Impact of the Glazing System on the *U*-Factor and Inside Surface Temperature of Windows

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Abstract: As a consequence of an increasing need for energy-efficiency, there is a growing interest on buildings with reduced energy consumption all over the world. Windows generally account for much higher proportion of the transmission losses through the building envelope, than their area fraction. Therefore, more attention is to be paid to the enhancement of the thermal insulation of fenestration products. In this article, the authors investigate the effect of the thermal performance of the glazing on the frame and edge-of glazing behaviour in a wooden-frame window commonly used in Central Europe. Windows' inside surface temperature with respect to condensation risk, as well as components of the total product U-factor according to both the European standard (ISO EN 10077-1 and -2) and the National Fenestration Rating Council (NFRC) were assessed by using THERM and WINDOW software packages to simulate respective U-factor and temperature distribution throughout the structure.

Keywords: U- factor; heat mirror; modelling; finite element model

Nomenclature

b	Dimension of the glass perpendicular to the direction of heat flow (mm),
C_1	Coefficient (according to EN ISO 10077-2, 0.025 [W/(m·K]),
C_3	Coefficient (according to EN ISO 10077-2, 1.57 [W/(m^2·K)]),
C_4	Coefficient (according to EN ISO 10077-2, 2.11 [W/(m^2·K)]),
d	Cavity length in the direction of heat flow [m],
$emis_1$	Infrared (long-wave) emissivity of the shade material, exterior-facing side,
$emis_2$	Infrared (long-wave) emissivity of the shade material, interior-facing side,
h_a	Convective heat transfer coefficient [W/(m^2·K)],

h_r	Radiative heat transfer coefficient [W/(m^2·K)],
K_{eff}	Effective conductivity [W/(m·K)],
R_S	Equivalent thermal resistance of the cavity [m^2·K/W],
SC	Shading coefficient,
$SHGC$	Solar heat gain coefficient,
T_{sol}	Solar transmittance of the shade material,
T_{vis}	Visible transmittance of the shade material,
U_c	Centre-of-glass *U*-factor [W/(m^2·K)], (NFRC),
U_e	Edge-of-glass *U*-factor [W/(m^2·K)], (NFRC),
U_f	Thermal transmittance of the frame [W/(m^2·K)], (ISO EN),
U_{fEN}	Frame *U*-factor determined according to EN ISO 10077-2 [W/(m^2·K)],
U_t	Total product *U*-factor [W/(m^2·K)], (NFRC),
U_w	Thermal transmittance of the window [W/(m^2·K)], (ISO EN),
λ_{eq}	Equivalent thermal conductivity of the cavity [W/(m·K)],
Ψ	Linear thermal transmittance [W/(m·K)].

1 Introduction

From the point of view of energy efficiency, windows are perhaps the most critical parts of a building, since the thermal performance of even a well-insulated window is inferior to the rest of the façade. Moreover, as a consequence of their structural complexity, and the environmental impacts they are exposed to, windows may be easily damaged over their service life resulting in significant degradation of their thermal performance.

One of the urgent tasks in our days is to find new possibilities for more efficient and rational energy consumption. The energy-efficiency of the existing stock of buildings in Hungary is rather low; the consumption index is twice as high as the average of the EU-15 countries [1]. The continuous decline of supplies of energy and the increase of their price justify the progression towards better thermal insulation of buildings. The European Union regulates the energy consumption of buildings through directives. From this follows the decree of 7/2006 that contains the requirements on the heat transfer coefficient (referred to as thermal transmittance in the standard EN ISO 10077-1) of fenestration products [1, 2]. Currently the allowable upper limit of the overall heat transfer coefficient (*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 least possible energy, while sustaining the occupants' comfort. As shown in Figure 1, roughly 80 % of the energy consumption is due to heating; windows are responsible for a significant part of this, even if heat not only escapes, but a significant gain through the windows is generally realised.

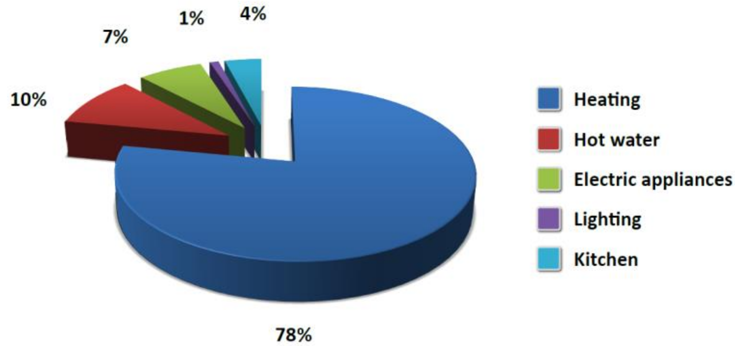

Figure 1
Energy consumption of households, according to use [3]

The primary objective of our investigation was to clarify the effect that modernisation of glazing may have on the components of the overall product *U*-factor and glazing indoor surface temperature in the case of a custom European wooden-frame windows of 68 mm profile depth.

