison and provided a graphic representation of the temperature distribution at different vacuum glazing installation positions within the frame. The primary objective was to determine the optimal installation position of the vacuum glazing within the wooden window frame. Subsequently, the dimensional parameters of the glazing groove were geometrically adjusted in the context of the vacuum glazing, upon considering the effect of the increased heat flow at the edge seal. Based on the declared thermal transmittance coefficient of the vacuum glazing U_g = 0.58 W/(m²·K), the equivalent thermal conductivity coefficient of the vacuum gap $\lambda_{ekv-vak}$ was numerically determined.

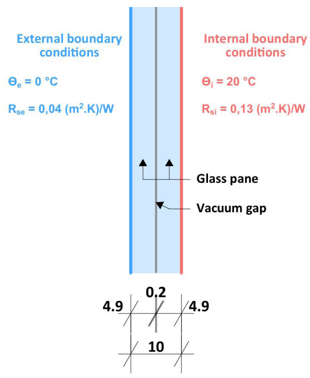

Fig. 11 Schematic of the glazing fragment applied in the 2D computational analysis for the numerical determination of the equivalent thermal conductivity of the vacuum gap.

The thermal conductivity coefficient of the vacuum gap calculated represents an equivalent value, as it accounts for the effect of the spacer pillars, which are arranged in a 40 × 40 mm grid. Before applying vacuum glazing for the numerical 2D analysis, the geometry of the "H.5" profile was modified to facilitate the optimal installation of vacuum glazing into the designated frame, referred to as "H.5-2.0". The height of the window sash was increased by 13 mm at the expense of the fixed part of the frame, thereby ensuring that the total visible width of the frame (b_f – frame width) remained at 110 mm. Additionally, the profile depth was adjusted from 83 mm to 90 mm. The position of the thermal insulation panel was also modified. This adjusted profile will serve as the basis for the 2D computational analysis.

