BUDAPESTI UNIVERSITY OF TECHNOLOGY AND ECONOMICS
FACULTY OF ARCHITECTURE

ASPECTS OF THE IMPROVED THERMAL MODELING OF TRADITIONAL DOUBLE-SKIN BOX TYPE WINDOWS

Kéthéjú történeti ablakok pontosabb hőtechnikai modellezésének egyes kérdései

Thesis statements

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1. Introduction

Most of the windows in Central-Europe originating from the middle of the 19th century to the middle of the 20th century are double-skinned, so called *box type windows* (Kastenfenster in German). They have two layers of usually wooden sashes, each having a single pane of glass, with a 10-20 [cm] thick air cavity enclosed between them to provide increased thermal resistance. These constructions were the product of centuries of window development and represented an enormous leap forward in thermal comfort and insulation from previous windows with only a single glazing layer separating the interior and exterior environments. Many different subvarieties of such windows exist, characteristic of the country, region and in some cases even the decade of the building's construction. The two layers of sashes may both open towards the inside, or in opposite directions, but the essential principle, and the high quality of craftsmanship that went into their making is the same.

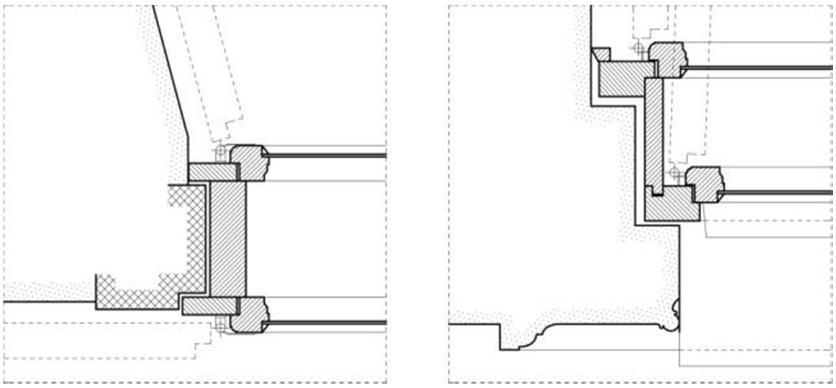


Fig. 1. – Schematic representation of the jamb detail of two typical 19th century box type windows

Due to the constant movement towards sustainability and ever increasing energy saving requirements the refurbishment of the large Central-European window stock poses significant challenges. As windows contribute significantly to the buildings' architectural character their preservation is very much preferred in most cases. In dealing with national monuments the need to reduce energy usage has to be met together with the requirement to preserve the actual authentic constructions. This is made even more pressing by the triple-R motto of sustainability in Europe: Reduce, Recycle and Reuse. Additionally, double-skinned window constructions have some significant merit that makes them interesting for the development of new products as well.

In the last few decades the preservation and restoration of historic windows in central-Europe and elsewhere was the subject of many studies. The most important structural details of 19th century windows, their common failures and the techniques to mend them are well documented, e.g. in books such as Neumann et al. [22], Gärtner et al. [16], Schrader [25] or Holste et al. [17], to cite just a few. However, though window restoration and refurbishment is mostly the area of specialized practitioners, even they base their work largely on rules of thumb and simple design guidelines (such as "HO.09 Runderneuerung von Kastenfenstern aus Holz" [27] or [11] in Germany) that can only ever provide generalized solutions and for only the less demanding cases. Furthermore, the thermal improvement of historic windows, though definitely part of many of the relevant publications, is usually not treated in a systematic fashion. The majority of works is limited to presenting one or two possible solutions leaving little room for optimization.

One of the prerequisites for the preservation of old windows is the ability to plan their retrofit with the same level of detail and precision as for contemporary constructions. Regarding questions of building physics one has to solve problems like quantifying the transmission heat losses, assessing the total energy balance during the heating period and the whole year or checking the resistance to condensation. These tasks are far from trivial since reliable and well documented measurements are scarce and most standards and calculation methods for windows used by the building industry today were developed for contemporary single-skin window constructions with insulating glass units that differ strongly from traditional double-skin window constructions. This raises questions regarding these models' applicability for box type windows.

A comprehensive program for validating existing or establishing new modelling methods for double-skin box type windows will eventually have to cover all of the following topics:

a) the investigation of glazing area heat transfer models' ability to calculate glazing systems with cavities of much larges thickness but lower vertical aspect ratio than insulating glass units,
b) investigating the applicability of common window component heat transfer models to windows with glazing cavities displaying strongly multi-dimensional convective and radiative heat transfer effects,
c) investigating the accuracy of models to derive overall (complete window) heat transfer indices from component results to give acceptable results for box type windows,
d) creating and validating models for the interaction between transmission and in/exfiltration heat transfer in the large unsealed glazing cavities of box type windows,
e) investigating the calculation methods of window-to-wall interface heat transfer with regards to their ability to accurately compare different window options,
f) investigating the possibilities to accurately model the hygrothermal behavior of box type windows and their installation details,
g) the specification of the design methodology and fenestration heat balance modeling practices most suitable for historic buildings and double skin windows and the necessary modification of common models based on findings from the previous points.

