EXPERIMENTAL AND NUMERICAL INVESTIGATION OF THERMAL IMPROVEMENT OF WINDOW FRAMES

by

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This article presents experimental and numerical determinations of thermal transmittance performed on three different types of window frames (vinyl, aluminium, and wooden) within the same insulated glass unit. Good agreement between experimental and numerical results was attained. Using the numerical models, thermal improvement techniques of the frames and their influence on thermal transmittance of frames were studied. The first thermal improvement technique was using the insulation materials inserted inside large air cavities. By filling the cavity of vinyl frame with the polyurethane foam, thermal transmittance of vinyl frame was lowered by 10%. The second technique was based on repeating the procedure with materials installed inside frames with the materials that have lower thermal conductivity. This technique can be applied on thermal breaks and on steel profiles inside cavities. The result of this thermal improvement (attained by replacing thermal break material with material that has lower thermal conductivity) was certain reduction of the thermal transmittance of frames, by 9%. Using stainless steel instead of the oxidized steel was reduction of the thermal transmittance of vinyl frame by 3%. For the case of wooden frames the influence of shifting glazing unit deeper into profile upon the thermal transmittance of the frame was analyzed. Installing the glass unit by 5 mm deeper into the wooden frame reduced glass thermal transmittance by 5%.

Key words: *window frame, thermal transmittance, thermal improvements, numerical simulations, experimental analysis*

Introduction

Heat gains and heat losses of buildings mostly depend on the thermal and physical properties of construction elements and materials. The 25% of the total energy required for heating and cooling is caused by the heat losses or heat gains across the building windows [1]. Each window consists of transparent (glass unit) part and opaque part (frame). In the last ten years research and development of insulated glass unit (IGU) has taken huge attention [2-5]. As a result of these efforts low values of thermal transmittance of the glass units were obtained. Glass unit is mostly designed as double or triple glazing with low-e coatings, filled with low conductive gas. For instance (in Denmark) Larsson *et al.* [3] have analyzed some IGU prepared by triple glazing with two low-e coatings filled with inert gas krypton. In the high energy efficiency glass units the thermal transmittance of 0.5 W/mK could be reached [4]. The thermal transmittance of the frame is larger than that of IGU, while the frames bear

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about 20-30% of the overall window area and their impact on thermal performance of window is not insignificant [6].

The window frames (in most cases) are equipped with few air cavities. In these air cavities generally all types of heat transfer mechanisms (conduction, convection, and radiation) are present. In the smallest air cavities dominant heat transfer mechanism is conduction, while influence of other mechanisms is negligible. In [2] the optimum design was defined as value of frame air cavity chamber which was 20 mm, where the optimum design value is dimension of cavity in the direction of dominant heat flux. For dimensions of cavity less than 20 mm, heat transfer by conduction is more dominant than convection and radiation. When the real dimension of cavity is larger than the optimum design value, convection and radiation should be taken in consideration as well and in this case filling cavities with different type of low conductivity materials improves thermal performance of the window frame [2]. As the filling material mostly are used polyurethane, polyisocyanurate, different types of sponges, *etc.* In [2] it was found that thermal resistance of frame can be multiplied by six times using aluminium with low emission surfaces.

Increasing thermal performance for wood constructions could be made by making a *sandwich* frame construction using polyurethane or cork [4]. Today is popular the use of wood-aluminium construction. Primary use of this type of constructions is luxury design and better thermal performance than that was attained by simple wood constructions [7].

For improving the numerical model, instead of the 2-D standardized FEM model, it was necessary to deal with 3-D heat transfer effects and use much more detailed radiation models of air cavities [8, 9]. Higher differences between experimental and numerical results were presented for low-conductance window frames with the lowest thermal transmittance of all window frames [10]. For these types of frames with small cavities it is necessary to define accurate correlations for small aspect ratios. For aspect ratio between 0.5 to 6 interpolation was used since the exact scientific correlation does not exist [8]. The empirical equations could be evaluated using 3-D CFD software to determine convection and radiation coefficient inside the cavities with different type of geometry [9].