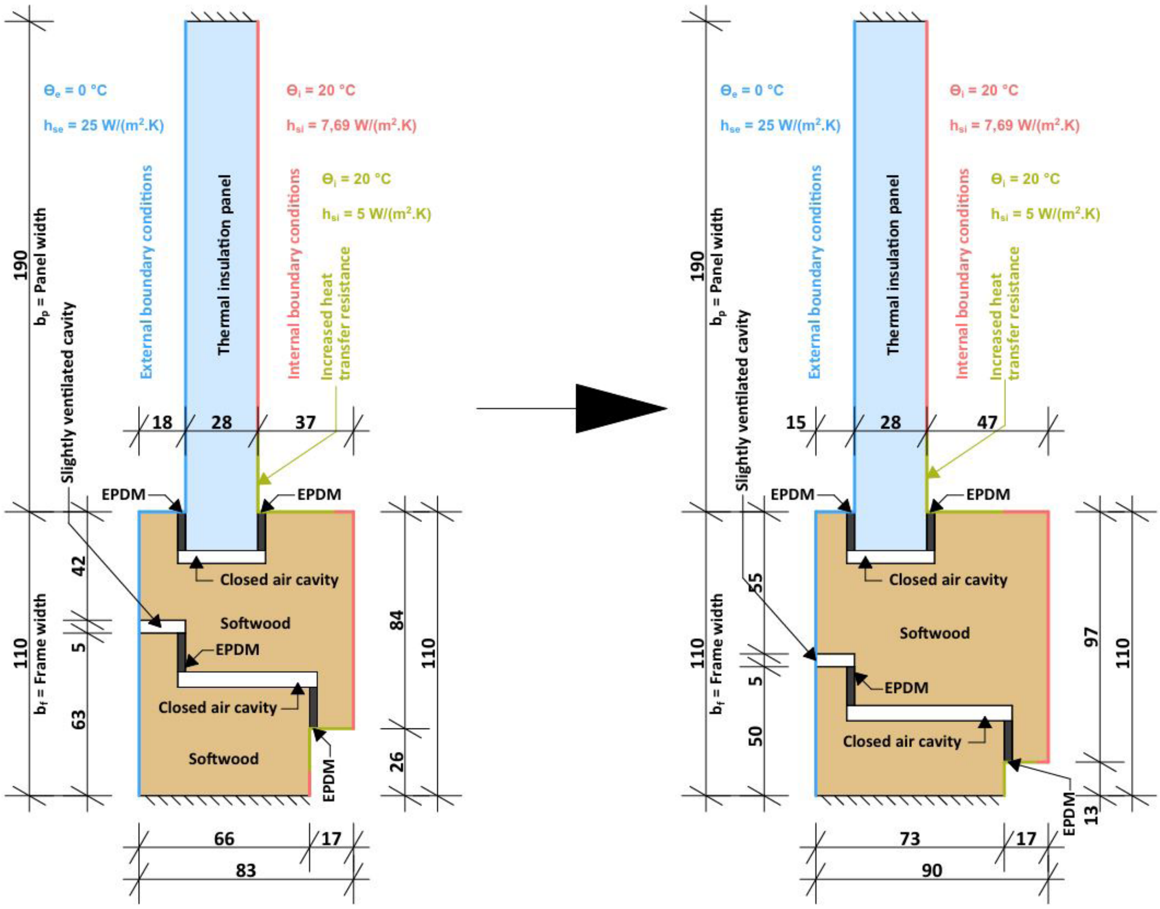

Fig. 12 *Modification of profile 'H.5' (left) to profile 'H.5-2.0' (right)*

Tab. 3 *Comparison of U_f values of frames "H.5" and "H.5-2.0" from 2D analysis*

	Frame "H.5"	Frame "H.5-2.0"
Thermal conductance of the section L_{2D}	0.3438 W/(m·K)	0.3367 W/(m·K)
Frame thermal transmittance coefficient U_f	1.3448 W/(m²·K)	1.2804 W/(m²·K)

Based on the 2D computational analysis, the values for the "H.5" profile were compared with those for the "H.5-2.0" profile using the Therm simulation software. The parameters compared were thermal conductance Lf_{2D} and the frame thermal transmittance coefficient U_f.

The primary objective is to determine the optimal installation position of vacuum glazing within the wooden window frame. This involves geometrically adjusting the dimensional parameters of the glazing groove in the context of the vacuum glazing, by considering the effect of the increased heat transfer at the glazing edge. For a wooden frame with an operable 90 mm wide sash, the first installation position of the thermal insulation panel/vacuum glazing is set 15 mm from the left edge of the operable part of the frame ("A"), while the last position is also 15 mm from the right edge ("K"). The interval between the individual positions in the horizontal direction is 5 mm, which results in a total of 11 positions in the horizontal axis.

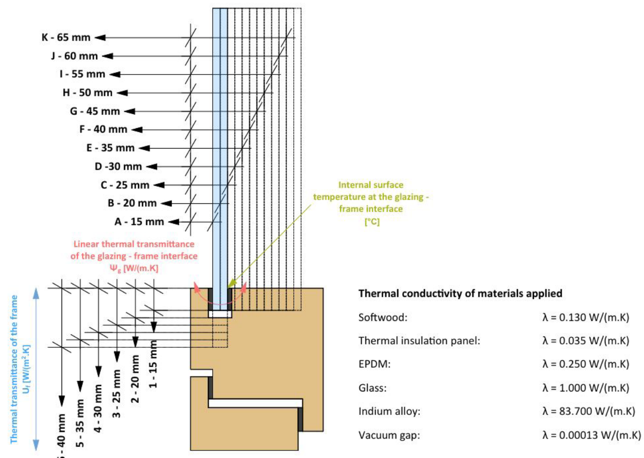

Fig. 13 *Graphic representation of the various positions of the vacuum glazing installation in the wood-based window frame "H.5–2.0", along with an indication of the parameters monitored in the 2D analysis (window frame "H.5-2.0" without phenolic-foam insulation)*

The boundary conditions were adjusted from positions "I," "J," and "K" to account for the reduction of the zone with the increased heat transfer resistance (this zone is highlighted in light green in the figures).