The completion of this research program would create a toolset suitable for making truly reliable design decisions when creating refurbishment scenarios for traditional double-skin box type windows. Since this type of fenestration is a largely regional occurrence research interest in its thermal modeling is also localized and such a comprehensive study is as of jet missing in the international literature. There were several individual works that touched on the question of box window thermal modeling, but none of the publications presented a thorough scientific investigation of existing thermal modeling techniques. Hot box measurements reported in Holste et al. [17] and in [24] were not compared with calculations and are not documented in great enough detail to be useful for further study. Homb et al. [18] is perhaps the only source that did perform a comparison of measurements and standard calculations, but although they reported a good agreement between the two their publication is not detailed enough either to recreate their results or investigate their technique. Similar measurements of storm windows, an Anglo-Saxon construction somewhat similar to European box type windows, are found in Smith et al. [26], a publication similar to Homb et al. in its conclusion and the limited scope of the research. A shorter study of box window heat transmission calculations, but without laboratory validation or a substantial analysis of the literature and heat transfer modeling principles, is found in Laustsen et al. [20]. Another noteworthy work is published by Brandl and Ruisinger in [21]: they studied box type windows with 2D CFD simulation but without the calculation of thermal transmittance or model validation. Most other works are focused on window refurbishment principles, their possibilities for reducing energy usage or questions of preservation and use standard fenestration heat transfer calculations of box windows as a tool, not as the subject of study.

A consistent methodology is needed to investigate and if necessary improve the reliability of window thermal and hygrothermal modelling tools for use on double-skin box type windows, on which combines all of the methods and results found in the existing literature and expands on it with the careful study of fundamental fenestration thermal and hygrothermal modeling principles. However, the entire research program outlined above far exceeds the possible limits of a single doctorate thesis. The work needs to be divided into smaller, manageable parts that are to be undertaken in a suitable order. The goal of this thesis could only be to make the first steps along this road. The dissertation studies point a) b) and c), the main steps for calculation of window thermal transmittance, in detail, as well as points e) and g), i.e. the calculation of installation thermal bridges and the methodology for refurbishment design and heat balance calculations. Points d) and f), the interaction of thermal transmittance with air in- and exfiltration and the problem of hygrothermal modeling, are only very briefly touched upon. A comprehensive study of these aspects is a job for the future, but one which would not be feasible without the foundations created by taking steps a) through c) first.

2. Summary of scientific findings

Finding I: Fenestration thermal models and sub-models: assessing the range of validity of standardized calculation tools for double-skin box type windows

Designers have a large number of fenestration thermal design tools (models, software, etc.) at their disposal that are based on two main series of standards, one in the EU[1] and one in North America[2]. The models in these standards were, however, initially developed for the single-skin windows of contemporary manufacture and use. In order to keep the necessary calculations manageable the standards are based on simplifying assumptions enabled by a good knowledge of the thermophysical processes in these contemporary windows. As a result they rely on a series of implicit assumptions in their methodology. Like in most standards, however, these assumptions are often not reported in the text, nor are there any references given to the research works they were based on. As the standards do not explicitly state their range of validity the question can arise whether they are suitable for the calculation of traditional double-skin windows at all?

To answer this question I performed a thorough analysis of the models in these standards and a detailed survey of the relevant literature on the basis of which I have concluded, that main implicit assumptions in the method are, that:

- the heat transfer in glazing cavities is approximatively one-dimensional,
- the natural convection in the glazing cavities is in the conduction or transition regime,
- the temperature stratification in the glazing cavities, if at all present, is minimal, confined to the very top and bottom edges of the cavity, and the convective heat transfer is still well represented by effective one-dimensional models,
- the temperature field in the glazing cavities is close to satisfying the Laplace equation,
- lateral heat transfer between glazing and frame is minimal and spatially limited to a narrow region at the glazing's edge.

Comparing these assumptions with the characteristics of traditional double skin windows I have reached the following conclusions that I published in Bakonyi and Becker [3] and Bakonyi and Dobszay [7]:

I. a) With the analysis of standard models and a detailed survey of the relevant literature I have shown what the implicit simplifying assumption, and their scientific basis, in the fenestration thermal calculation standards are and showed that they are vital in determining the range of validity for the standard models.

[1] EN 410 [12], 673 [13], 1077-1 [14], 1077-2 [15]
[2] ISO 15099 [19], NFC 100-2010 [23]

