Roof windows – solutions and limitations

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Abstract. Paper deals with the roof windows (skylights) from building physics point of view. Based on several introductory analyses an innovative solution of the frame and sash construction was developed in close cooperation with the industrial partner. Resulting parameters correspond to requirements set for passive house level windows (minimized heat transfer, avoided risk of water vapor condensation). The frame and sash consist of effective combination of soft wood and hardened plastics. Glazing unit can be traditional, triple glazed, or double glazed with additional two transparent foils dividing the space into 3 cavities. The analyses also showed that the effect of sloping, and the effect of thermal coupling between window and roof, play a significant role in the overall performance. Thermal transmittance of the roof window, $U_w$, in the best category developed here, is 0.5 W/(m²K). When both the effects are included, its real thermal transmittance, $U_{\text{real}}$, is increased to 0.82 W/(m²K). Further development ideas and impulses for theoretical studies are mentioned in the final part of the paper.

1. Introduction
Roof windows (also known as skylights) are often considered to be problematic by designers of energy-optimized buildings (i) due to their relatively high thermal transmittance, which must be somehow compensated within the overall building envelope, (ii) due to the difficulties in solving connection details in the roof, and (iii) due to increased risks of overheating in spaces below.

Research and development project performed together with an industrial partner [1] dealt with problems connected with roof windows both in theory and in search of technical solution limiting some known disadvantages. Key findings were published [2] and presented to wider public, including a prototype at a building fair [3].

2. Theoretical consideration

2.1. Comparison with vertical windows and setting targets
By comparing roof windows with vertical windows in walls, the following significant differences can be found:

- Roof windows are generally smaller, so the frame area is more significant in thermal transmittance.
- At the component level, there is a usual requirement for cold moderate climate not to exceed thermal transmittance ($U$-value) of 0.8 W/(m²K) by keeping the linear thermal transmittance due to connection to building envelope negligible for reaching the passive house standard.
regardless to window position. (Note that the values of the glazing units are given (measured) for the vertical position).

- Heat transfer in the cavities between glazing panes is larger due to increased heat convection caused by air movement (the more inclined the more significant). Detailed calculation [4] includes cavity thickness, emissivity of glass surfaces, inclination angle. As a typical real result, $U$-value of the roof window is increased in the range of 0.1 – 0.2 W/(m²K), related to the whole window.

- External perimeter of the window is situated in the cold area of the roof. So, it is not possible to achieve the so called thermal-bridge free solution (see Figure 1). The result expressed as linear thermal transmittance, $\psi$ in W/(m·K), should be considered.

- Surface heat transfer coefficient, $h$ in W/(m²·K), describing the heat transfer between internal surface of the window and surroundings varies. In the case of larger vertical windows one can expect the standard values across the area. In smaller, inclined roof windows, additionally often influenced by heaters close by, the situation can be different [2].

- Radiation heat exchange between the external surface and the (clear) sky is higher for roof windows (e.g. multiplied by factor 1.5 for 45° sloped windows). This fact leads to an increase of the external surface heat transfer coefficient.

- Generally, there is a higher passive solar gain due to the inclination of roof windows. This may be beneficial at low winter temperatures, but may cause problems at other times (room overheating). Moreover, efficient and controlled external shading such as venetian blinds are not available for roof windows.

- Specific effects can be observed in summer conditions: The external air close to the roof surface can be significantly warmer (heated by the roof covering) compared to ambient. This further increases the risk of the room overheating.

- Requirements on the thermal transmittance of the roof construction result in an overall thickness of approximately 400 mm or more. This can negatively influence the daylight quality due to the very deep side lining taking into account the rather smaller dimension of roof windows. Therefore, the distribution of daylight in rooms as the primary function of each roof window should also be studied very carefully.

