Wood windows in the 21st Century: end user requirements, limits and opportunities

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Abstract

The increasing pressure on construction industry for development of energy efficient structures and building elements resulted in the appearance of new products and manufacturing technologies. Considering the ever increasing demand on low energy consumption, more and more attention is to be paid to enhance the thermal insulation of the weak points of buildings, which are the windows. In this paper the optimization of heat transfer coefficient (*U*-value or *U*-factor) for a conventional wood-frame window is presented using different glazing systems and frame materials. For the U-value calculations and isotherms determination WINDOW and THERM software have been used. According to the results sufficiently low *U*-value of the glazing can be attained with triple glazing systems, using inert gas cavity fills and soft-coat technology (*i.e.* Low-E coatings). However, frames of drastically reduced *U*-values can be only attained by using profiles comprising thick layers of materials of low thermal conductance, resulting in unusually deep profiles. Therefore potential new directions of research and development may include improvement of the heat mirror techniques for windows, development of intelligent glazing, and development of novel concepts for installing and operating windows.

1. Introduction

One of the most important challenges of today is to find new possibilities and solutions to an efficient and reasonable use of energy. This is a pressing necessity not only because of the limited resources but is also a demand of sustainability. In the course of the last decades, as a development of the technology used in the Scandinavian residential houses of low energy consumption in the mid-80s, a new, more economical building standard that provides comfort of the occupants in an energy-efficient and environmental friendly manner has been introduced. The new notion of passive house is used for buildings in which the climatic conditions necessary for the continuous presence of human can be assured exclusively by tempering the amount of air that is necessary for ventilation. This notion has been introduced by Dr. Wolfgang Feist the founder of the Passivhaus Institut Darmstadt, Germany (Feist, 1997).

In Hungary, there are currently a few passive houses only. Their spread is restrained by the fact that their design and implementation requires such a complex approach that is not yet common in the Hungarian building business. Furthermore, the roles of the state and subsidisation have not yet been clarified. Nevertheless, similarly to the other countries in Europe, energy saving, environmental friendly building and sustainability is more and more at issue.

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The energy-efficiency of the existing stock of buildings in Hungary is rather low (the consumption index being twice as high as the average of the EU countries). The European Union regulates the energy consumption of buildings through directives. From these follows the decree of 7/2006 that contains the requirements on the heat transfer coefficient of fenestration products (Prohászka 2007). Today the upper limit of the overall heat transfer coefficient (*U*-value or *U*-factor) for a wood-frame or PVC-frame window is U_w=1.60 W/m^{2}K. Apart from the ever more severe stipulations the users of a building are interested in consuming the less possible energy while sustaining the occupants’ comfort. Out-of-date types of windows still in use generally occupy a relatively low percentage of a façade, nevertheless, they are responsible for a majority of heat-loss through the envelope of a building. Even the thermally insulated windows lag behind the rest of the wall (Thomas 2006). The ideal solution would be to improve the windows’ thermal insulation to be equal with that of the wall.

Considering the ever increasing demand on energy efficiency, more and more attention is to be paid to enhance the thermal insulation of the weak points of buildings, that is of windows. This can be achieved by decreasing the heat loss on the one hand, and by increasing solar gain through the window on the other. The heating energy consumption of a household is largely contributed to by ventilation and by thermal bridging. Heat flow is higher, thus in side surface temperature is lower at locations of higher thermal conductance, causing not only increased heat loss but impairing of comfort. Besides, low surface temperatures may give place to mould development (Zöld 1999).

