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Building Physics as a Tool for Development of New Components: Roof Window

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Abstract. Knowledge and instruments of building physics (calculation methods and measuring procedures) can be used as key tools and perspectives to develop new components for building envelopes. This paper illustrates this fact by presenting the successful development of a roof window fulfilling higher requirements on reduction of overall heat losses and avoiding the risk of water vapor condensation on surfaces at very low external temperatures (thermal transmittance below 0.7 W/m^{2}K in the first generation, close to 0.5 W/m^{2}K in the second one) and better daylight distribution for the interior. This is the result of a publicly supported project with an industrial partner: from a general idea through detailed analysis of thermal performance in geometrical and material alternatives up to construction, prototyping, and verification by measurements and certification. Building physics tools applied in the project are discussed here together with lessons learned which are important for technical design. An effective shading system equipped with PV elements for energy smart harvesting is mentioned in the conclusion.

1. Introduction

Roof windows are traditionally known as the weakest part of the building envelope concerning thermal transmittance. For this reason, they are not commonly accepted by designers of energy optimized buildings (passive house level etc.). Nevertheless, they should be used in some cases and the consequence due to increased heat transmission must be compensated in order to achieve the passive house criteria [1]. On the component level, there is a usual requirement for cold moderate climate not to exceed thermal transmittance of 0.8 W/(m^{2}K) by keeping the linear thermal transmittance due to connection to building envelope negligible. These values should be critically analyzed with respect to specific situations of roof windows in order to derive correct targets for new developments.

2. Comparison to vertical windows in the wall

By comparing roof windows with vertical windows in walls, the following significant differences can be found (see Fig.1, Fig.2):

- Heat transfer in the air cavities between glazing panes is larger due to increased heat convection caused by air movement (the more inclined the more significant.) Result: U value increased in the range of 0.1 – 0.2 W/(m^{2}K), relative to the whole window.

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- Heat transfer in the connection of the window to the opaque part: In roof windows a very important problem arises from the geometrical situation (Fig.2). The 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 Fig.3). The result is expressed as linear thermal transmittance ψ [W/(m.K)] in the range of 0.05 – 0.03 W/(m.K) by optimized solution.
- Surface heat transfer coefficient h [W/(m^{2}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 [2]. In smaller, inclined roof windows, additionally often influenced by heaters close by, the situation can be dramatically different: To be on the safe side from the energy perspective, the h-Value can be up to twice as high as the standard value. This is the preliminary result of our own in-situ experiments.
- The radiation heat exchange between the external surface and the (clear) sky [3] is higher for roof windows (e.g. multiplied by factor 1.5 for 45° sloped windows). This fact leads to an increase of the total external surface heat transfer coefficient.
- Passive solar gains in the rooms and risk of their overheating is primarily influenced by the orientation of the façade/roof, by the shading from external obstacles, by shading devices, and by the coefficient of the permeability of total solar radiation (solar factor) g [-] of glazing unit. The overall effect cannot be related to window quality itself. It depends on several other parameters of the (occupied) room, including thermal inertia, ventilation strategy and actual climatic data. Generally, there is a higher passive solar gain due to the inclination of roof windows. Moreover, efficient external shading such as venetian blinds are not applicable for roof windows.
- Specific effects can be observed in roof windows in summer conditions: The external air can be significantly warmer close to the roof surface (heated by the roof covering) compared to climatic data. This further increases the risk of the room overheating.

From the list above 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/(m^{2}K) or less, ideally approaching 0.5 W/(m^{2}K). Simple parametric studies (Fig.3) have shown that the unavoidable heat transfer due to the thermal coupling of the window to the roof plays an important role, especially in energy optimized windows. Corresponding compensation must be found in other components of the building envelope.

For this reason it is recommendable to integrate the additional heat transfer due to thermal coupling in the (extended) thermal transmittance $U_{w,inst}$ to have a „full picture" in one value [4]:

$$U_{w,inst} = \frac{A_g.U_g + A_f.U_f + \Sigma(\psi_g.l_g) + \Sigma(\psi_w.l_w)}{A_g + A_f}$$

where the $\Sigma(\psi_w.l_w)$ describes the influence of installation. It is illustrated in Fig.2 for a hypothetical window of excellent quality: Assumed thermal transmittance of the glazing unit U_g 0.60 W/(m^{2}K), frame U_f 0.60 W/(m^{2}K), thermal bridges of glazing edge expressed by linear thermal transmittance ψ_g 0,03 W/(m.K), thermal bridge due to installation in the roof (ψ_w 0.05 W/(m.K), considering the reference window size 1.14 m x 1.40 m. It can be seen that for improvements of roof windows all parts are of a high importance: glazing, frame, installation method and overall geometry.