The thermal performances of the cavity frames have been determined both by the experimental methods and (in the present time) by increasingly using the numerical (simulation) calculations [1]. The utilized experimental methods are mostly being based on the standardized hot-box method [11], while the numerical calculations have been performed by using the standardized numerical models as according standards ISO 15099 [12] and IS0 10077-2 [13].

In this article thermal transmittance of vinyl, aluminium and wooden frame was analyzed. In all cases the same IGU (double-glazed window) was filled with argon. The main aim was obtaining the experimental and the numerical thermal transmittance, *U*-value, for given types of frame and determining main differences between them. Next main aim was finding out different measures for improving thermal transmittance of frame.

Materials and methods

Experimental procedure was performed in Laboratory for thermal technique and fire protection of IMS Institute, Belgrade, Serbia using standardized hot-box method, while numerical calculations were done by THERM software [14]. Most scientific papers in this research field have been performed only by numerical calculations software (THERM, BISCO, *etc.*), while experimental measurements have not been always performed. In general there is still some mismatch between numerical and experimental results of determination *U*-value of windows. In order to obtain more accurate value of thermal transmittance of frame it is necessary to use experimental measurements, because the heat transfer in air cavity is too complex for numerical simulation.

The thermal optimization of window's frames was achieved by using different types of optimization techniques. The primary and the easiest technique is filling the large air gaps with low conductive materials. This technique is recommended for thermal improvement of metal and vinyl frames (frames with large air cavities). In this article was analyzed the biggest air cavity gap of vinyl frame, filled by polyurethane foam. For metal frames one of possible and the best thermal improvement is reduction of surface emissivity, because reduction of surface emissivity reduces radiation heat transfer inside frame cavities.

Materials

The Insulated glass unit

For the numerical and experimental analyzes three different window frames fabricated from vinyl, aluminium, and wood were used. The IGU consists of double glazed glass filled with inert gas argon. For analysis different types of frames with the same IGU were chosen. The windows were made of glass panels (4 + 16 + 4 mm) that consist of two glass plates (thickness of both plates is 4 mm), one is type FLOT and the other one is low emission glass (low-e). Between the glass plates aluminium spacer was installed. The information about spacer materials and dimensions was not delivered by windows producer and for numerical analysis was used representative metal spacer incorporated in an IGU. Representative spacer materials and dimensions of spacer, which could be used for numerical simulations, were defined in standard [13]. Dimensions and materials of spacer for vinyl window were known and representative spacer was not used in numerical simulations [1]. All calculations for glass unit were performed in WINDOW software [14] and results of simulations were imported inside in THERM.

Window frames

Detailed experimental and numerical analysis of vinyl window frame (Frame 1) that is shown in fig. 1, with six cavities were described in [1]. Examinations of aluminium frame (Frame 2), shown in fig. 2, and wooden frames, shown in fig. 3, were performed in the same way as in the case of Frame 1. On the wood window, fig. 3, the three different ways of simulation for sill Frame 3a, head Frame 3b, and middle window cross-sections Frame 3c, were performed.