Plenty of studies relating to the effect of glazing properties (gas type, gap thickness, coatings and films) on thermal performance were published during the last two decades. Apart from enhancing the performance of glazing, window design improvements over that period focused on spacer bar technology and frame details, including edge sealants. However, relatively little information can be found in the literature about the interaction of frame details and glazing properties and their contribution to thermal bridging and other additional effects; likewise, their consequences with regard to condensation are not fully explored.

2 Theoretical Background, Review of Literature

The resultant heat transmittance of a window is influenced by a number of factors: the glazing system, the material and profile of the frame and sashes, the way of fitting the sash to the frame, and by the method of joining the window to the wall. The heat flow directed outwards through a window is composed of the heat transfer by conduction, convection and radiation due to temperature difference (generally termed as transmission), and the convective flow due to air leakage.

A window's operation cannot be conceived without the presence of fitting surfaces with their inherent imperfectness, leading to gaps, through 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 a window is increased when due to environmental effects the sealing profiles (weather-strips) used for the frame-sash fitting become aged and get brittle, or wear in some other way, so that they cannot provide their function properly anymore. Further, locks and hinges wear in the course of use and their adjustment may be spoiled, leading to imperfect closing of the sash to the frame, hence increase of filtration heat loss [4].

As far as the thermal transmittance through the cavities of double or triple glazing is concerned, besides heat transfer by convection of the gas fill, which is slightly influenced by the thickness of the gap, an important part may happen due to radiant heat exchange between the warmer glass surface and the cooler one on the two sides of a cavity. Therefore, overall transmittance is largely influenced by the emissivity (ε) of those surfaces. Purposefully designed coatings applied to the glass surfaces reduce their emissivity in the long-wave infrared range, lowering thereby the heat transfer by radiation substantially.

A general method of calculating the net energy flux through the glazed area of a window has been worked out in the 1980s already [5]. Within the model, natural convection of the gas fill and emitted energy fluxes are calculated. The two-dimensional finite-volume analysis of vertical gaps, developed by Wright and Sullivan [6] proved to be capable of realistically modelling fill gas flow and heat transfer. The method of analysis was extended to simulate heat flux patterns and temperature profiles for a number of glazing systems [7]. Simulation results agreed well with guarded heater plate measurements. In a publication by wright [8] a method has been presented for the extension of the two-dimensional frame and edge-glass numerical analysis to account for fill gas convective motion. The method requires computational fluid dynamics (CFD) calculation. Simulation results indicate the dominance of the influence of edge-seal conductance and gas motion over low-e coating and argon filling with respect to minimum indoor glass surface temperature. Three-dimensional CFD simulations were conducted and validated for window frame cavities by Gustavsen & al. [9]. Wright and McGowan [10] develop modifications to the "conventional" modelling concept used in the USA and Canada to determine the total product *U*-factors for windows. Modifications include modelling the convective motion of the fill gas and local variation of the indoor heat transfer coefficient at recessed corners. In order to be in line with highly insulating IGUs, Fang & al. [11] experimented with multi-material frame design consisting of skeleton framework and cavities filled with insulating material. Their simulations by two-dimensional finite element models, including evacuated glazing with low-emissivity coatings resulted in about 80% heat loss of that in a window of single material solid frame.

In a research project aimed at the improvement of thermal performance of light-weight construction wooden buildings, a resultant heat flow close to the value calculated in standing air was attained in the air cavity of the wall system. That was achieved by dividing the cavity in a number of parallel layers of small thickness with the use of thin aluminium foil [12]. This was possible because convection was almost non-existent in thin air layers; besides, due to the low emissivity of aluminium in the infrared range, heat transfer by radiation was also minimised.

3 Model Building, Material and Method

Product overall *U*-factor and the distribution of indoor glazing surface temperature was simulated for a 1230 mm by 1480 mm typical Central-European single casement, tilt-and-turn window with double thermal glazing. The 68 mm deep frame and sash profiles were made of laminated Scots pine wood (*Pinus sylvestris*). Taking the maximum available depth for glazing (24 mm) in the sash profile, a number of different configurations of glazing build-up analysed beforehand were selected for simulation (see Figure 2). The optimal cavity thicknesses in the case of the different gas fills can be identified in these curves. In the case of air and argon fill there was no significant difference between the optimum and the value at 16 mm, used in our model. With krypton as filling gas, a smaller cavity is justified. Xenon was shown the best and most insensitive to cavity thickness in these analyses; however, our study was not extended to that type of cavity fill, because it has an adverse effect on sound insulation.