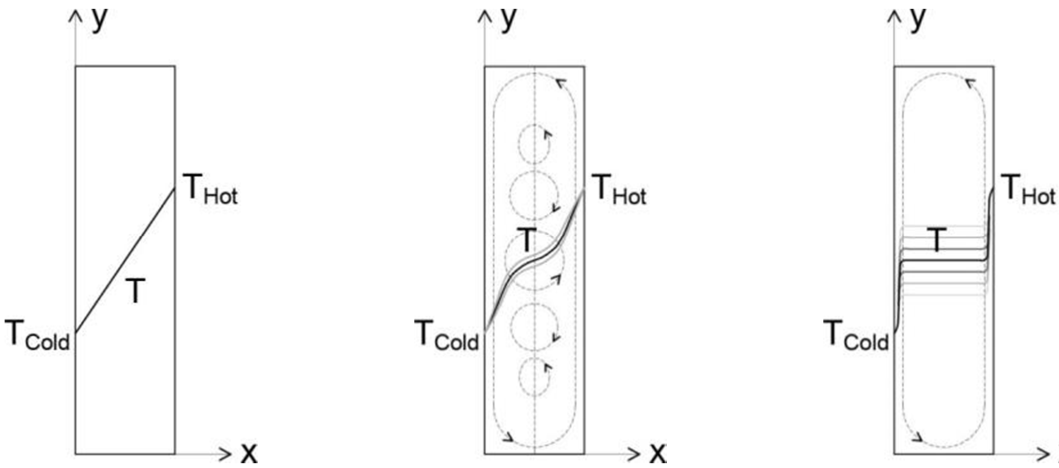
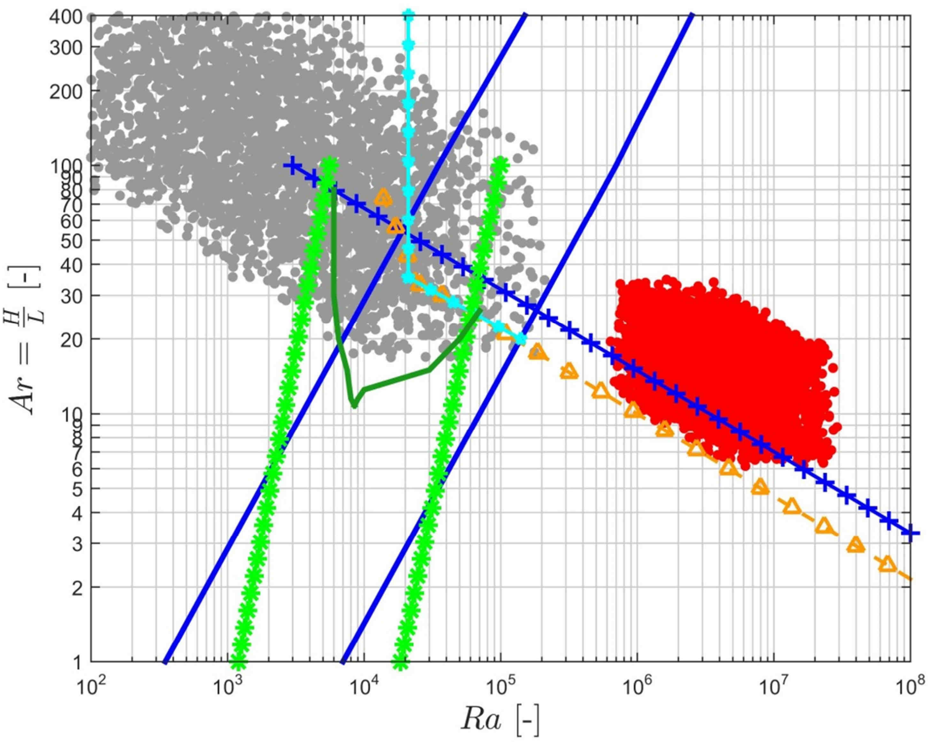


Fig. 2. – schematic representation of the type of natural convection and temperature field found in near rectangular vertical cavities: conduction regime (left) and transition regime (middle) flows characteristic of insulating glass units, and boundary layer flows (right) representative of traditional double-skin windows

I. b) Comparing the characteristics of traditional double-skinned box type windows (primarily the turbulent boundary layer natural convection in their large thickness small aspect ratio cavities as opposed to the conduction or transition regime flows of IG units) with the implicit modeling assumptions shown in I. a) I have concluded, that these types of windows lie outside the range of validity of standard fenestration heat transfer calculations, and therefore their accuracy has to be investigated and if necessary their models improved.



3. ábra – the type of natural convection flow in near rectangular vertical cavities as a function of Rayleigh number and vertical aspect ratio (Ar)

Finding II. - A new dedicated correlation for calculating the convective heat transfer coefficient in the glazing cavities of double-skin box type windows depending on the vertical aspect ratio and the Rayleigh number.

I have performed a Monte Carlo simulation to identify the Rayleigh number and vertical aspect ratio range which is most often encountered in the glazing cavities of box type windows. I reviewed the literature to find the turbulence model most suitable for the CFD modeling of this flow regime. With the help of the k-ω SST turbulence model selected and validated based on a turbulence benchmark measurement in the literature I performed an extensive parameter study to investigate the convective heat transfer in box type window cavities. The study was used to investigate the Rayleigh number and vertical aspect ratio dependence of the heat transfer, the creation of a Nusselt correlation dedicated to box type windows and the characterization of the temperature field and stratification in their cavities.