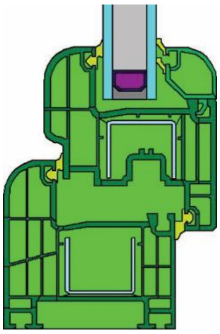

Figure 1. Vinyl window cross-section, Frame 1

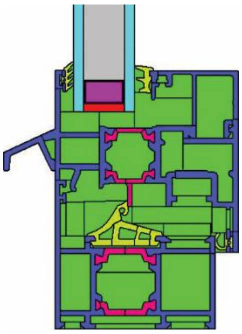

Figure 2. Aluminium window cross-section, Frame 2

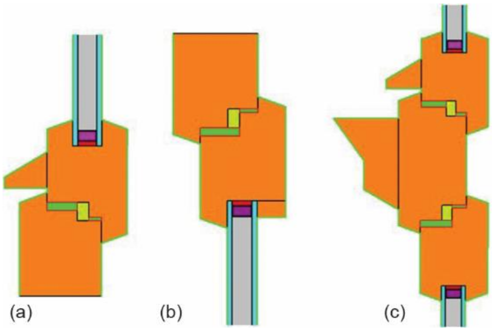

Figure 3. Wooden window cross-sections; (a) Frame 3a, (b) Frame 3b, (c) Frame 3c

Experimental method

Experimental analysis of the windows was performed using standardized hot-box method [11]. Hot-box method is stationary method for determination of thermal transmittance of the windows and the other building constructions. Analyzed windows were installed between hot and cold conditioned air chambers. Thermal transmittance of window is usually noted as U-value. For determination of thermal performance of window it is necessary to know dimensions of frame, glass unit and their share in entire window area. Furthermore, it is necessary to determine thermal transmittance for frames, U_f, and glass units, U_g. Thermal transmittance of a window is computed by [15]:

$$U_\mathrm{w} = \frac{\sum A_\mathrm{g} U_\mathrm{g} + \sum A_\mathrm{f} U_\mathrm{f} + \sum l_\mathrm{g} \psi_\mathrm{g}}{A_\mathrm{g} + A_\mathrm{f}} \tag{1}$$

where l_g is the total perimeter of the glazing or the perimeter of the glass panes in the window [15]. The linear thermal transmittance, y_g, depends on the combined thermal effects of glazing, spacer and frame [15].

The temperature and the velocity fields inside the hot-box chambers are being controlled using a data acquisition system which maintains stationary heat transfer process across the window construction. When stationary (steady-state) mode inside any chamber was reached, data acquisition of heat fluxes and/or temperatures on the frame and glass was initiated. After determination of the parameters, thermal resistances R_f and R_g could be calculated:

$$R = \frac{\Delta T}{\dot{q}} \tag{2}$$

where $\dot{q}$ is the measured value of heat flux across the frame or glass unit and ΔT – the temperature difference between the exposed hot and cold surfaces of the examined sections of the window. By adding the values of the surface thermal resistance R_si = 0.13 m^{2}K/W and R_se = 0.04 m^{2}K/W for the inside and the outside surfaces, total thermal resistance of examined part can be determined as a sum of all resistances. The reciprocate numerical value of total thermal resistance is the mean thermal transmittance of the examined section of the window.

At all the examined frames three thermocouples on the cold as well as on the hot frame surfaces were installed. Temperatures used for calculation of thermal transmittance are the average temperatures of the frame and glass surfaces. In the center of each glass surface were installed three thermocouples each per a single surface. For temperature measuring in frame and glass the thermocouples T-type were used. These thermocouples were connected on 24-bit acquisition card and accuracy of temperature reading was 0.5%. Heat flux meters were installed only on the cold side of examined frames and glass. Heat flux measuring HFP01 sensors were used with high sensitivity of $60\cdot10^{-6}$ Vm^2/W. Figure 4 shows a detail of installed measuring equipment on the examined frame.

Numerical method

Numerical determination of the thermal transmittance for the windows was performed by using freeware THERM software. The simulations within this software are based on algorithm defined in the ISO 15099 standard [12].

The boundary conditions on the 2-D cross-sections are the thermal resistances on the *hot* and *cold* side of the window, as well as the temperatures of air in the chambers. The thermal resistance and air temperature on *hot* (inner, right) side are R_{si} = 0.13 m^{2}K/W and 20 °C. The thermal resistance and air temperature on *cold* (outer, left) side are R_{se} = 0.04 m^{2}K/W and 0 °C. The same conditions were defined for all the previously defined frames.

All the thermal performances of the frames were analyzed at the mean frame temperature value of +10 °C, which conforms with the standard procedure for the determination of any product in building industry. These boundary conditions are popularly known as the *winter boundary conditions* [1, 12]. For the vinyl frame all radii of curvatures and radii in the frame cavity were being simplified according to standard [12], while the approximations on the other frames were not performed. Air cavities inside the frame profiles were defined as Frame Cavity NFRC 100 [14]. Values of the thermal conductivities of all materials used in simulations are given in tab. 1.