2. Material and methods

The *U*-factor of a window is defined by the glazing system, the material and profile of the frame and casement(s), way of fitting casement to frame and by the method of jointing the window to the wall. The heat flow directed outwards through a window is composed of the heat transfer by transmission, and the convective flow due to the air permeability of the window. A window’s operation can not be conceived without the presence of fitting surfaces, with their inherent imperfectness that is the presence of gaps trough which air filtrates due to the pressure difference between the inside and the outside. This pressure difference results from the difference between the inside and outside air temperature and from the effect of wind; thus it can be purposefully influenced by the orientation of the windows with respect to the prevailing wind directions. Air filtration through the window is increasing when due to environmental effects the sealing profiles (weather-strips) used for the frame-casement fitting become aged and get brittle or wear up in some other way so that can not provide their function properly any more. Besides, locks and hinges wear in the course of use and/or their adjustment may be spoiled, leading to imperfect closing of the casement to the frame, hence increase of filtration heat loss. As far as the heat transfer by transmission through double or triple glazing is concerned, an important part of it happens by radiation due to the different temperature of the glass surfaces facing each other. Therefore it is largely influenced by the emissivity (ε) of those surfaces. Purposefully designed coatings applied on the glass surfaces result in the reduction of the emissivity in the near-infrared range of wavelength lowering thereby the heat transfer by radiation substantially (Kovács 2000).

In the case of passive houses outstanding thermal insulation of the walls, highly insulated windows, connections free of thermal bridges, air tightness and controlled ventilation with heat recuperation assure that there is no heat loss due to filtration and extra ventilation and the total heat energy consumption is not more than one tenth of that of a traditional building. The solar heat is transmitted to the inside of the house through the windows where an equilibrium state is arrived at between the total heat loss and the solar gain. From these it follows that windows have a decisive role in passive houses. The total heat loss of a building is such a low value that its replacement does not need the building of an active heating system. Passive houses react to outside temperature drop with retardation, thus it takes a few days while inside temperature decreases to a sensible extent. There is a ratio of five to one between the *U*-values specified for windows and wall units in the case of passive houses. Considering the very low *U*-values (in the order of 0.1 W/m^2K) of walls this justifies the need for an enhancement of the thermal performance of windows. The thermal analysis of windows is a complex problem. The *U*-factor of glazing alone, though decisive, does not characterise a window's thermal behaviour with the required exactness. At the same time, data for a more detailed calculation is seldom at hand. From the point of heat transfer, a windows is made of two parts, glazing and frame (fix frame and framing of movable parts). Correspondingly, its *U*-factor can be composed of the two partial *U*-factors of U_g of glazing and U_f of frame.

A less known property of glazing is the *g*-value, showing the proportion of the solar heat flux that is transmitted through the glass sheets. Windows for passive houses have to have a glazing *U*-factor not worse than U_g= 0.50 to 0.60 W/m^2K while the overall window's *U*-value not higher than U_w=0.8 W/m^2K; at the same time the proposed minimum value for solar heat transfer is *g*=50%. This latter requirement can be interpreted in the way that the solar heat transmitted through the window should be at least half of what could get in through a corresponding opening of the wall without a window. Windows with traditional, double glazed thermal insulation unit are not capable of providing the required thermal insulation. A solution frequently applied for their improvement is the use of an additional sheet of glass fixed onto the casement. Newer glazing systems are triple glazing units with inert gas fill and Low-E coatings. A crucial point of comfort in passive houses is the inside surface temperature of the glazing units in windows. Low surface temperatures result in a downward air flow on the cold surface that in the case of a French window spreading horizontally on the floor forms a cool layer of air. This phenomenon is so much important that in contrast with traditional buildings, in passive houses there is no heater below the window to counterbalance this effect (Pflunger 2003.).

The required thermal performance of the frame can be attained with wood, plastic or aluminium profile or a combination thereof, but generally with the inclusion of a layer of highly insulating foam. The sealing between the fix frame and movable parts shall guarantee an airtight closing so that the air permeability at 50 Pa pressure difference should not exceed the value of Q_{50}=0.0006 m^3/h. In the case of such airtight buildings ventilation has multiple advantages over fresh air ingress through windows. On the one hand it assures controlled air volume exchange. On the other hand via central air supply unit the temperature and relative humidity of the fresh air can be controlled easily while the heat of used air is regained. Ventilation apparatuses used in passive houses are not simply air-conditioning apparatuses.