Another 2D analysis was conducted to investigate the effect of adding a thermal insulation strip to the wooden rame, while maintaining the same geometry as in the previous analysis ("H.5-2.0"). The insulation strip was assumed to be made of a phenolic foam-based material with a width of 15 mm. The height of the insulation was adjusted according to the depth of the glazing installation, specifically 15, 20, 25, 30, 35 and 40 mm. The insulation strip was placed in front of the glazing on the exterior side. The thermal conductivity of the phenolic foam-based insulation strip is λ_{phenol} = 0.025 W/(m·K).

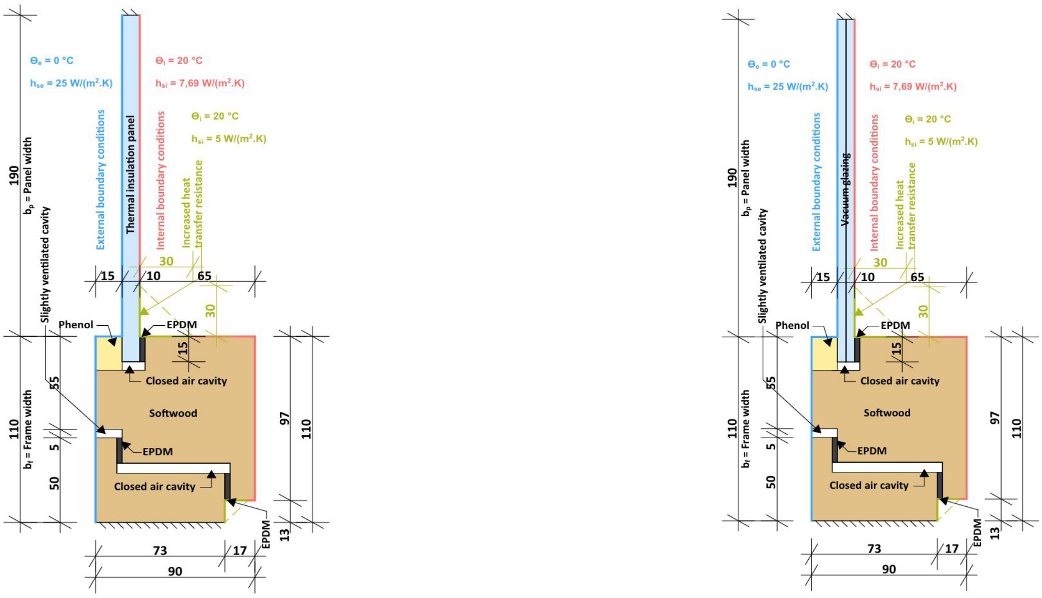

Fig. 14 Model geometry and boundary conditions for the 2D analysis with an installed thermal insulation panel (left) and vacuum glazing (right) in position 'A1' with an installation depth of 15 mm (window frame "H.5–2.0" with phenolic-foam insulation)

4 RESULTS

The graph and computational results reveal that the optimal frame thermal transmittance coefficient U_f is achieved at position "E6" (U_f = 1.2369 W/(m²·K)), which corresponds to a thermal insulation panel installation depth of 40 mm and a 35 mm offset from the left edge of the window sash. The least favorable value is at position "K1", with U_f = 1.4775 W/(m²·K), where the installation depth is 15 mm, and the distance is 65 mm.

Similarly, for the linear thermal transmittance coefficient Ψ_g, the lowest value occurs at "E6" (Ψ_g = 0.0411 W/(m·K)), while the highest additional heat loss is at "K1" (Ψ_g = 0.1078 W/(m·K)). The graph confirms that Ψg is primarily influenced by the depth of the installation of the vacuum glazing, while the distance from the left edge has a minimal impact.