Summer situation should be analyzed carefully as well and new ways of effective sun-protection should be found.

- Requirements on U-value of the roof construction result in overall thickness approx. 400 mm and more. This can negatively influence the daylight quality due to very deep side lining. Therefore, the daylight distribution in rooms as the primary function of each window should be studied very carefully as well.

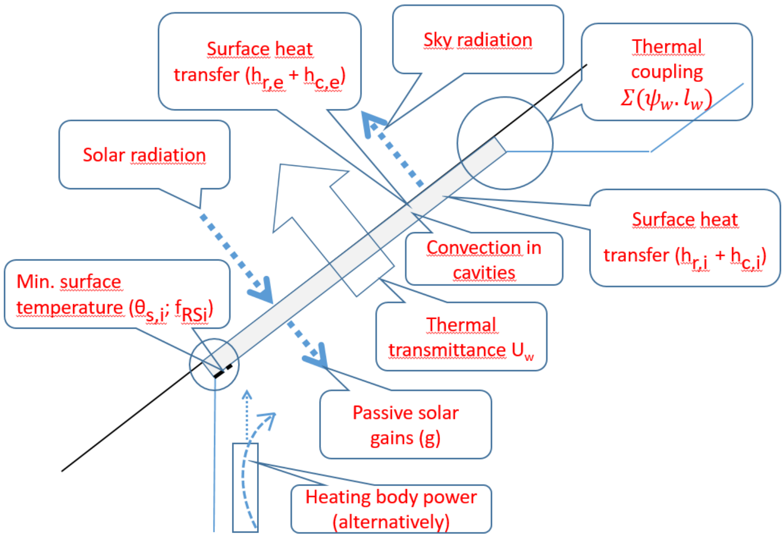

Figure 1. Significant thermal phenomena related to roof windows.

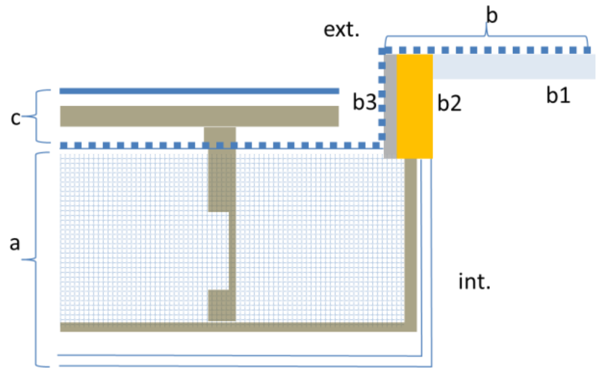

Figure 2. Schematic horizontal cross section of a typical position of roof window in a pitched roof. Dotted line represents the surfaces exposed to the exterior temperatures. (a typical pitched roof assembly (from interior): indoor gypsum board lining, OSB boards, thermal insulation, protective membrane open to water vapor diffusion), b roof window (simplified): b1 glazing unit, b2 frame and sash, b3 possible additional thermal insulating shield), c roof covering)

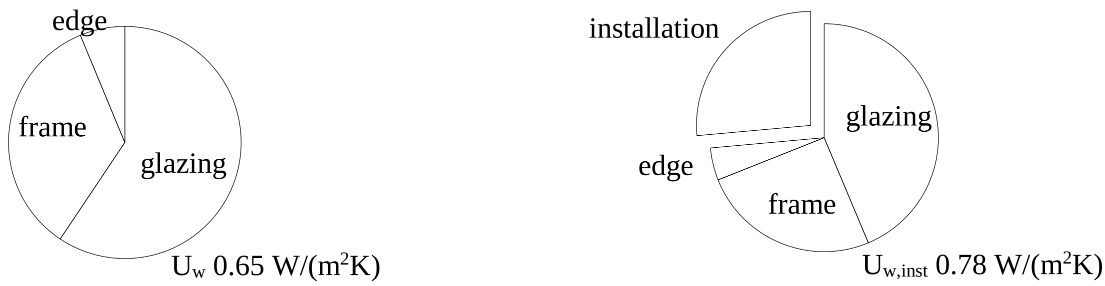

Figure 3. Result of a parametric study for (hypothetical) excellent roof window. Heat transfer (left), heat transfer including the effect of installation into roof (right) based on 2D calculations for all relevant cross sections.