Windows with 68 mm thick frame profile (see Figure 1.) can meet the current Hungarian specifications relating the thermal efficiency of buildings. In threelayer profiles mostly made of European softwoods, glazing units of 4-16-4 mm with air fill are most often installed

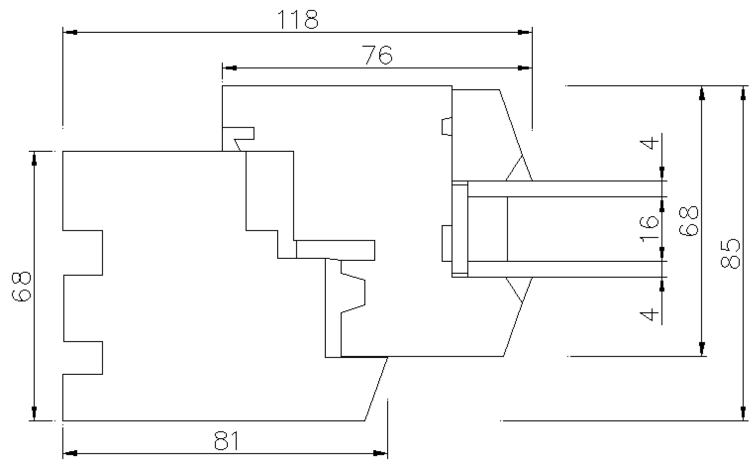

Figure 1. – Horizontal section of a window system typically used in Hungary (sizes in mm)

Due to its more favourable properties, gaps filled with Argon result in increased thermal insulation. Wooden windows of profiles 68 mm thick and glazed with a double insulation unit with aluminium edge spacer and air fill may have an overall heat transfer coefficient (*U*-factor) of U_W=2.8 W/m²K. This value can be improved to U_W=1.7 W/m²K when applying Argon fill instead of air. An even better thermal insulation can be attained by applying Low-E coating (imparting low emissivity in the infrared wavelength range) on the outward surface of the inside glass pane. Such a coating does not impede solar radiation energy to pass through from the outside to the inside while reduces considerably the heat flow from the inside to the outside. Thanks to this so-called soft coats technology, an overall heat transfer coefficient of U_W=1.1 W/m²K can easily be attained.

The total product *U*-factor for a window can be calculated by using the expression below:

$$U_w = \frac{\mathrm{A_g} \cdot U_g + \mathrm{A_f} \cdot U_f + l_g \cdot \psi_g}{A_g + A_f} \qquad [1]$$

where:

- U_w - *U*-factor of the window [W/m²·K]
- A_g - glazing area [m²]
- U_g - glazing *U*-factor [W/m²·K]
- A_f - projected area of the frame and sashes [m²]
- U_f - frame *U*-factor[W/m²·K]
- l_g - perimeter length of the glazed area [m]
- ψ_g - linear heat transfer coefficient of the perimeter of the glazed area [W/m·K]

3. Results

In the case of a window, frame and glazing has to be analysed separately because of the difference in thermal properties. The overall *U*-value of a window is influenced to a large extent by the nature of gas fill and edge spacing applied between the individual glass panes, whereas glass thicknesses are only influential from the point of view of sound reduction. In Hungary, windows with glazed units manufactured with 16 mm aluminium edge spacing are common. In the case of these windows, due to the temperature difference between inside and outside, condensation on a 50 to 60 mm wide glazing edge area is experienced quite often. Because of this standardised width of spacer, the totals thickness of the glazing unit is not varying. Recently in the domestic market there appeared edge spacers combined of plastic and aluminium or manufactured entirely of plastic. A great advantage of a spacer of low thermal conductivity embedded into vapour resistant butyl mastic is that it reduces the extent of thermal bridging at the edges, improving thereby the overall thermal isolation and comfort. As stated by suppliers, the use of such edge spacers may reduce the window's overall heat transfer coefficient by 0.1 W/m^2K. Thanks to the flexibility in their manufacturing technology, the width of these edge spacers can be varied between 6 mm and 20 mm, so that one can construct glazing systems of different overall thicknesses. This has a great importance if we think of the different physical and chemical properties of the gases used as fills; that is, they yield the optimum of their properties at different thicknesses.