In order to study the effect of the glazing build-up on the window's overall *U*-factor and on its components (frame *U*-factor, glazing edge *U*-factor), as well as on the inside glass surface temperature, we constructed three pairs of different models with air, argon and krypton fill respectively. In all three cases, in one of the two models the cavity thickness was divided in half by a film (0.08 mm thick heat mirror diaphragm). To allow studying the effect of glazing configuration only, total glazing thickness of 24 mm was used throughout the six resulting models, with a gas cavity thickness of 16 mm, or 7.96 mm + 7.96 mm, depending on the case. The 16 mm gas gap thickness was chosen in order to allow for reasonable cavity size when divided. It should be noted that in practice, 12 mm gap thickness is regarded as ideal in the case of air and argon fill, and 7 mm to 8 mm for krypton fill, as also reflected by the curves in Figure 2. It can be seen, that the change in thermal performance is small in the range of 12 mm to 16 mm gap thickness for all three fill types studied; however, air and argon exhibit more pronounced change when going down to 8 mm gap size. Table 1 summarises the glass and foil properties used in the models.

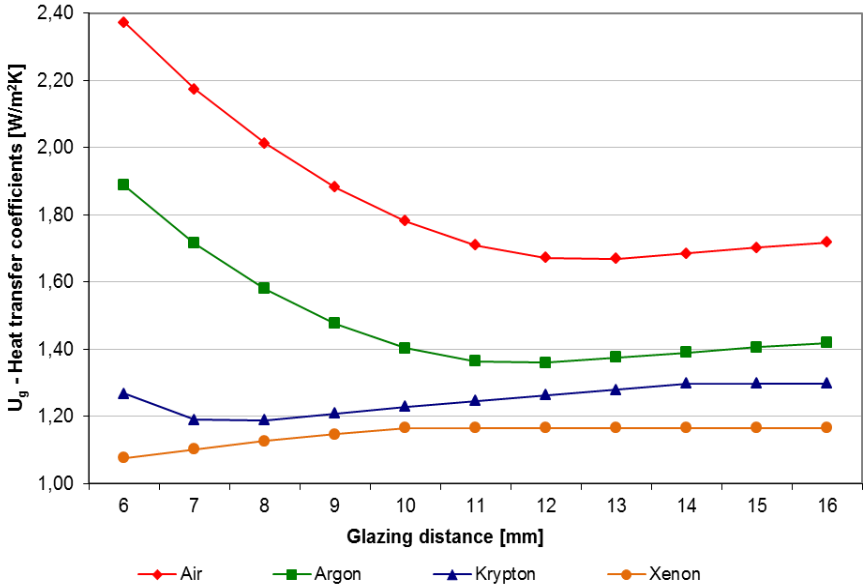

Figure 2
Change of *U*-factor of double glazing as a function of the gap size and the type of the fill [13]

Table 1
Properties of the components of the glazing with heat mirror

	Thickness [mm]	T_{sol}	T_{vis}	$emis_1$	$emis_2$	Cond
Float glass (7194)	4.00	0.84	0.900	0.837	0.837	1.000
Heat mirror (1518)	0.08	0.38	0.760	0.760	0.045	0.140
Low-E glass (7110)	4.00	0.59	0.890	0.037	0.837	1.000

Analysis of the window sections was performed by using THERM and WINDOW freeware packages developed at Lawrence Berkeley National Laboratories. THERM is based on Finite Element Method; WINDOWS uses Computational Fluid Dynamics (CFD) as a computation tool [14]. THERM was used by Hantos in a study to optimise a lightweight construction building [15]. In his case windows were taken into account with an average heat transfer coefficient, without analysing their effect in detail. In our case the calculation models were graphically defined; an AUTOCAD drawing of the window section was made (Figure 3) and used in THERM as an underlay for reproducing the geometry. Material properties could be assigned either by using library materials or defining custom materials with known thermal conductivity and surface emissivity.