In Bakonyi and Dobszay [8] I have published the following results:

II. a) By fitting a new set of empirical equations to a dataset of convective heat transfer results, derived for the Rayleigh number and vertical aspect ratio range of double-skin box type windows, I created a new correlation for calculating the Nusselt number that better expresses the aspect ratio dependence of convective heat transfer for a given Ra number than other equations found in the literature:

$$Nu = \max \begin{cases} Nu_1 = 0.0776 Ra^{0.3041} \\ Nu_2 = 0.0193\left(1 + Ra^{0.0897} Ar^{-0.0382}\right)^{3.9826} \end{cases}$$

where: Nu [-] – the Nusselt number
Ra [-] – the Rayleigh number based on cavity thickness (L)
Ar [-] – the vertical cavity aspect ratio (Ar=H/L)

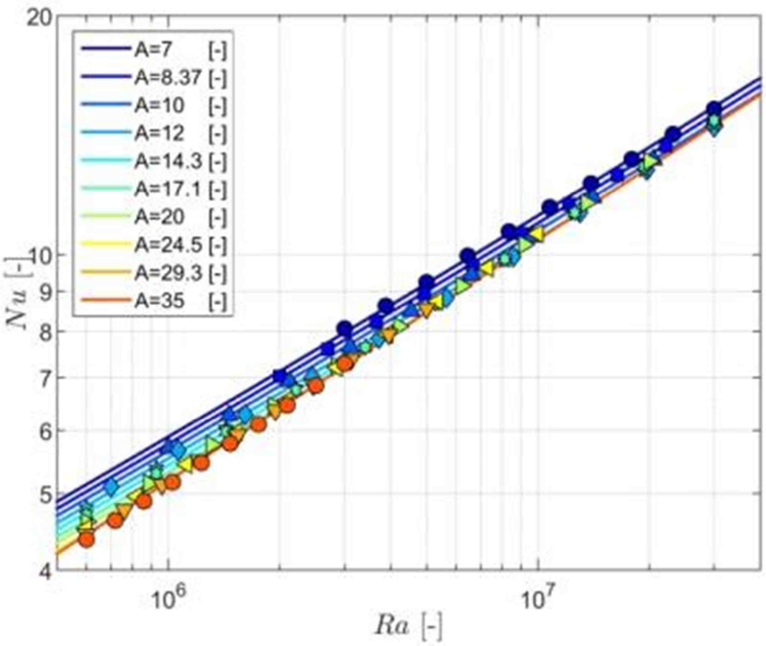


Fig. 4. – the new Nusselt number correlation (derived for the large cavities of double-skin box type windows) compared to parameters study datapoints it is based on

II. b) By studying the dimensionless temperature field in the cavities of box type windows it can be concluded that, within the turbulent boundary layer regime, they constitute a transition point between near-rectangular and higher aspect ratio cavities. In box window cavities with very small aspect ratios the vertical temperature stratification is near linear with the dimensionless height (y/H), while at higher aspect ratios the stratification is significantly reduced in the middle of the cavity and it is mostly constrained to the very top and bottom of the flow (0.1<y/H and 0.9>y/H). To summarized the results of the study I introduced a new correlation for the vertical temperature stratification.

$$f = 0.5 + 0.8963 \cdot b + 0.0159 \cdot b^2 - 1.5771 \cdot b^3 - 0.0341 \cdot b^4 + 5.2452 \cdot b^5 \ldots$$

$$-0.0238 \cdot Ar \cdot b - 0.0010 \cdot Ar \cdot b^2 + 0.1176 \cdot Ar \cdot b^3 + 0.0025 \cdot Ar \cdot b^4 - 0.1282 \cdot Ar \cdot b^5$$

$$b = \left(\frac{y}{H} - 0.5 \right)$$

where: f [-] – the dimensionless temperature of the core: $f=(T-T_{s,cold})/(T_{s,hot}-T_{s,cold})$
Ar [-] – the dimensionless aspect ratio (Ar=H/L)
y [m] – the height above the cavity's bottom
H [m] – the total height of the cavity

As a next step I extended the model used in the parameter study to the whole glazing system (the glazing consisted of typical 3 [mm] thick float glass panes) to eliminate the need to define the cavity walls isothermally like in the earlier studies. This made it possible to investigate the temperature field on the glazing surfaces as well (as a function of the same parameter set). The results showed that the temperature stratification in the core of the cavity causes a stratification of the glazing surface temperature as well. This stratification reached ±10% of the total cavity temperature difference on the cold side (the coldest point of the cold size glazing can be up to 10% of the cavity temperature difference colder than its mean temperature) and up to 20% on the warm side. This is an important phenomenon when trying to assess the condensation resistance of box type windows. Therefore:

II. c) I demonstrated, that the difference between mean glazing surfaces temperatures reported by one-dimensional glazing heat transfer models and actual maximum and minimum surface temperatures can reach up to ±10% of the total temperature difference in the internal glazing cavities of traditional double-skin box type windows on the cold and ±20% on the hot side. This difference can prove decisive in predictions of interpane condensation, therefore I have concluded, that one-dimensional thermal models of glazing systems are not suitable for such calculations due to their disregard of temperature stratification.

Finding III. – The accuracy of standard fenestration U_w calculations for traditional double-skin box type windows (the comparison of standard 2D and 3D CFD simulations results)

The standard fenestration heat transfer models in the literature do not take into account the three-dimensional nature of the flow and the radiative heat transfer or the temperature stratification of certain flow regimes when calculating the overall window thermal transmittance. I created three-dimensional models of simplified generic, and as a control a realistic and geometrically complex, box type window to study the accuracy of said calculation methods. I compared the results of standard fenestration heat transfer calculations, 3D heat conduction calculations based on the standard fenestration models and 3D CFD/conjugate heat transfer simulations for simple and thermally improved versions of the model windows' glazing system. I performed the standard calculation with both standard and the improved correlations for the cavity Nusselt number I introduced in II.a. The inability of the standard models to compute 3D heat flow with only 1 and 2D approximations was clearly demonstrated in the significant errors between the 2 and 3D thermal calculations. I could reduce the errors by increasing the edge-of-glazing area in the 2D thermal calculations compared to the standards thereby capturing more of the multi-dimensional effects in the edge-of-glazing thermal transmittance. I identified the minimum edge-of-glazing width to get an edge-of-glazing width independent window thermal transmittance by observing the calculations' convergence.