Figure 4. Position of thermocouples and heat flux meters

Table 1. Thermal conductivity of various materials

Material	Thermal conductivity [Wm^{-1}K^{-1}]
Polyvinylchloride (PVC)/vinyl – rigid	0.17
Polyvinylchloride (PVC)/vinyl – flexible	0.14
Aluminium (oxidized, mill finished)	237
Aluminium alloy	160
Wood (pine)	0.14
Steel (oxidized)	50
Stainless steel (oxidized)	17
Polyamide	0.25
Polyurethane foam	0.026
Sponge	0.03
EPDM (ethylene propylene diene monomer)	0.25
Butyl rubber	0.24
Silicone	0.35
Polysulphide	0.4

Results and discussion

According to the results of laboratory determination of thermal transmittance on the three equal glass units with different types of frame, the mean value of thermal transmittance across glass unit, U_g, was determined as 1.1 W/mK. The thermal transmittances for the all frames that were determined experimentally and numerically are given in tab. 2.

Based on obtained data it was concluded that there is a good agreement between numerical and experimental results. Maximum relative difference between experimental and numerical results is less than 10% and results obtained by using the simulation software are appropriate for engineering use. Differences between experimental and numerical data are due to frame geometry and heat transfer mechanisms approximation and uncertainty of measurements.

Frames 3a and 3b have pretty same experimental values, because these cross-sections are quite similar. Numerical results of these frames also show small differences between

Table 2. Results of experimental and numerical analyzes

Frame	$U_{f,exp}$ [Wm^{-2}K^{-1}]	$U_{f,num}$ [Wm^{-2}K^{-1}]	Relative difference [%]
1	1.21	1.17	3.30
2	2.10	2.29	–9.05
3a	1.70	1.80	–5.88
3b	1.72	1.84	–5.23
3c	1.84	1.66	9.78

sill and head thermal transmittance. The main reason of difference in thermal transmittance for these wood frames is a result of the fact that glass of Frame 3a is more shifted into wood frame than the one in Frame 3b. Furthermore, the Frame 3b has higher value of thermal transmittance than Frame 3a because of the fact that it has asymmetrical frame cross-section. Frame 3c has many profiled external surfaces and installation of measurement equipment was complex. On the external side of window Frame 3c was not possible to place plate heat flux meter and heat flux on that surface was not measurable.

On the internal side of this frame it is necessary to install many heat flux meters to measure exact heat flux on every exposed surface. This is reason of higher relative difference between experimental and numerical U_f values.

Thermal improvements of frames

Vinyl frame

According to [4] thermal transmittance of Frame 1, U_f value, can be reduced down by 50%. Primary problem of these types of frames are steel profiles located inside frames that are necessary for static stability of windows. Using stainless steel instead of non-stainless steel could reduce the U_f value of vinyl frame because stainless steel has lower thermal conductivity. Thermal conductivity of stainless steel is 17 W/mK, while oxidized steel has the thermal conductivity of 50 W/mK. Thermal transmittance results of frame with stainless steel profile were previously determined and shown in tab. 2, U_f = 1.17 W/mK. Repeating the same numerical procedure with the oxidized steel profiles, yielded the value of U_f = 1.20 W/mK. Applying this thermal improvement decreased the U_f value by 3%.

In [4] was analyzed a composite vinyl framework component without the steel profile. This frame had additional cavities and static stability was conserved. The additional air cavities decreased the thermal transmittance of window frames and these composites have lower thermal conductivity than the original vinyl material.

A further improvement could be done by using reflective paints on steel profile surface to reduce the emissivity of that surface. Any paints with emissivity less than 0.8 could be used for reduction of radiation heat transfer component.

Air cavity with an installed steel profile has a relatively high equivalent thermal conductivity. In order to reach lower value of equivalent thermal conductivity of that space (0.1198 W/mK, that was determined using the subroutine THERM) in the described research, as filling material, polyurethane foam with thermal conductivity of 0.026 W/mK was used. In fig. 5 frame cross-section filled with polyurethane is shown, while numerically obtained thermal transmittance of this frame was 1.05 W/mK. The reduction of thermal transmittance was roughly 10%. This is a great improvement of vinyl frame and in engineering practice it is possible to perform this improvement in a relatively easy way.