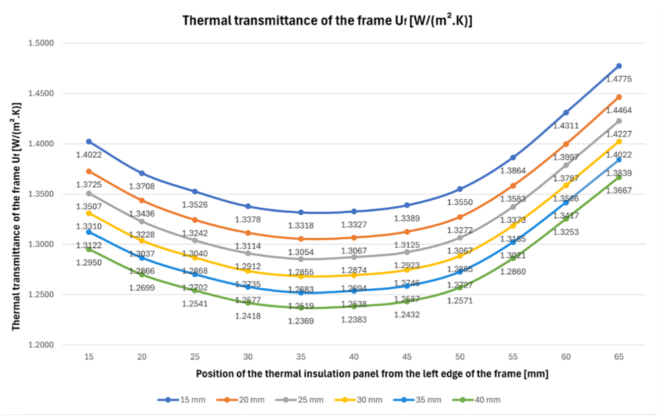

Fig. 15 Graphic representation of the thermal transmittance values of the frame U_f [W/(m²·K)] (window frame "H.5-2.0" without phenolic-foam insulation)

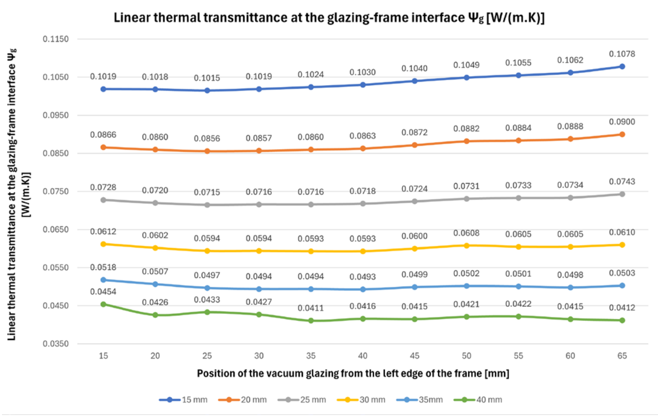

Fig. 16 Graphic representation of the linear thermal transmittance values at the glazing-frame interface Ψ_g [W/(m·K)]; (window frame "H.5-2.0" without phenolic-foam insulation)insulation)

The lowest internal surface temperature is observed at "A1" (8.5 °C), with a 15 mm installation depth and a 15 mm distance from the left edge. The highest surface temperature occurs at "K6" (15.5 °C), with a 40 mm installation depth and a 65 mm distance. The graph suggests that increasing the installation depth raises the surface temperature and that a 15 mm depth is unsuitable for vacuum glazing with an indium-based edge seal, as temperatures at several positions fall below the dew point (Θ_{dp} = 9.26 °C).

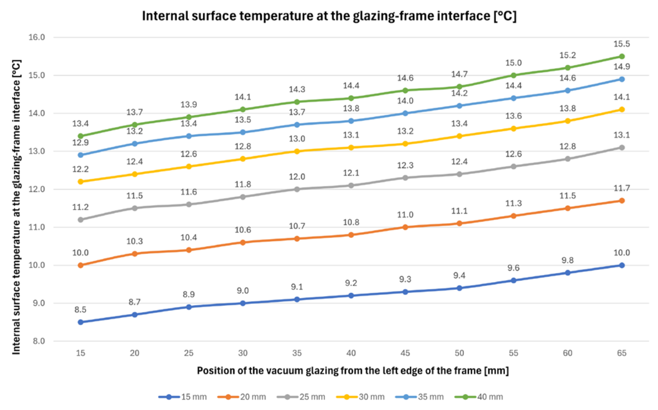

Fig. 17 Graphic representation of the temperatures at the interface between the vacuum glazing and the wooden frame from the interior side in °C (window frame "H.5-2.0" without phenolic-foam insulation)

Effect of the Phenolic Foam Insulation Strip:

The addition of a phenolic foam insulation strip enhances thermal performance; it yields optimal U_f values at positions "E6" and "G6" (U_f = 1.1017 W/(m²·K)), which is an improvement of ΔU_f = 0.1352 W/(m²·K) compared to the uninsulated scenario. The least favorable result remains at "K1" (U_f = 1.3425 W/(m²·K)).