When comparing the calculated thermal transmittance of standard and CFD simulations the error is dependent on the buildup of the glazing system: unmodified glazing is better, while thermally improved (low-e coated or using insulating glass units) glazing systems is more poorly predicted by the standardized calculations. Changing the Nusselt number correction in the standard method to the new improved correction does not increase the calculation accuracy in every case. The fact that the removal of the Nusselt number correlation as source of error can, in certain circumstances increase calculation error clearly shows that there are additional sources of error in the standard models. The standard model can't be enabled to accurately calculate box type windows with just simple modification to its equivalent thermal conductivity approach.

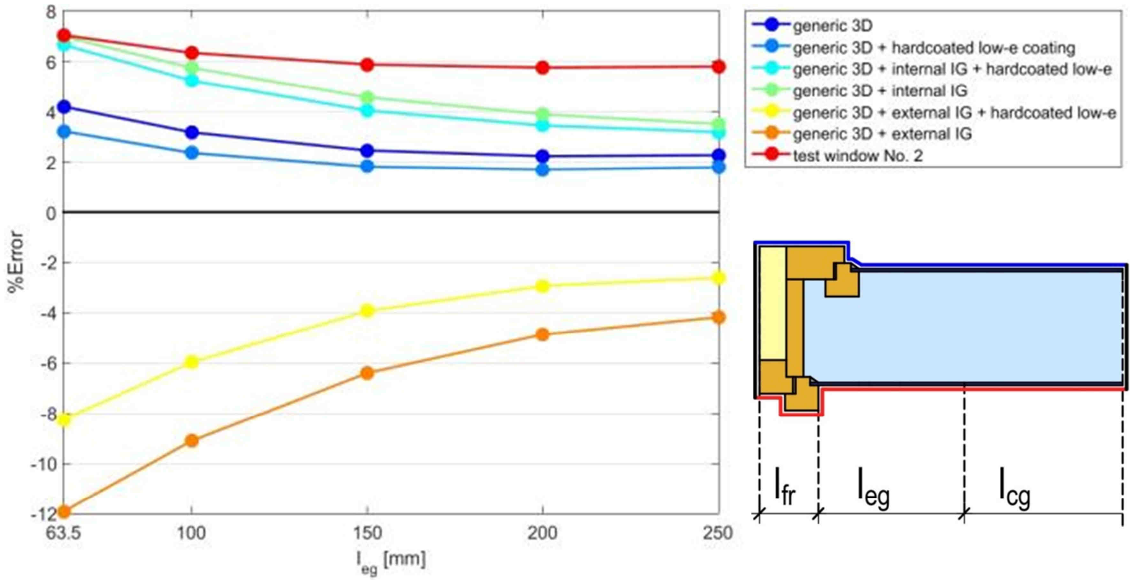
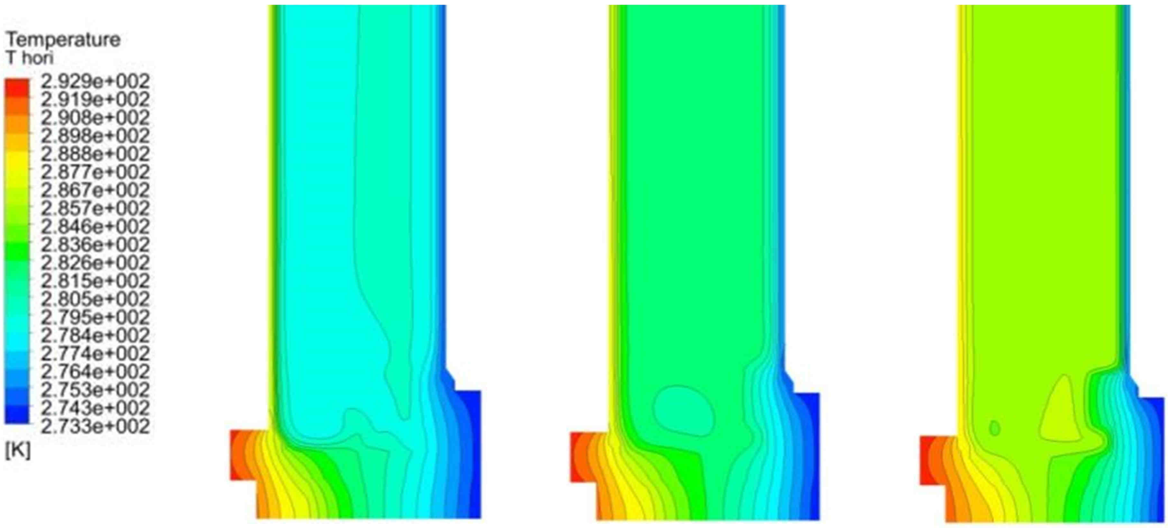


Fig. 5. – %Error in Uw between 2 and 3D calculation for box type windows with different glazing systems, investigated as a function of leg (the width of the edge-of-glass area)