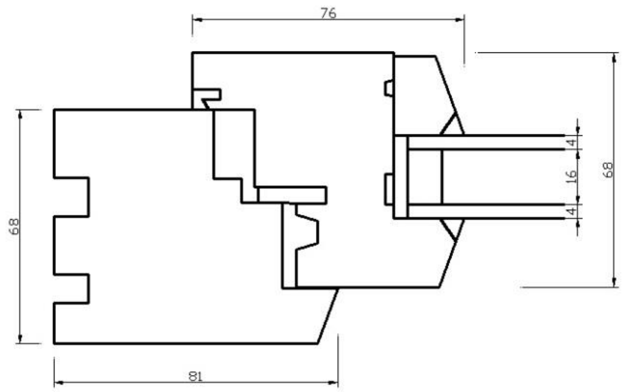

Figure 3
Horizontal section of the window studied (sizes in mm)

Thermal calculations were performed in two ways. First, we followed the procedure specified in the standard EN ISO 10077-2: 2004. Accordingly, we replaced the glazing unit in the model by an insulation panel with the prescribed thermal conductivity of λ = 0.035 [W/(m·K)], and calculated the thermal transmittance of the frame, U_{fEN} [W/(m^2·K)] from the simulation results as stipulated in the above-mentioned standard. Then, after reinserting the glazing unit in its place, the linear thermal transmittance, Ψ [W/(m·K)] due to the combined thermal effects of glazing, spacer and frame, used in EN ISO 10077-1: 2006 was calculated from the simulation results as given in EN ISO 10077-2: 2003 [16, 17]. These two calculation results, along with the known U-value of the central area of glazing, allowed us to compute the window's overall thermal transmittance, U_w [W/(m^2·K)]. Thereafter, the same model was also used for determining the values of frame and edge-of-glazing thermal transmittances, U_f [W/(m^2·K)] and U_e [W/(m^2·K)] respectively, as described in the international standard ISO 15099 [18]. This modelling concept is used by the National Fenestration Rating Council (NFRC) and is described in detail in the THERM6/WINDW6 NFRC Simulation Manual [18].

For all simulations performed, glazing units were prepared and values of the centre-of-glazing U-factor, U_c [W/(m^2·K)] were calculated using the software package WINDOW. In Table 2, properties of the glazing unit with krypton fill and heat mirror diaphragm are shown as calculated by WINDOW.

Table 2
Properties of the glazing unit with krypton fill and heat mirror

	Thickness of glazing [mm]	*U*-factor [W/(m^2·K)]	SC	SHGC	Rel. Heat Gain [W/m^2]	T_{vis}	K_{eff} [W/(m·K)]
Glazing	24	0.829	0.4	0.346	258	0.62	0.0157

For a correct modelling of the conductance of frame cavity (formed along the frame and sash joining area), this cavity was divided according to the standard EN ISO 10077-2: 2004, see Figure 4. This division also met the criterion set in the NFRC 100-2001 document for the Nusselt numbers.

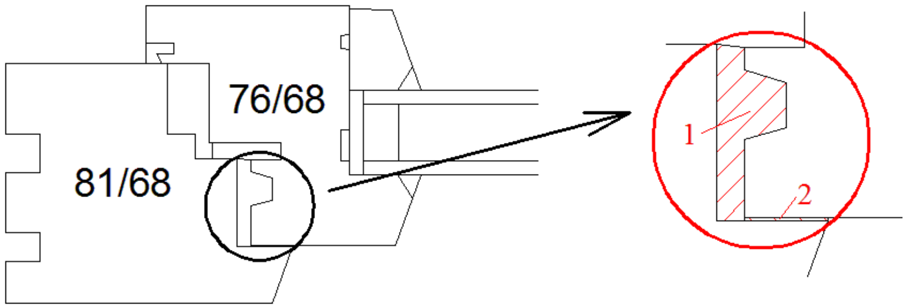

Figure 4
Division of the non-ventilated air cavity formed by the frame and sash profile in the exterior-facing side

Equivalent thermal conductivity values for the divided air gaps were calculated by using the equations below [17]:

$$\lambda_{eq} = \frac{d}{R_S} \tag{1}$$

$$R_S = \frac{1}{h_a + h_r} \tag{2}$$

$$h_a = \max\left\{\frac{C_1}{d}; C_3\right\} \tag{3}$$

$$h_r = C_4 \cdot \left(1 + \sqrt{1 + \left(\frac{d}{b}\right)^2} - \frac{d}{b}\right) \tag{4}$$