![Figure 1. Schematic horizontal cross-section of a typical position of a roof window in a pitched roof. ext.: exterior air temperatures; int: interior air temperature.](image)

It can be concluded that the actual desired $U$-value of roof windows for passive house quality must be lower compared to vertical windows. It should be 0.7 W/(m²K) or less, ideally approaching 0.5 W/(m²K). Moreover, simple parametric studies [2] have shown that the unavoidable heat transfer due to the thermal coupling of the window to the roof plays an important role. Corresponding compensation must be found in other components of the building envelope.
2.2. Introductory parametric studies
Introductory parametric studies [2] involving 2D-heat transfer calculations using the COMSOL Multiphysics modeling software [5] were carried out to map the key dependencies of the overall layout and geometry of window and frame material on the window’s thermal performance. The calculation model followed the rules given in [6]. Connection to the roof is considered here as adiabatic; this means that the effects of thermal coupling are not included. For that reason, the estimation of the minimum interior surface temperature is only indicative.

In this case, high-performance homogeneous materials for the frame were considered. The thermal conductivities of the fixed and movable parts (frame and sash) were 0.039 W/(m·K) and 0.065 W/(m·K), respectively. This corresponds to the use of hardened polystyrene [7] with densities of 100 kg/m$^3$ and 400 kg/m$^3$, respectively. The thermal transmittance of the triple glazing is considered 0.6 W/(m$^2$K).

Calculations were performed for indoor and outdoor air temperatures of 20 °C and 0 °C, respectively. During the parametric studies, several geometrical parameters and material parameters were changed over a relatively wide range in order to determine their importance within the whole configuration, see Figures 2 and 3. It can be concluded that the most significant parameters are (i) the setting depth of the window frame into the thermally insulated roof layer, (ii) the overall width of the frame and sash, and (iii) the material of the frame and sash. Other material and geometrical parameters are less important.

![Figure 2. Schematic of window cross-section showing the most important parameters analyzed in parametric studies.](image)

3. Real design solution
Repeated 2D-heat transfer calculations in steady state conditions were performed for selected configurations according to consultations within the development team. The HT-Flux software [8] was used to analyze representative cross-sections (for head and sill, over and under the hinge). The thermal transmittance of the frame, the linear thermal transmittance due to the connection between the glazing and frame, and the resulting thermal transmittance for the reference window size (1.14 m × 1.40 m) were estimated for each variant.

The effects of thermal coupling between the window and the roof construction were analyzed as well, and the resulting thermal transmittance of the installed window, $U_{w,\text{inst}}$, was estimated for the reference window size. Moreover, the minimum window surface temperature and corresponding surface temperature factors, $f_{Rsi}$, were evaluated [9].

Figures 4 and 5 show two final design variants as suggested by the development team, considering the results of preliminary studies as well as technical and manufacturing limitations. The frame and sash are made of a combination of soft wood and hardened plastics (thermal conductivity 0.039 W/(m·K)).

The window in Figure 4 (Var.I) is equipped with triple glazing ($U_g$ 0.5 W/(m$^2$K)). The window in Figure 5 (Var.II) is equipped with a special glazing unit in which two transparent polyester foils divide the space between two glazing panes into three cavities to reduce the overall heat transfer ($U_g$ 0.3 W/(m$^2$K)). The thermal performances of the presented window variants are summarized in Table 5.
Figure 3. Key tendencies discovered in the parametric studies, expressed as the thermal transmittance of the window and the minimum surface temperature factor [9]. Filled points represent basis values. For legend, see Fig.2.

Figure 4. Schematic cross-section of the window with triple glazing (left), and calculated heat flux distribution (air temperatures: interior +20 °C, exterior −17 °C) (right). Brown for wood, violet for hardened plastics.
Figure 5. Schematic cross-section of the window with special glazing using two foils dividing the cavity between two glazing panes (left), and calculated heat flux distribution (air temperatures: interior +20 °C, exterior −17 °C) (right). Brown for wood, violet for hardened plastics, turquoise for Aerogel stripes.