I published my findings in Bakonyi and Becker [9]:

III. a) I performed a comparative study of standardized conduction-only fenestration thermal transmittance models in their original 1/2D form, their extension with 3D heat conduction simulations and 3D CFD/conjugate heat transfer models for a set of generic and a realistic box type window geometries, with the use of both standardized and my proposed correlation for the glazing cavity Nusselt number. I have concluded that the standard edge-of-glazing area/width in the NFRC 100-2010/ISO 15099 calculation method is inadequate to capture in fullness of even the 2D heat flow and results in large errors when compared to 3D thermal calculations (which is not subject to the same limitations). I concluded that the edge-of-glass area width must be increased to at least 200 [mm] (from the 63.5 [mm] in the standard) to produce an edge-of-glass width independent result.



6. ábra – CFD szimulációk: hőmérséklet mező az ablak vízszintes metszetei mentén különböző magasságokban (y/H=0.1, 0.5, 0.9 [-])

III. b) By comparing the thermal transmittance calculation methods listed above I have concluded, that:

- ***The hitherto unknown accuracy of using the NFRC 100-2010 / ISO 15099 based standard calculations for predicting overall thermal transmittance of traditional double-skin box type windows is within ±10% when compared to 3D CFD/conjugate heat transfer simulations. The use of the standards tends to overpredict heat transfer.***
- ***The standard calculations' accuracy is increased by using 3D heat conduction simulations instead of 2D component simulations.***
- ***The NFRC 100-2010 / ISO 15099 based calculation method used with the improved correlation for the Nusselt number is more accurate for un-refurbished windows, while it tends to underpredict thermal transmittance for glazing systems with larger thermal insulation. The fact that the new correlation which more accurately predicts the convective heat transfer rate of the CFD simulations fails to increase accuracy in every case demonstrates, that there are multiple sources of errors in the standard method that are important. Based on this it is questionable that it would be possible to increase the standards' accuracy further by only modifying the way the air layer's equivalent thermal conductivity is calculated.***

Finding IV. - *A proposed new methodology for treating windows installation thermal bridges in the simplified calculation of non-repeating thermal bridge corrections of external walls*

The constructional and thermal properties of windows are in strong connection with the thermal bridges that are created at their interface with the surrounding wall. When comparing different window options it is necessary to calculate the window installation thermal bridges too as they can show opposite tendencies than the U_w value of the windows (see in Bakonyi and Becker [1]). To study the effect this window installation thermal bridge has on the overall heat transfer I created a new method for the simplified calculation of non-repeating thermal bridges in external walls. In the process of deriving this methods I created an algorithm to generate virtual façade geometries and perform detailed thermal transmittance calculations and compute accurate thermal bridge correction factors. I demonstrated that these factors are in a near-linear relationship with the specific length of thermal bridges depending on the building typology and a few constructional parameters (thermal insulation thickness, position and detail quality). Based on the analysis of thousands of automatized detailed heat transfer calculation results. I have realized that the simplified thermal bridge correction in the current national building energy calculation method [10] can under- or over-predict the effect of non-repeating thermal bridges in the overall thermal transmittance of external walls. This becomes highly important when governmental grants for energy reduction measures with thermal insulation are awarded based on savings calculated with this unreliable method. With the help of the new method I have demonstrated that it is not possible to create thermal bridge correction factors with acceptable accuracy that are not dependent on the building type and main constructional parameters.

The essence of creating a simplified calculation method is identifying the most important influencing factors and the reduction of the necessary input parameters to a minimum, without sacrificing too much accuracy when compared to more detailed but time-consuming calculation methods. I set out to refine the new model with this in mind. During the development I have investigated the effect of window installation type and installation thermal bridge on the value of the thermal bridge correction factor, and found it to be significant. The effect is too big to be ignored, but the extremely large space of window and window installation options make it unfeasible to incorporate them all into the calculation. Window and window installation type can’t be simply expressed mathematically (unlike e.g. thermal insulation thickness) and different variants can’t simply be interpolated between. These realizations led me to propose that that the window-to-wall interface’s thermal bridge is to be accounted for in the windows’ thermal transmittance and be removed from the set influencing the walls’ average U value.

I published my findings in Bakonyi [2], Bakonyi and Dobszay [4] and Bakonyi and Dobszay [6] and can be summarized as follows:

IV. a) I have demonstrated a new method that is capable of calculating the thermal bridge correction factor for the external walls of buildings with well typifyable facades and well specified constructions with much higher accuracy than the existing method in the Hungarian national building energy regulation, and without increasing the calculation workload considerably. I have derived and tested the method for three distinct, ubiquitous building types: 19th century urban apartment buildings, rural and suburban single storey houses based on type plans (‘cube houses’) and ca. 1960’ urban apartment buildings based on type plans and built with prefabricated wall blocks (‘block houses’).