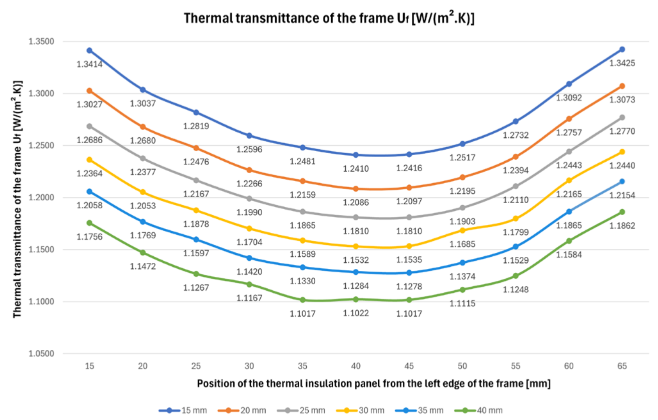

Fig. 18 Graphic representation of the thermal transmittance values of the frame U_f [W/(m²·K)] (window frame "H.5-2.0" with phenolic-foam insulation)

For Ψ_g, the most favorable value occurs at "B6" (Ψ_g = 0.0404 W/(m·K)), while the highest additional heat loss is again at "K1" (Ψ_g = 0.1031 W/(m·K)). The depth of the vacuum glazing installation remains the key factor influencing Ψ_g.

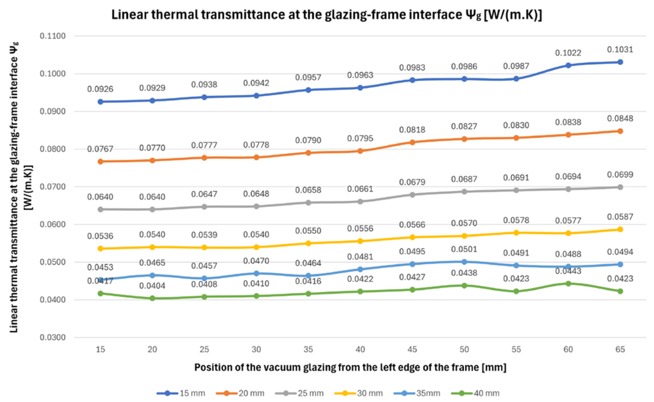

Fig. 19 Graphic representation of the linear thermal transmittance values at the glazing-frame interface Ψ_g [W/(m·K)] (window frame "H.5-2.0" with phenolic-foam insulation)

The lowest surface temperature remains at "A1" (9.5 °C), with a 15 mm depth and 15 mm distance, which shows a Δt = 1.0 °C improvement over the uninsulated case. The highest surface temperature is recorded at "K6" (16.0 °C), with a Δt = 0.5 °C increase. The graph confirms that a greater installation depth results in higher surface temperatures and that with the insulation strip, all the surface temperatures are now above the dew point (Θ_{dp} = 9.26 °C). However, an exterior temperature of Θ_e = -1.5 °C should be considered for a condensation risk assessment. This value is defined by the Slovak technical standard and represents a typical design temperature corresponding to the average temperature of the coldest month of the year (January)