3. Other technical and non-technical facts

Of course, not only building physics related phenomena should be studied before starting any development works. From the discussions with the experts (including unpublished results of questionnaire campaign) one can conclude following: a. total weight of the window should not

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increase, b. installation work on roof should not be more complicated, c. acceptable price increase of new, high performing product is approximately 10-20 %.

4. Methodology

Several steps were performed in order to support the development activities in close cooperation with our industrial partner:

a. Introductory parametric studies based on repeated 2D-heat conduction calculation [5,6]. Search for general relation among geometry of frames, position of glazing, material and construction. The quality of glazing unit and methods of installation in the roof were set as fixed.
b. The construction team selected a solution from parameters found in a), and a 2D-heat conduction calculation was used to check its plausibility, respecting the technological limitations. Some prototypes were built accordingly after.
c. Measurements in climatic double-chamber. Prototype installed in a fragment of roofing structure for studying surface temperatures on window and lining.
d. Detailed 2D-heat conduction calculation supporting fine-tuning in detailing of selected prototypes.
e. Declarative heat transfer calculations. Estimation of thermal transmittance (U-value) for standardized reference window size, estimation of temperature factor for evaluation of surface temperatures. Performed for promising alternatives and for two types of glazing units.
f. Simulation of daylighting in the room [7]. Study of influence of side lining geometry (perpendicular and slanted, “open” to the room).
g. Measurement of daylight distribution on a model of under roof space in the scale 1:4 under artificial sky. Alternatives for different side lining geometry were analyzed.
h. Catalogue of overall solution in interactive form. It serves for the selection of proper alternative including detailed solution of roof construction and joints window-roof considering type of construction, roofing and geometry.

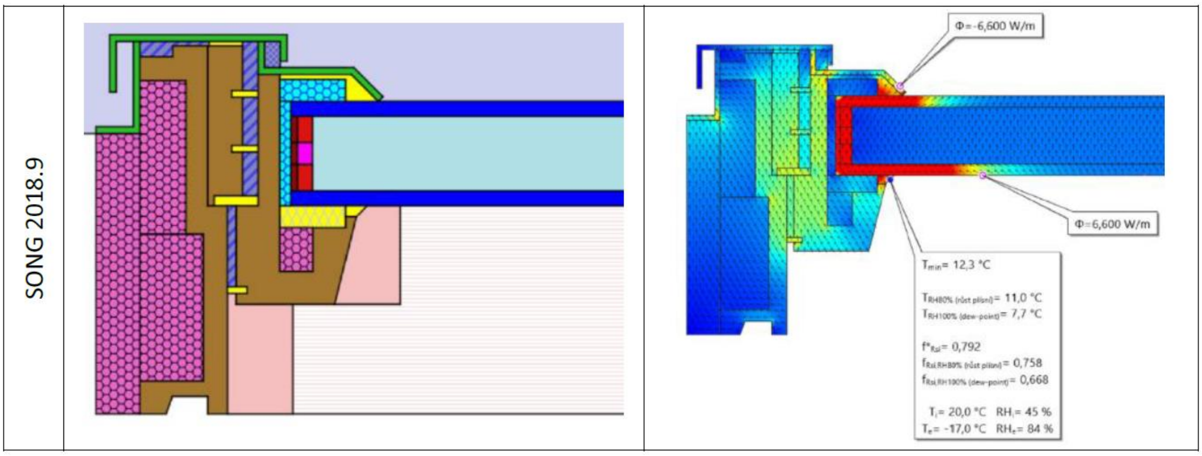

Figure 4. Example of analysis. Left: simplified geometry of a cross section. (Violet color corresponds to hardened polystyrene placed in the window frame, brown for wood, turquoise for aerogel stripes.). Glazing unit with two transparent foils. Right: Results of 2D-heat conduction calculation in HT-flux software.

5. Results

For the real technical solution, the following principles were applied:

a. Profiles made of hardened polystyrene (thermal conductivity 0.039 W/(m.K) are used here in combination with wood for increasing of thermal resistance of the frames in both directions, perpendicular and parallel to roof layer (Fig.4).

b. Glazing unit: Triple glazing with thermal transmittance 0.5 W/(m^{2}K) or special glazing having two transparent foils between glazed panes (glazing pane – air gap – foil – air gap – foil – air gap – glazing pane) with thermal transmittance 0.3 W/(m^{2}K) are applied alternatively.
c. No additional insulated mounted frames in the roof are used.
d. Surface temperature is safe: high enough to prevent the risk of condensation of water vapor, including all critical areas.
e. Smart detailing can be applied for even higher surface temperatures at the edges (use of aerogel stripes).
f. Slanted side linings are recommended in most cases in order to support better daylight distribution in rooms. Additional slightly increased heat transfer due to limited space for placing of the thermal insulation is neglectable.
g. Low emissivity coating at external surface of external glazing can be advantageous additionally.