Table 1. Thermal performance for window variants according to Figures 4 and 5.

| Variant | Heat transfer [W/K] | Mean linear thermal transmittance for glazing edge [W/m·K] | Thermal transmittance for reference window size [W/(m²K)] |
|---------|---------------------|-----------------------------------------------------------|--------------------------------------------------------|
|         | Glazing $H_{T,g}$  | Frame $H_{T,f}$   | Edge $H_{T,\psi}$ | $\psi$ | $U_w$ |
| I (Fig.4) | 0.530   | 0.503            | 0.103          | 0.025 | 0.71  |
| II (Fig.5) | 0.303   | 0.344            | 0.148          | 0.037 | 0.50  |

Table 2 shows the effects of thermal coupling to the roof construction, $\Delta U$, for perpendicular and slanted window linings for variant II. The values of $U_{w,\text{inst}} = U_w + \Delta U$ were derived here from the calculated thermal transmittance of the window and the linear thermal transmittance at both vertical sides, the sill and the head. A significant influence of thermal coupling is evident. The slanting (for possible better daylight distribution) itself plays a minor role in the heat transfer.

Table 2. Effects of thermal coupling for the perpendicular and slanted linings.

| Perpendicular Lining | Slanted Lining (α = 45°) |
|----------------------|---------------------------|
| $\psi$ [W/(m·K)]    | $U_{w,\text{inst}}$ [W/(m²K)] | $\Delta U$ [W/(m²K)] | $\psi$ [W/(m·K)] | $U_{w,\text{inst}}$ [W/(m²K)] | $\Delta U$ [W/(m²K)] |
| 0.071               | 0.72                      | 0.22                    | 0.093            | 0.79                      | 0.29                    |

4. Further steps
Different innovative approach in design of roof windows is presented in Figure 6. The loadbearing elements in the frame and sash are situated in the middle of the element, surrounded by profiles made of hardened plastics (thermal conductivity 0.039 W/(m·K)). The very thin loadbearing elements with their simple geometry can be made of laminated veneer lumber (thermal conductivity of 0.25 W/(m·K)), alternatively of fibre reinforced plastics (thermal conductivity of 0.40 W/(m·K)). Such a window can reach the thermal transmittance, $U_w$, of 0.5 W/(m²K) or slightly lower. The key issue here is to test the surface treatments of hardened plastics (paints, foils or high pressure laminate (HPL) stripes).
5. Discussion

Very promising results were reached in the design process based on theoretical considerations in building physics. Solutions presented in Figures 4 and 5 were already prototyped by the industrial partner. Idea presented in Figure 6 is subject of further technical studies.

Positive effects of slanting of side linings on daylight distribution were demonstrated by measuring in daylight laboratory [2]. In some cases, the better daylight distribution and higher overall mean level of daylight factor could theoretically lead to smaller sizing of roof windows (reduction of approx. 10%) which can have a positive effect on thermal transmission of the roof.

For correct heat transfer calculations, it is necessary to respect both the window slope and the thermal coupling with the roof structure. The thermal transmittance of the roof window as a product on the market, $U_w$, remains independent (constant value). The real performance $U$-value is obtained by adding the effects of its position in the roof: $U_{real} = U_w + \Delta U_{slope} + \Delta U_{coupling}$. Example: $U_w 0.5$ (see Figure 5), $\Delta U_{slope} 0.1$ (slope 45°, glazed area approx. 50 %, [4]), $\Delta U_{coupling} 0.22$ (Table 2), $U_{real} 0.82$ (164%). The values of $\Delta U_{coupling}$ can be elaborated in a catalogue for typical roof configuration. The values of $\Delta U_{slope}$ can be elaborated in a table according the geometry of glazing, slope of the window, emissivity, type of gas filling based on [4].

As a next step we would like to follow the idea of advanced controlled shading with smart energy harvesting [10,11] to minimize the overheating risks while keeping the daylight quality at the same time.

Detailed studies on surface heat transfer at both interior and exterior sides of roof windows can bring valuable information for building physics theory resulting in more precise calculations.

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