For cavity 1, see the calculation below:

$$h_a = 1.57 \quad \left[\frac{W}{m^2 \cdot K}\right]$$

$$h_r = 2.11 \cdot \left(1 + \sqrt{1 + \left(\frac{0.025}{0.01} \right)^2} - \frac{0.025}{0.01} \right) = 2.52 \quad \left[\frac{W}{m^2 \cdot K} \right]$$

$$R_S = \frac{1}{h_a + h_r} = \frac{1}{1.57 + 2.52} = 0.244 \quad \left[\frac{m^2 \cdot K}{W} \right]$$

$$\lambda_{eq} = \frac{d}{R_S} = \frac{0.025}{0.244} = 0.102 \quad \left[\frac{W}{m \cdot K} \right]$$

Calculations in the case of cavity 2 are next shown:

$$h_a = \frac{C_1}{d} = \frac{0.025}{0.0005} = 50 \quad \left[\frac{W}{m^2 \cdot K} \right]$$

$$h_r = 2.11 \cdot \left(1 + \sqrt{1 + \left(\frac{0.0005}{0.012} \right)^2} - \frac{0.0005}{0.012} \right) = 4.134 \quad \left[\frac{W}{m^2 \cdot K} \right]$$

$$R_S = \frac{1}{h_a + h_r} = \frac{1}{50 + 4.134} = 0.018 \quad \left[\frac{m^2 \cdot K}{W} \right]$$

$$\lambda_{eq} = \frac{d}{R_S} = \frac{0.0005}{0.01847} = 0.027 \quad \left[\frac{W}{m \cdot K} \right]$$

After specifying the boundary conditions on the inside and outside boundaries in the model as shown in Table 3, the calculations were performed.

Table 3

Boundary conditions according to EN ISO 10077:1 and EN ISO 10077:2

Inside temperature: Θ_i	20 °C
Outside temperature: Θ_e	0 °C
Inside surface resistance: (R_{si})	0.13 [$m^2 \cdot K/W$]
Outside surface resistance: (R_{se})	0.04 [$m^2 \cdot K/W$]

4 Results

The frame *U*-factor and the linear thermal transmittance, Ψ [W/(m·K)] due to the combined thermal effects of glazing, spacer and frame, defined in EN ISO 10077-1 and 2 are summarised in Table 4 for the individual models. Table 5 shows thermal transmittance values of frame, edge-of-glazing and central glazing area, as well as total product *U*-factor calculated according to the NFRC model. The last column in table 5 contains the ratio of NFRC to EN ISO results for the windows in question.

Table 4

Thermal calculation results according to EN ISO 10077-1 and 2

Glazing type	EN ISO 10077		$U_{f(EN)}$ [W/(m^2·K)]	Ψ [W/(m·K)]	U_w [W/(m^2·K)]
1	Air	Normal	1.375	0.0862	1.8706
2		HM	1.375	0.0902	1.7508
3	Ar	Normal	1.375	0.0915	1.7253
4		HM	1.375	0.0951	1.5988
5	Kr	Normal	1.375	0.0931	1.6651
6		HM	1.375	0.1003	1.4328

Table 5

Thermal calculation results according to the NFRC model

Glazing type	ISO 15099		U_f [W/(m^2·K)]	U_e [W/(m^2·K)]	U_c [W/(m^2·K)]	U_t [W/(m^2·K)]	U_t/U_w
1	Air	Normal	1.8160	2.3481	1.792	1.8734	1.0015
2		HM	1.8103	2.1703	1.602	1.7438	0.9960
3	Ar	Normal	1.8074	2.1417	1.559	1.7159	0.9946
4		HM	1.8019	1.9586	1.360	1.5810	0.9889
5	Kr	Normal	1.8040	2.0589	1.465	1.6523	0.9923
6		HM	1.7930	1.7320	1.097	1.4043	0.9801

It should be noted that the simulation model does not contain hardware parts; isotherms obtained in the frame and sash profile would be somewhat different in reality for that reason too. Because of the changing geometry of hardware components along the frame length, their contribution to thermal bridging could only be truly assessed by three-dimensional modelling. Temperature distributions in the modelled section exhibit themselves similar with all three fill gases. Figures 5 to 7 demonstrate the isotherms and colour IR visualisation for air, argon and krypton fill respectively. It should be noted that these isotherms in a window will be different depending on whether the section modelled is a head, sill or jamb part, and will change depending on the cavity height, which is by default 1 m in THERM.