In the case of a triple glazing the two edge spacers can be of different width; as a result, the total thickness of the glazing unit can be less than usual. Because of the changed glazing thicknesses the design of the glass supporting part of a sash/casement profile can differ from the usual. The *U*-value of a double or triple thermal insulation unit as defined by the choice of gas fill and widths of spacers (gap size) can be further improved with Low-E coatings applied on one or more glass surfaces adjacent to the gas gaps. It is however important to know that the low-emissivity coats applied change the optical properties of the glazing and may influence visible transmittance to a considerable extent. That is, the improvement of thermal insulation via the reduction of heat transfer due to glass surface radiation is realised on the expenses of the reduction of light transmission and requires a trade-off between those two properties of the glazing.

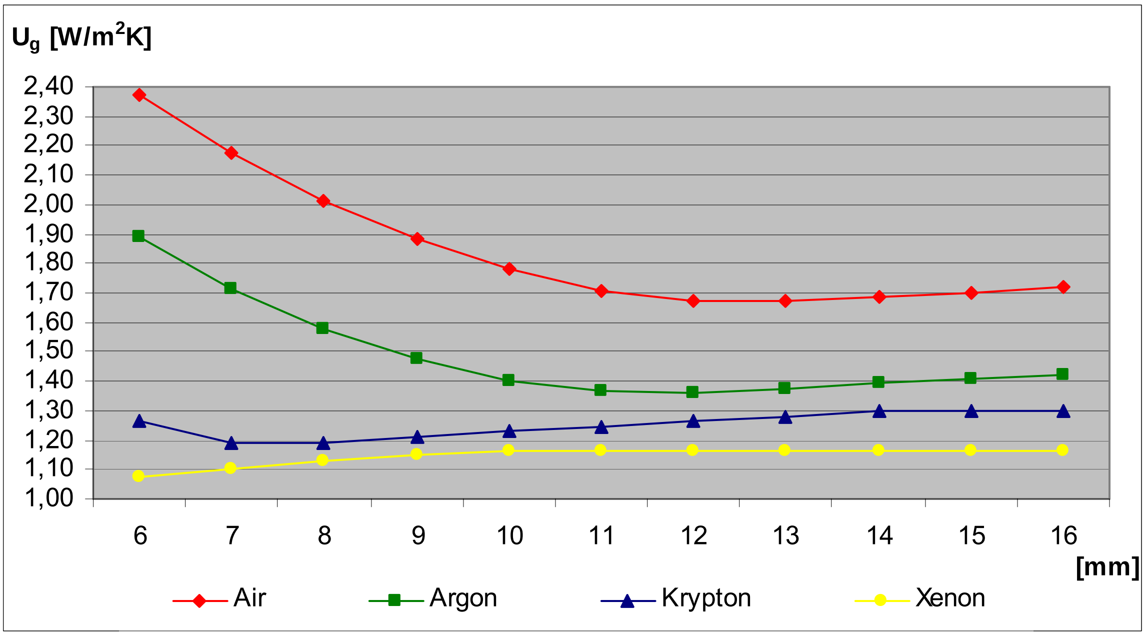

Figure 2. – Change of *U*-value of double glazing as a function of the gap size and the type of the fill