IV. b) With the help of the new simplified thermal bridge correction method and the evaluation may thousands of automated calculations I have concluded that the effect of the window installation thermal bridges is best not incorporated into the thermal bridge correction of the external wall, but instead into the thermal bridge corrected $U_{w,install}$ thermal transmittance of the window. This is the only way to avoid large calculation errors when comparing different window options without a constant re-calculation of the entire wall's thermal bridge corrected thermal transmittance, as well as the only possibility to keep the number of necessary input parameters of the proposed simplified thermal bridge calculation method at a practical level. I made the modification to the new proposed method for all three building types mentioned above, and demonstrated the possible reduction in the number of influencing parameters and overall complexity .

$$U_{w,inst} = \frac{A_w U_w + \sum_{i=1}^{n} l_i \psi_{install,i}}{A_w}$$

where: $U_{w,inst}$ [W/m^{2}K] – the installation thermal bridge corrected window thermal transmittance
- A_w [m^2] – the window surface area
- U_w [W/m^{2}K] – the standard window thermal transmittance
- l_i [m] – the length of the ith window installation thermal bridge
- $\psi_{install,i}$ [W/mK] – the linear thermal transmittance of the ith installation thermal bridge

$$\dot{Q}_{trans} = \sum_{p=1}^{z} A_p U_p \left(1 + \chi_{new,p}\left(\frac{\sum l_{tb}}{A_p}, ...\right)\right) + \sum_{k=1}^{q} A_{w,k} U_{w,inst,k} + \sum_{j=1}^{m} l_j \Psi_j$$

where: $\dot{Q}_{trans}$ [W/K] – the total heat transfer coefficient of the external environment
- A_p [m2] – the surface area of opaque construction p
- U_p [W/m2K] – the thermal transmittance of opaque construction p
- $\chi_{new,p}$ [-] – the thermal bridge correction factor of opaque construction p calculated with the proposed new method
- $A_{w,k}$ [m^2] – the surface area of window k
- $U_{w,inst,k}$ [W/m^{2}K] – the installation thermal bridge corrected thermal transmittance of window k
- l_j [m] – the length of plinth / basement wall detail j
- ψ_j [W/mK] – the linear thermal transmittance of plinth / basement wall detail j

V. - *Fenestration heat balance calculations to support the design decisions in the retrofit of historical double-skin box type windows*

A frequent problem when designing the refurbishment of traditional windows is that design decisions are not supported by heat balance calculations of suitable accuracy. In Bakonyi and Dobszay [5] I published the new methodology and calculation software developed for a specific design project and the experiences gained during their development and use. Based on a review of the relevant literature and my own experiences I have concluded that a single-zone or room based dynamic building energy simulation is the minimum level of modeling complexity required to capture all of the fenestration related heat transfer effects needed to accurately compare different window options. The creation of a new program, as opposed to the use or modification of existing software, was necessary to seamlessly integrate all current and future findings regarding the thermal modeling of tradition double-skin box type windows and to start the development of a dedicated design tool. My results are summarized as:

V. a) I created a single zone dynamic building energy simulation program package, EPICAC BE, explicitly optimized for historic buildings and traditional double-skin windows, to perform fenestration heat balance simulations and test custom algorithms. I performed the validation of the program with the help of the IEA BESTEST suit of simulation test cases which is a method recognized by researchers and software developers alike. EPICAC BE met all of the relevant test requirements.

V. b) With the help of the new program I have demonstrated that in certain situations it is possible for alternate retrofit solutions, such as the use of higher thermal transmittance but higher g value glazing system in combination with dynamically controlled shading devices, to reduce the heating and cooling energy demand of valuable historic box type windows further than it is possible with thin IG units (even with the same shading devices). During the planning of window refurbishments for a prestigious Hungarian national monument this allowed the creation of a design concept that suits the combined building energy and monument preservation goals better than previous design practices.

V. c) A detailed sensitivity analysis of the models for the above mentioned design project demonstrated that the calculated heating and cooling energy demand in a window heat balance model is highly sensitive, besides constructional and environmental parameters, to a number of building use and occupant behavior factors. I have demonstrated that though this limits the possibilities for very accurate predictions of energy demand the near-linear and monotonic influence of the main uncertain parameters still allow for a very consistent prediction of relative ranking between individual design options as well as the prediction of relative energy savings.

V. d) Based findings of the previous points I created a new proposed design methodology for refurbishment projects of valuable historic windows in the preliminary, design and validation phases. In addition to the elements of current domestic and international practice the new methodology incorporates the methods of heat balance calculations and modifications to the preliminary surveys required to increase the accuracy and reliability of said calculations. I have demonstrated that the design methods and guidelines found in the literature and widely used at home and abroad do not necessarily lead to optimal solutions for realistic complex requirements. The use of proper design methodology and suitable simulation tools can lead to alternate options that do not require the irreversible destruction of even parts of the window stock.

3. Acknowledgements

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4. My publications of the new scientific findings in the thesis

[1] Bakonyi D., Becker G. (2011) The heat transfer coefficient of traditional box type windows respecting the effects of the window-to-wall interface (in Hungarian) In: Horváth S., Pataky R. (Eds.) II. Épületszerkezettani konferencia: épület- és szerkezetfelújítás, Deparment of Building Constructions, Budapest University of Technology and Economics, Budapest, Hungary, 21-22. November 2011, pp. 10−18, ISBN: 978-963-313-043-8

[2] Bakonyi, D. (2013) The role of thermal bridges in reducing the energy usage of buildings with valuable historical facades (in Hungarian), In Horváth, S., Pataky, R. (Eds.) *IV. Épületszerkezettani konferencia, Vízszigetelések*, Department of Building Constructions, Budapest University of Technology and Economics, Budapest, Hungary, 19 November 2013, pp. 100−107, ISBN: 978-963-313-092-6