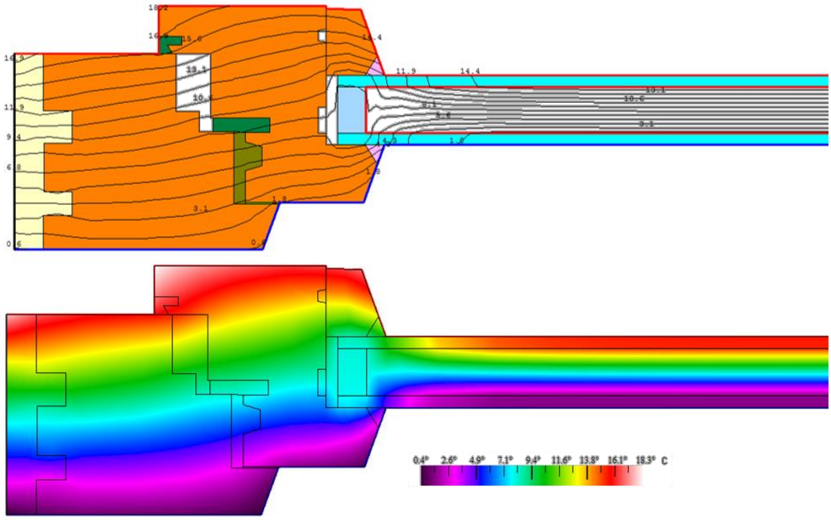

Figure 5

Isotherms and continuous temperature distribution diagram in the window section in the case of air fill. (Temperature in °C)

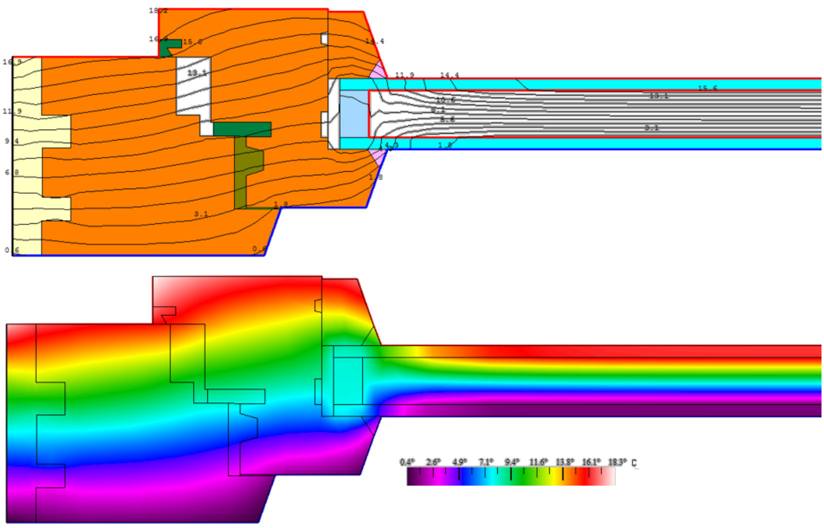

Figure 6

Isotherms and continuous temperature distribution diagram in the window section in the case of argon fill. (Temperature in °C)

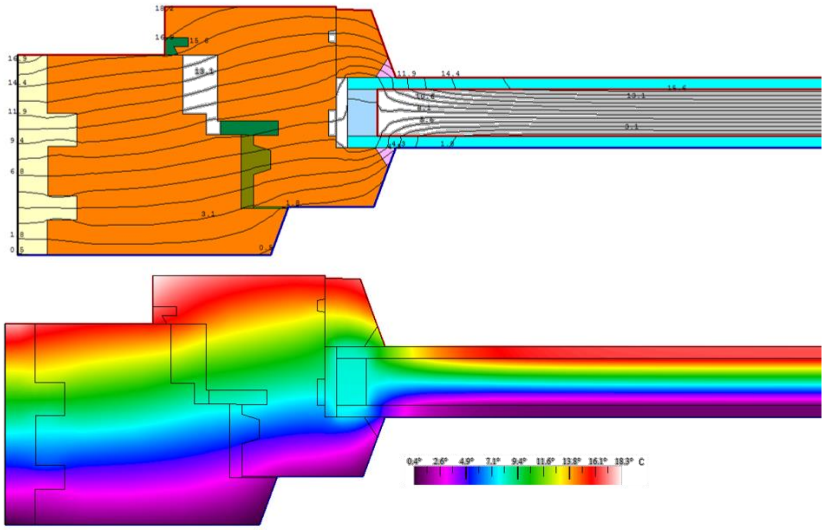

Figure 7
Isotherms and continuous temperature distribution diagram in the window section in the case of krypton fill. (Temperature in °C)

Division of the cavity by heat mirror film resulted more favourable values in all three cases (Figures 8 to 10).