The change of heat transfer coefficient of the central part of a double glazing unit as a function of the gap size in the case of different gas fills is show in Figure 2, whereas the tendencies for a triple glazing are shown in Figure 3 and Figure 4. In the double glazing unit the outside glass pane is a 4 mm thick clear float glass, the inside pane is a 4 mm thick glass with Low-E coating. The *U*-values shown in the diagrams have been calculated by using the free software package Window6 developed in the University of California, Berkeley. [WINDOW 6]

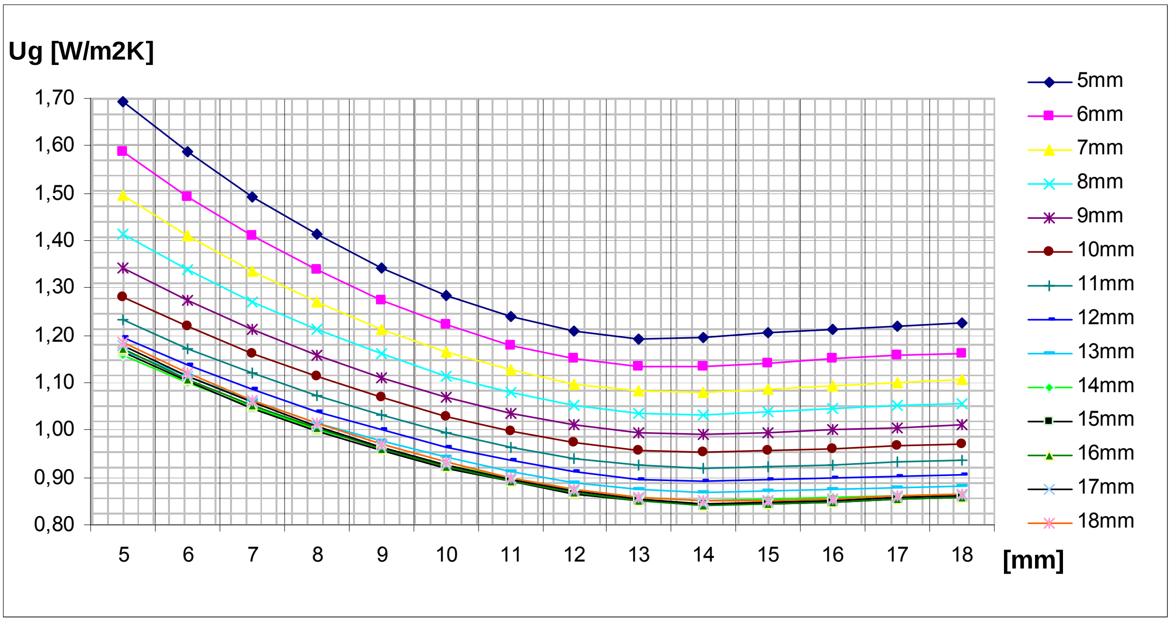

Figure 3. – Change of *U*-value of triple glazing with air fill as a function of the gap size (horizontal axis: outer gap size; the individual curves correspond to the different inner gap sizes)