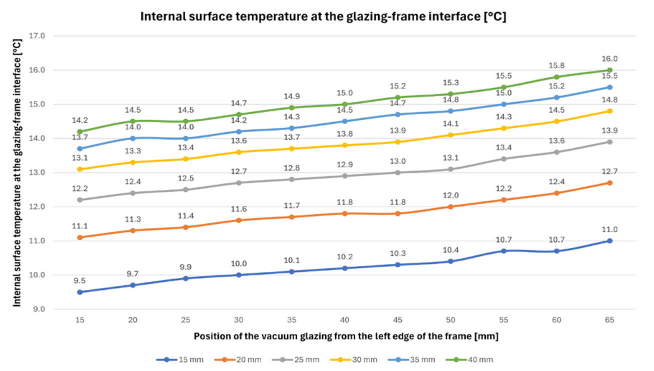

Fig. 20 Graphic representation of the temperatures at the interface between vacuum glazing and the wooden frame from the interior side in °C (window frame "H.5-2.0" with phenolic-foam insulation)

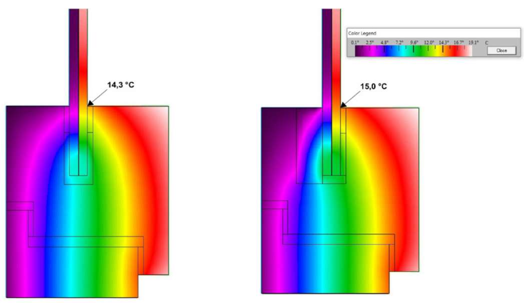

Fig. 21 2D temperature field for window frame H.5-2.0 without phenolic-foam insulation (left) and with phenolic-foam insulation (right), showing the surface temperature at the glazing–frame interface

5 CONCLUSION

The 2D computational analysis of the vacuum glazing application in a wooden frame with an operable sash confirmed that the depth of the installation significantly affects the linear thermal transmittance coefficient Ψ_g, thereby influencing thermal losses at the edge seal. A deeper glazing installation results in lower Ψ_g values, which reduces heat losses, while the distance from the left frame edge has no significant impact.

The study focused on optimizing the installation position of vacuum glazing to minimize heat losses and the risk of condensation. The analysis used vacuum glazing with a total thickness of 10 mm; it consisted of 4.9 mm thick glass panes and a 0.2 mm vacuum gap. The edge seal, which is assumed to be made of indium alloy, represented the worst-case scenario for thermal losses, with a seal height of 12 mm.

A modified wood-based frame (H.5-2.0) with a simplified operable sash geometry was used for the analysis. A total of 66 installation positions were evaluated by varying the depth (15–40 mm) and the distance from the left edge (15–65 mm).

- The lowest Ψ_g values were observed at a 40 mm installation depth, ranging from 0.0411 to 0.0427 W/(m·K).
- Best result: Ψ_g = 0.0411 W/(m·K) at position "E6" (40 mm depth, 35 mm from the left edge).
- The highest Ψ_g values occurred at a 15 mm installation depth, ranging from 0.1019 to 0.1078 W/(m·K).
- Worst result: Ψ_g = 0.1078 W/(m·K) at position "K1" (15 mm depth, 65 mm from the left edge).

In addition to Ψ_g, the internal surface temperatures at the glazing-frame interface were analyzed. These temperatures should not fall below the dew point (9.26 °C at 50% relative humidity). The results indicate that a 15 mm installation depth is unsuitable, as most positions exhibit temperatures below the dew point, thereby increasing the risk of condensation.

Installing vacuum glazing deeper into the frame (optimal at 40 mm) significantly reduces heat losses at the edge seal and minimizes the risk of condensation. The distance from the left edge has no major impact on Ψ_g or on the risk of condensation, although aesthetic and structural design factors should also be considered.

As standardized Ψ_g values for vacuum glazing are not yet established, it is advisable to rely on simulation-derived Ψ_g values, following the STN EN ISO 10077-2: 2019 methodology, which can be adapted to the specific frame and glazing configuration.

The results presented in this study are based on a softwood window frame with typical thermal properties and focus only on the bottom part of the window. The effect of other frame components, such as the side frame, lintels, or dividers, is not included. However, the main goal was to analyze and optimize the position and depth of a vacuum glazing installation in a wood-based frame, which justifies the simplified scope. In future work, it would be useful to investigate other types of wood and complete frame assemblies to improve the general applicability of the findings.

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