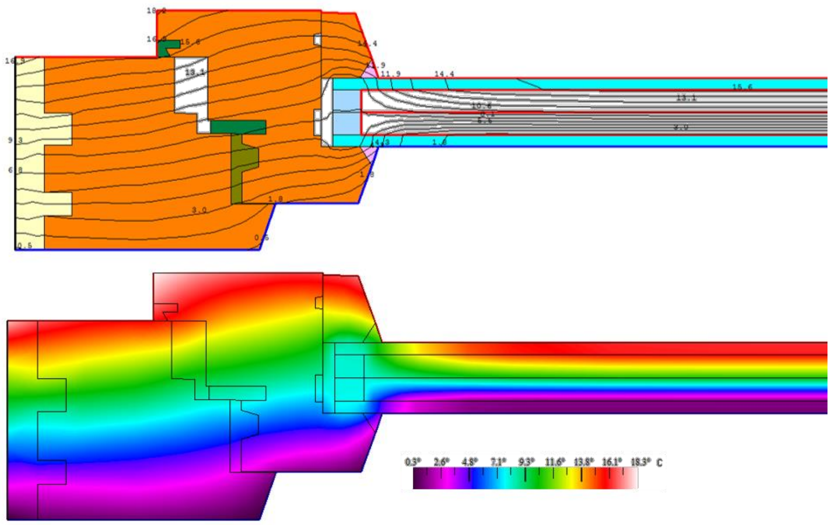

Figure 8
Isotherms and continuous temperature distribution diagram in the window section in the case of air fill and heat mirror. (Temperature in °C)

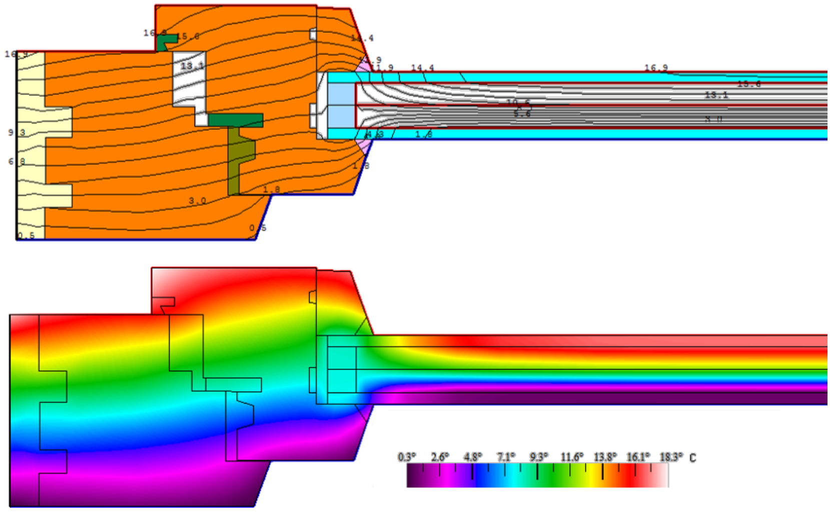

Figure 9

Isotherms and continuous temperature distribution diagram in the window section in the case of argon fill and heat mirror. (Temperature in °C)

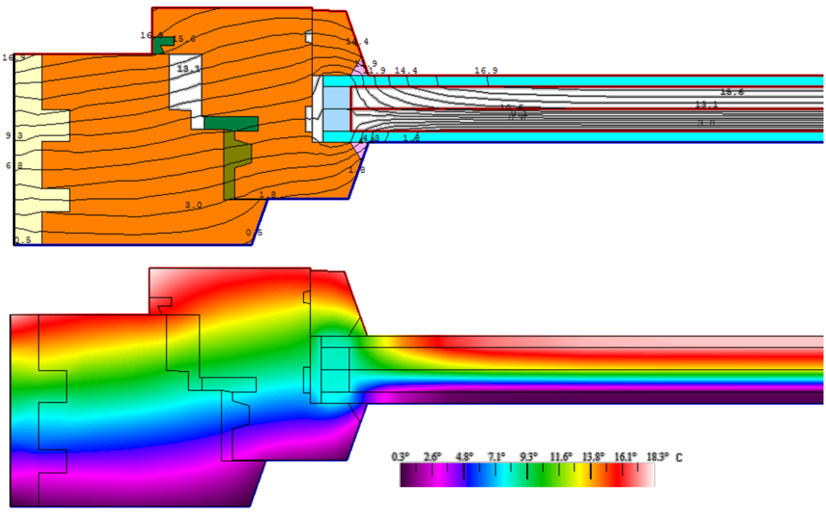

Figure 10

Isotherms and continuous temperature distribution diagram in the window section in the case of krypton fill and heat mirror. (Temperature in °C)

It is apparent in the figures that there are no important differences in the resulting temperature distributions. The point of interest for us was how condensation risk is influenced by improving glazing insulation with unchanged frame. We took the dew-point temperature corresponding to a room temperature of 20 ºC and relative humidity of 65% as a basis for comparison, which turns out to be 13.2 ºC. On the basis of the location of the 13.2 °C isotherm on the interior glass surface, it can be established that the extension of the edge effect caused by the steel spacer considerably was reduced by the application of the heat mirror diaphragm. The observed values of the distance of the 13.2 °C isotherm from the inside edge of the sash are summarised in Table 6.