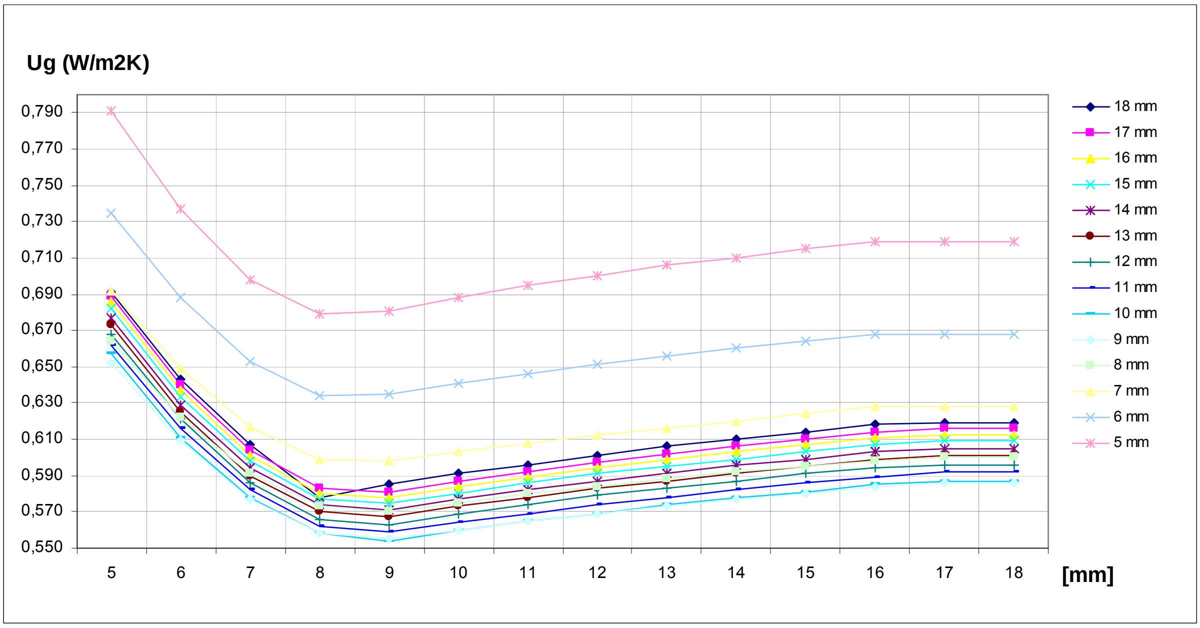

Figure 4. – Change of the *U*-value of triple glazing with Krypton fill as a function of the gap size (horizontal axis: outer gap size; the individual curves correspond to the different inner gap sizes)

The glazing units are generally positioned by means of setting blocks and shear blocks and fixed in the casement by means of glass beads. In the case of triple glazing systems the increased mass requires reconsidering the casement profile and using hinges of increased load-bearing capacity. A relatively new solution is that the glazing unit is fixed beside the edges to the casement profile by continuous adhesive joint. Beyond a gap-free sealing between the glass and the casement profile it has the additional advantage of improved stability and operational safety.

Windows of wood frames in Hungary are mostly manufactured of 3-layer laminated Scots pine (*Pinus sylvestris*) wood. Profiles of 68 mm deep are generally applied for windows of double glazing systems, the heat transfer coefficient of the frame is typically U_f =1.3 W/m^{2}K. With a same profile depth, air gaps formed in the solid wood cross section may result in a more favourable value of U_f =1.0 W/m^{2}K, while the same solution in the case of a 78 mm deep profile results U_f =0.94 W/m^{2}K. It holds for most types of windows that the sill part is characterised by a worse *U*-factor than the upright and bottom parts due to the difference in the frame and sash/casement profile that allows water canalisation. When required, one can attain lower heat transfer coefficients for the frame by applying sandwich-type cross section profiles. Thanks to certain light-weight synthetic foams which have much better thermal insulation value as compared to solid wood, significantly increased profile depth can be attained without important increase of the total mass of the window. The arrangement of the individual layers and the thickness of the different materials in these profiles may be varied. This way a value of U_f =0.75 W/m^{2}K is easily attained with a depth of profile of 85 mm.

An optimally designed sandwich profile with purposeful glazing system may meet the requirements of passive houses. The depth of the frame and casement/sash profile can be reduced if an additional aluminium profile filled with polyurethane foam of suitable thickness is fixed on their outer surfaces. This additional thermal insulation may add significantly to the cost of the window, however one can attain more easily or even exceed the required thermal insulation value. In the overall heat transfer coefficient of a window, the heat transfer of the glazing unit is dominating, since glazing area is generally much larger than the projection area of the frame. However, the smaller the window, the higher is the share of frame area. Very often the share of frame is underestimated, while it may amount to 30-35% of the total product area. The change in the nominal sizes of a window directly affects the size of the glazing unit(s); in the case of identical profile cross section, an absolute increase of the nominal sizes entails the same absolute increase of the corresponding size of glazing unit, thus resulting in a more favourable overall *U*-value.