[3] Bakonyi, D., Becker, G. (2014) Possibilities of simulations in the planning of the retrofit of historical double skin windows, *Advanced Materials Research Journal*, Vol. 899, pp. 155-160, DOI: 10.4028/www.scientific.net/AMR.899.155

[4] Bakonyi, D., Dobszay G. (2014) A proposed methodology for the improvement of the simplified calculation of thermal bridges for well typified facades, *Periodica Polytechnica, Civil Engineering*, Vol. 58, pp. 309−318, DOI: 10.3311/PPci.7215

[5] Bakonyi, D., Dobszay, G. (2016) Simulation aided optimization of a historic window's refurbishment, *Energy and Buildings*, Vol. 126, pp. 51-69, Accepted for Publication, DOI: 10.1016/j.enbuild.2016.05.005

[6] Bakonyi, D., Dobszay, G. (2016) Simplified calculation of non-repeating thermal bridges of the typical Central-European small suburban houses, *Pollack Periodica*, Accepted for Publication

[7] Bakonyi, D., Dobszay, G. (2016) Thermal models for box type windows – Part 1: A review of the flow characteristics and convective heat transfer calculation of very large glazing cavities, *Periodica Polytechnica-Architecture*, Accepted for Publication

[8] Bakonyi, D., Dobszay, G. (2016) Thermal models for box type windows – Part 2: A new dedicated correlation for predicting convective heat transfer in the very large glazing cavities of box type windows, *Periodica Polytechnica-Architecture*, Accepted for Publication

[9] Bakonyi, D., Becker, G. (2016) Evaluation of fenestration thermal transmittance calculations for historical double-skin box type windows, *Magyar Építőipar*, Accepted for Publication

5. Other references in this booklet

[10] 7/2006 (V. 24.) (2006) Decree of Minister without portfolio about the determination of energy efficiency of buildings (in Hungarian) Hungarian Ministerial Decree

[11] Benitz-Wildenburg, J. (2009) Energetische Sanierung von Kastenfenstern im Zeichen der EnEV, IFT Rosenheim, e-print: https://www.ift-rosenheim.de/documents/10180/177163/FA_GET0910.pdf/c9b12b14-6d50-4bea-a71e-1e39289b8fcd

[12] EN 410 (2011) Glass in building. Determination of luminous and solar characteristics of glazing

[13] EN 673 (2011) Glass in building. Determination of thermal transmittance (U value). Calculation method

[14] EN 10077-1 (2006) Thermal performance of windows, doors and shutters - Calculation of thermal transmittance - Part 1: General

[15] EN 10077-2 (2012) Thermal performance of windows, doors and shutters - Calculation of thermal transmittance - Part 2: Numerical method for frames

[16] Gärtner, M., Gerner, D. (1196) Historische Fenster. Entwicklung, Technik, Denkmahlpflege, Verlag Deutsche Verlags-Anstalt DVA, Stuttgart, ISBN: 3421031045

[17] Holste, F., Urban, A., Wilken, M. (1996) *Erhaltung der Kastenfenster durch gezielte Verbesserungsmaßnahmen*, Report: Für das Bundesministerium für Raumordnung, Bauwesen und Städtebau (BM Bau), Bonn, IFT Rosenheim, ISBN: 978-3-8167-4778-9

[18] Homb, A., Uvslok, S. (2012) Energy Efficient Windows with cultural value, Measurements and calculations, Technical Report, SINTEF Byggforsk

[19] ISO 15099 (2003) Thermal performance of windows, doors and shading devices - Detailed calculations

[20] Laustsen, J. B., Jensen, C. F., Svensdsen, S. (2007) Calculation procedures for determination of the energy performance of windows with large glazing distance, Report, Technical University of Denmark

[21] Mach, T., Grobbauer, M., Götzhaber, W. (2013) Dankmalaktiv I – Sanierung alter, denkmalgeschützter Gebäude auf Aktivhausstandard?, Report, e-print: http://www.get.ac.at/tl_files/Download/Endberichte/Publizierbarer_Endbericht_denkmalaktiv_I_31052013.pdf

[22] Neumann, H., Hinz, D., Müller, R., Schulze, J. (2003) *Fenster im Bestand - Grundlagen der Sanierung in Theorie und Praxis*, Expert Verlag, 1. Edition, ISBN: 3-8169-2203-1

[23] NFRC 100-2010 (2010) Procedure for Determining Fenestration Product U-factors

[24] Pilkington (1997) Sanierung von Verbund- und Kastenfenster mit K-GLAS, Technical information brochure

[25] Schrader, M. (2001) *Fenster, Glas und Beschläge als historisches Baumaterial*, Anderweit Verlag GmbH, Suderburg-Hösseringen, ISBN: 3-931824-04-7

[26] Smith, N. (2012) Thermal performance of secondary glazing as a retrofit alternative for single-glazed windows, Energy and Buildings, Vol. 54, pp. 47-51, DOI: 10.1016/j.enbuild.2012.07.038

[27] Verband Fenster und Fassade (VFF) (2003) HO.09 Runderneuerung von Kastenfenstern aus Holz, Report