Table 6
Distance of the 13.2 °C isotherm from inside edge on the glass surface

Type of gas fill	Normal double glazing [mm]	Double glazing with heat mirror [mm]	Improvement [%]
Air	30	23	13
Argon	21	18	14
Krypton	20	14	30

As a result, the distance of the 13.2 °C isotherm from the inside edge reduced from 14 mm to 7.2 mm with a resultant thermal transmittance of the window of 1.27 [W/m^2·K].

5 Discussion

A summary of the simulation results is given in Tables 4 to 6. Table 7 summarises the ratios of the total product *U*-factors and glazing *U*-factors, as well the improvement of *U*-factors due to heat mirror for the different glazing types investigated. In terms of the thermal transmittance of the window as a whole, it could be expected that values higher than those determined for the central area of glazing (column U_c in table 5) will result. In the case of a normal double glazing window with argon fill the increase is 10% to 16%, while with krypton fill it attains almost 13% to 28% depending on the lack or presence of heat mirror. On the contrary, with air fill, this increase was only 4.5% to 8.9%, due to the comparatively higher thermal transmittance of the glazing unit.

When the cavity is divided by a heat mirror diaphragm, results are more remarkably different with different gas fills. The most pronounced improvement of thermal transmittance was observed in the case of krypton fill; that can be explained by the fact that the optimal thickness of krypton-filled cavity is 6 mm to 8 mm (as our divided cavities) rather than 16 mm, see Figure 2. From this, it follows that the window's resultant *U*-factor in the case of krypton fill exceeds glazing *U*-factor more (by 28%), than with other glazing configurations investigated. The effect of heat mirror can also be evaluated through the ratio of U_{tHM} *to* $U_{tnormal}$, see the last column is Table 7, where the subscript $_{HM}$ refers to heat mirror. The values in the table tell us, that the gain attained by the application of heat mirror is enhanced with the use of thermally superior fill gas. This is the good part of using high-performance glazing with unchanged frame systems; the bad part being the fact, the higher the thermal performance of the glazing, the less remains the rate of its exploitation in the total product *U*-factor.

As an effect of the application of heat mirror, the distance of the 13.2 °C isotherm from the frame's inner edge (in other words the spread of low surface temperature) was reduced by nearly 14% in the case of argon fill, while with krypton fill an improvement of 30% could be justified, as can be read in table 6. The trend is similar to that of the ratio of U_{tHM} *to* $U_{tnormal}$.

Table 7

Ratios of *U*-factors for glazing and total product and with and for windows with and without heat mirror

Glazing type	Description		U_c [W/(m^2·K)]	U_t [W/(m^2·K)]	U_t/U_c	$U_{tHM}/U_{tnormal}$
1	Air	Normal	1.792	1.873	1.045	0.931
2		HM	1.602	1.744	1.089	
3	Ar	Normal	1.559	1.716	1.101	0.921
4		HM	1.360	1.581	1.163	
5	Kr	Normal	1.465	1.652	1.128	0.850
6		HM	1.097	1.404	1.280	

Conclusions

Thermal transmittance of the glazing not only defines thermal transmittance of the window with a given frame system, but influences the spread of the low surface temperature zone along the inside glazing perimeter. Among the available low-e coated glazing types those with krypton fill provide the best results that also depend on gas cavity thickness. Further improvements can be attained by the use of heat mirror diaphragms within the glazing system.

However, higher cost of glazing units of extremely low emissivity and or those equipped with heat mirror, as well as and an important decrease of visible light transmittance with their use obstacle the spread of such glazing units. On the other hand, these low-e glazing systems with gas fills of increased thermal resistance, when used with current framing systems, seem to approach the upper limits of attainable thermal performance. Major improvements in the thermal performance of window framings, and/or new concepts of fitting together movable and fix parts in window systems may become necessary in the future. In other words, the less we can approach the thermal resistance of glazing around the glazed area of a window, the less the enhancement of the glazing's thermal properties can be exploited.

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