The overall *U*-value of a window is defined jointly by the glazing unit and the frame. The Finite Element Analysis based software package Therm developed in the University of California, Berkeley [THERM 6] was used to study the overall thermal performance of windows of different frame and glazing systems. The software supports steady-state thermal problems only; therefore we assumed constant boundary conditions both for the inside and outside surfaces. AutoCad drawings were made for the sections of the windows necessary for the analysis. The parameters used are listed in Table 1.

Table 1. – Boundary conditions set according to EN ISO 10077:1 and 10077:2

Inside temperature of air: Θ_i	20°C
Outside temperature of air: Θ_e	-9°C
Resistance to thermal transmittance inside: (R_{si})	0,13 $m^2 \cdot K/W$
Resistance to thermal transmittance outside: (R_{se})	0,04 $m^2 \cdot K/W$
Linear heat transfer coefficient: (ψ_g)	0,06 $W/m \cdot K$

Isotherms for a wooden window of 68 mm profile depth used in Hungary, with a double thermal insulation unit are shown in Figure 5, while Figure 6. depicts the isotherms of a window of sandwich-type profiles, meeting the requirements of passive houses.

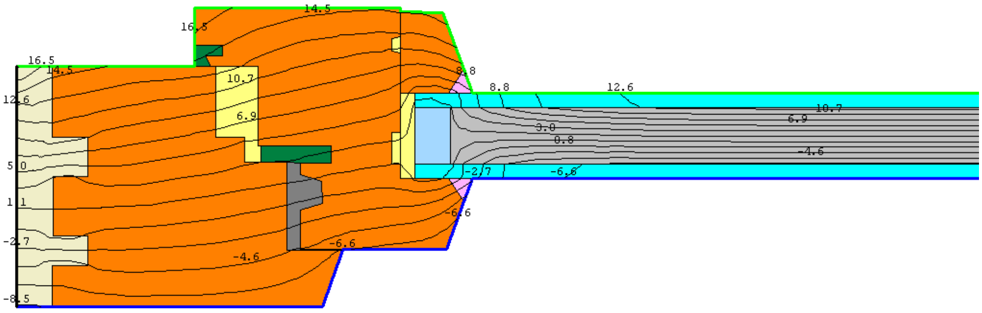

Figure 5. – Isotherms of a window section of wood frame profiles used in Hungary (Gap filled with air)

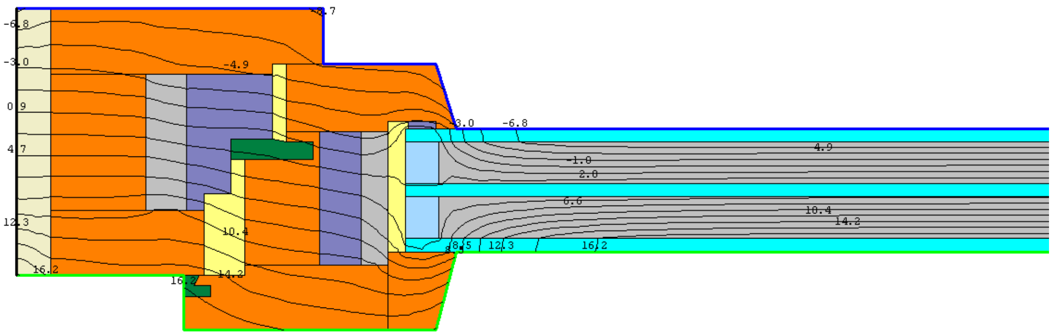

Figure 6. – Isotherms of a window section of frame profiles used for passive houses (Gaps filled with Krypton)

While windows in Figure 5 and Figure 6 represent the common and lead edge solutions of contemporary windows respectively. In the case of double glazing frame is 68 mm wood profile while triple glazing is used with sandwich profile designed for passive houses.