Based on the results of standard calculations (reference size of window, vertical position, standard value of surface heat transfer) it can be concluded that U-value of 0.7 W/(m^{2}K) is feasible with our newly developed frame for usual triple glazing and near to 0.5 W/(m^{2}K) for glazing with two foils (with extra bonus of lower weight).

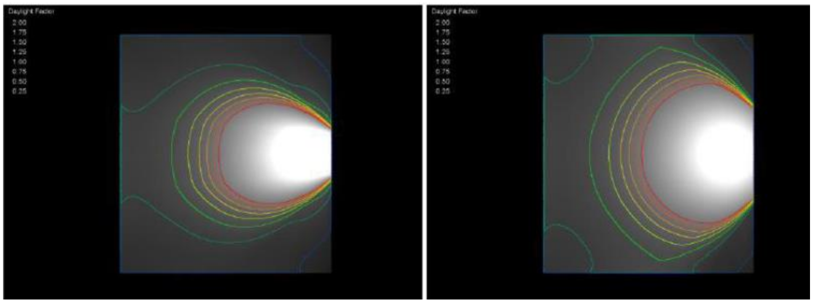

Figure 5. Results of daylight simulation [7] for a typical under roof room with one roof window centered. Side lining perpendicular (left), slanted (right). Isophotes in distance of 0.25 %.

Figure 6. Measurement of daylight distribution. Model 1:4 (left) of a typical small room equipped with one roof window in the center, swappable roof for testing of various side linings. Preparation in the artificial sky-laboratory (right)

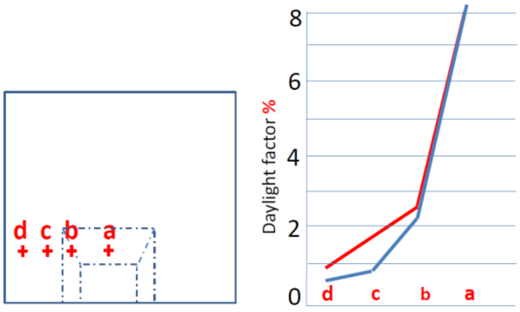

Figure 7. Key results of the measurement of daylight distribution. Left: Floor plan of a room with one roof window in the center with/without slanted side lining. Right: Daylight factor for perpendicular side lining (blue), for slanted side lining with 45° degree (red).

Figure 8. Figure shows the prototype presented at a building fair in September 2018.

6. Conclusion and outlook

In general, roof windows cover only a small area of the overall building envelope of each house. But their influence can be significant. During the project with the industrial partner a new generation of roof window was developed, including sub-variants. Technical information and construction detail can be found in an interactive catalogue [8], adjusted for different roof construction. Analyses using building physics tools played a key role in overall process. One prototype was tested on all obligatory parameters according to EN 14351-1 [9] in independent certification institution with very good results (thermal transmittance, airtightness, resistance against wind driven rain). The first product is ready to be placed on the market, but the development can continue.

We tested the possibility of further reduction of thermal transmittance to 0.4 W/(m^{2}K) level which seems to be possible through significant change of the frame construction using identical materials. On the other hand, we should keep in mind the additional heat transfer caused by thermal coupling to roof construction: In such case it will be in the same range as the window itself. Therefore, a future development should be focused on other phenomena, especially on reduction of overheating risk by keeping the daylight quality in interior.

Exterior shading system with integrated function for roof windows was designed (patent pending). Such system consists of a set of movable lamellae, partly covered by photovoltaics elements. The small amount of harvested energy is used preferably for fans supporting the air movement in the air cavity between shading and external surface of glazing and it is used for movement of lamellae as well. Such system can operate partly in autonomous mode or according to information from local control unit or superordinate control unit of the house.

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[8] Project TH01021120 Final report, not public. UCEEB, 2018.
[9] EN 14351-1 Windows and external pedestrian doorsets without resistance to fire and/or smoke leakage.

Nomenclature
D daylight factor, %
U thermal transmittance, W/(m^2K)
g solar factor, dimensionless
h surface heat transfer coefficient, W/(m^2K)
l length, m
ψ linear thermal transmittance, W/(m.K)
indices
c convection, g glazing, e exterior, f frame, i interior, inst installed, r radiation, s, S surface,
R required, w window