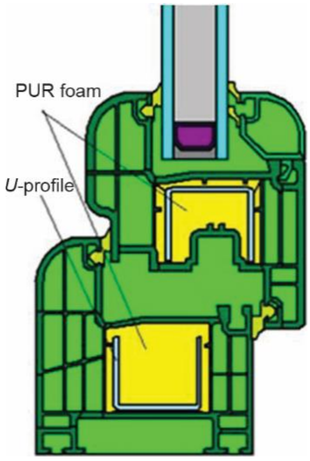

Figure 5. Vinyl window cross-section filled with polyurethane foam

In [4] authors analyzed a similar vinyl frame with additional central gasket in space between sash and frame. The thermal improvement after using central gaskets was less than 4% for transmission heat losses. The main purpose of utilizing central gasket is reduction of the ventilation heat losses.

According to [4] other significant thermal optimization technique is shifting IGU deeper into the vinyl profile. This shifting could decrease thermal transmittance value up to 29% [4]. This type of optimization was not conducted on Frame 1, because it was not possible to shift glass deeper in frame without decreasing static stability of whole window. In theory it is possible, but static stability of construction is primary to be kept, after any change is made.

Aluminium frame

In this paper was analyzed a profile where all cavities were filled with polyurethane foam of thermal conductivity at 0.026 W/mK. The result of simulation of thermal transmittance across aluminium window frame was 2.28 W/mK and reduction of U_f value was less than 0.5%. Thus, this improvement technique for Al frame is not worth any attention.

The following possibility of the thermal improvement is, with no doubt, the optimization of window frame thicknesses which was conducted and outlined in [4] where thermal improvement was about 1%.

In numerical simulation for Frame 2 the thermal break was of polyamide with thermal conductivity of 0.25 W/mK. In the same article [4] it was outlined how the thermal break material impacts onto the thermal transmittance of frame. In order to obtain pertinent thermal transmittance improvement (about 9%) the result of the performed numerical analysis was that thermal break material should have thermal conductivity less than 0.15 W/mK. The significant thermal improvement can be achieved with other type of material than polyamide, as well.

Shifting the IGU deeper into profile, *i.e.* from 15 mm to 30 mm, reduces the thermal transmittance of frame up to 10% [4]. However, in our case glazing shifting and installing glass deeper into the profile without any modification on geometry of profile was practically impossible because the static stability of the whole window could be decreased.

In the space between glazing and frame an expandable sponge with low value of thermal conductivity of 0.030 W/mK could be installed. This highly expandable sponge with small thickness expands at ambient temperatures and fills up the open cavity. The thermal transmittance for the frame was reduced in this way by 3.4%. This thermal improvement could be performed on windows which are already installed in walls. This improvement is not only responsible for reduction of heating and cooling costs, but it also improves the acoustic performance of windows.

Many researchers have performed analysis of participation that aluminium frame exerts onto the thermal improvement in decreasing surface emissivity. Non-polished aluminium plate has emissivity of 0.055, while polished aluminium has emissivity between 0.039 to 0.057 [16]. The aluminium anodized profile on the exterior has the emissivity at about 0.84 [16]. This surface could be painted with low emission paintings with emissivity lower than 0.84. Internal cavities are not polished and have emissivity roughly at 0.055. If the cavities can be polished in some way with special tools after the extruding process, significant reduction of thermal transmittance across aluminium frame is achieved.

Aluminium alloys have lower thermal conductivity (160 W/mK) than aluminium (237 W/mK) [15]. Based on the same geometry (of the Frame 2) two materials, aluminium alloy (oxidized, mill finished) and aluminium (oxidized, mill finished), with the same surface emissivity of 0.2, were analyzed. Numerically obtained thermal transmittance of aluminium frame was 2.29 W/mK. However, thermal transmittance of aluminium alloy frame was 2.28 W/mK.