It can be established from this analysis that the average heat transfer coefficient of the window sections under study (that can be related to the window's overall U-value) as well as the position of the 10°C isotherm exhibit an improving trend as shown in Tables 2 and 3:

Table 2: Effect of the gas fill on the properties of a 4-16-4 mm glazing

Glazing	Distance of the 10°C isotherm from the edge [mm]	Average *U*-factor[1] [W/m²·K]	Glazing *U*-factor[2] [W/m²·K]
4-16Air-4	12.5	1.79	1.72
4-16Ar-4	11.7	1.56	1.42
4-16Kr-4	10.8	1.47	1.30

[1]Average of the frame, glazing and edge effect for the window section analyzed;
[2]Calculated for the central area of glazing as calculatad by WINDOW 6.

Table 3: Effect of the gas fill on the properties of a 4-12-4-12-4 mm glazing used in passive houses

Glazing	Distance of the 10°C isotherm from the edge [mm]	Average *U*-factor[1] [W/m²·K]	Glazing *U*-factor[2] [W/m²·K]
4-12Air-4-12Air-4	8.0	1.13	0.93
4-12Ar-4-12Ar-4	7.0	0.95	0.70
4-12Kr-4-12Kr-4	6.5	0.87	0.60

[1]Average of the frame, glazing and edge effect for the window section analyzed;
[2]Calculated for the central area of glazing as calculatad by WINDOW 6.

The glazing *U*-factor can be improved by incorporating a heat mirror. This 0.1 mm thick transparent foil of low-emissivity surface that divides the gap thickness may add to the price of glazing but significantly improves the thermal performance without an increase in the total thickness. In Table 4 the effect of heat mirror on the glazing *U*-factor is shown. As can be seen, an identical improvement is attained at different positions of the foil with unchanged gap thicknesses. When varying gap thicknesses, a further 8 per cent improvement can be attained. However it has to be noted that this way of *U*-value optimisation affects visible transmittance unfavourable.

Table 4: The effect of a heat mirror foil (HM) on the glazing *U*-factor calculated with WINDOW 6.:

Glazing system	**Glazing *U*-factor [W/m²·K]**
4-16Kr-4LowE-16Kr-4LowE	0.63
4-16Kr-4LowE-8Kr-HM-8Kr-4LowE	0.41
4-8Kr-HM-8Kr-4LowE-16Kr-4LowE	0.39
4-10Kr-HM-10Kr-4LowE-12Kr-4LowE	0.36

Conclusions

Passive houses require windows with an overall U-value less than 0.7 W/m²K that require that both glazing and the frame profile have exceptionally low heat transfer. Sufficiently low *U*-value of the glazing can be attained with triple glazing systems, using inert gas cavity fills and soft-coat technology (*i.e.* Low-E coatings). An extremely low glazing *U*-value however can not counterbalance the deficiencies of the frame because of the relatively high projection area of the frame and of the increased glazing-edge effect when there is a higher contrast between the heat transfer coefficients of the two meeting units..

The above discussed solutions for lowering heat transfer through windows may reach a practical boundary of their capability because of the need for visible transmittance on the one hand and because the fitting of movable parts of a window with the current operational concepts is a source of undesirable heat flows. Therefore, with an ever continuing demand on reducing heat transfer through windows for passive houses the solutions discussed above may not be sufficient in the future. Therefore, frames of drastically reduced *U*-value are necessary for passive houses. This reduction of frame *U*-value with the current concept of window systems can be only attained by using profiles comprising thick layers of materials of low thermal conductance, resulting in unusually deep profiles. Potential new directions of research and development may include improvement of the heat mirror techniques for windows, development of intelligent glazing, and development of novel concepts for installing and operating windows, by abandoning the traditional and current options when casements have to be displaced relative to a frame, both with limited thermal insulation capabilities.

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