Wooden frame

The wooden windows analyzed in this article have three different cases *i.e.* three different positions of cross-sections, fig. 3. Numerical analysis of thermal transmittance across sill, head and middle cross-sections was conducted. In accordance to the results of the numerical analysis, the Frame 3b has higher thermal transmittance than is the thermal transmittance of the Frame 3a. These differences have been produced primarily by the asymmetrical construction of the Frame 3b. The height of the internal glazing bead is somewhat lower than is the height of the external wooden element. However, if it happens that the static construction is completely symmetrical like it is at the sill cross-sections (geometrically shown in Frame 3a) better thermal transmittance values (by about 2%) could be obtained.

The glazing shifting deeper into frame profile is much easier for wooden profile than for any other frame material. The advantage of glaze shifting could be represented in analysis of Frame 3c. Upper glass is much deeper into wooden profile than installed down glass. The improvement of shifted glazing on thermal transmittance could be evaluated if the edge of glass effect is analyzed [1]. By numerical procedure were obtained thermal transmittance values for edge of glass: $U_{\mathrm{up.edge}}$ = 1.84 W/mK and $U_{\mathrm{down.edge}}$ = 2.05 W/mK. The upper glass was placed at the depth 21.5 mm. The lower glass was placed at the depth of 15 mm. The lower glass has lower thermal transmittance for the edge of glass (by about 10%). Installing glass deeper into the wooden profile reduces the thermal transmittance of edge of glass as well as of the entire frame. By using these results in the analyzed case, it was concluded that increasing the depth by 5 mm reduces edge of glass thermal transmittance by about 5%.

In [4] the operation performance of a sandwich wooden frame was analyzed. The window frame consists of three layers: 1 – cork, 2 – polyurethane, and 3 – cork. It was revealed that utilizing this type of construction could readily reduce thermal transmittance of a frame by about 47% [4]. This type of construction is only possible in theory because the stiffness of the construction is being highly reduced. The authors analyzed the sandwich designs of wood, cork, polyurethane, cork, and wood with the same widths. This construction is promising for future development of wood window frames.

Conclusions

In the present article a comparative study was performed to obtain the results of varying the thermal transmittance of three different window frames (vinyl, aluminium, and wooden) determined by using standard experimental procedure as well as the numerical simulation. The numerical results were validated by utilizing the standardized experimental method known as the hot-box method. The maximum difference between the experimental and the numerical results was lower than 10%. The numerical models were used for the analysis of numerous thermal improvement techniques.

Decreasing the thermal transmittance of vinyl frame was attained by using stainless steel profile instead the oxidized steel profile. In this way reduction of thermal transmittance for vinyl frame was kept below 3.0%. By filling the cavity of vinyl frame by polyurethane foam thermal transmittance of frame was decreased to 10%.

The same approach has been undertaken to the aluminium frame. All the cavities were filled with the polyurethane foam and thus the thermal transmittance was reduced to 0.5%. Replacing the fixed polyamide thermal break with the examined aluminium frame from the material having thermal conductivity of 0.15 W/mK has induced the decrease of thermal transmittance of frame by 9%. In the air gap between the glass unit and the frame it was installed expandable sponge with thermal conductivity of 0.030 W/mK and the thermal transmittance of frame was decreased by 3.4%.

From the performed analysis of the considered wooden frame it was concluded that the symmetrical frame has lower thermal transmittance than the asymmetrical frame and that this difference was nearly 2%. On the other hand, shifting the glazing unit by 5 mm into the wooden frame reduces the edge of glass thermal transmittance by 5%.

Nomenclature

A – surface, [m^2]
R – thermal resistance, [m^{2}KW^{-1}]
ΔT – temperature difference, [K]
U – thermal transmittance, [Wm^{-2}K^{-1}]
l – total perimeter, [m]
$\dot{q}$ – heat flux, [Vm^{2}W^{-1}]

Greek symbol

ψ_g – linear heat transfer coefficient of the insulated glazing edge seal, [Wm^{-1}K^{-1}]

Subscripts

w – window
f – frame
g – glass
se – external surface
si – internal surface
exp – experimental
num – numerical

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