BUDAPESTI UNIVERSITY OF TECHNOLOGY AND ECONOMICS
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THE THERMAL MODELING OF TRADITIONAL DOUBLE-SKIN BOX TYPE WINDOWS

Kéthéjú történeti ablakok hőtechnikai modellezése

Thesis statements
(Preliminary)

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2016

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, but with a 10-20 [cm] thick air cavity enclosed between them to provide increased thermal resistance. These constructions were the end 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 sub-varieties 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. These windows contribute significantly to the original architectural character of the buildings they are installed in, and thus their preservation should be a major question in dealing with historical buildings.

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. [18], Gärtner et al. [12], Schrader [21] or Holste et al. [13], 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" [23] 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:

- the investigation of glazing area heat transfer models' ability to calculate glazing systems with very large but low vertical aspect ratio cavities,
- 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,

- investigating the accuracy of models to derive overall (complete window) heat transfer indices from component results to give acceptable results for box type windows,
- creating and validating models for the interaction between transmission and in/exfiltration heat transfer in the large unsealed glazing cavities of box type windows
- investigating the calculation methods of window-to-wall interface heat transfer with regards to their ability to accurately compare different window options,
- investigating the possibilities to accurately model the hygrothermal behavior of box type windows and their installation details,
- the specification of 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.

Since box type windows are a regional construction research interest in their thermal modeling is also localized and such a comprehensive study is 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. [13] and in [20] were not compared with calculations and are not documented in great enough detail to be useful for further study. Homb et al. [14] 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. [22], 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. [16]. Another noteworthy work is published by Brandl and Ruisinger in [17]: 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 more consistent methodology is needed to investigate and possibly increase the reliability of box window thermal and hygrothermal modelling. A combination of all the elements found in the existing literature expanded by the study of fundamental fenestration thermal and hygrothermal modeling principles. However, the entire program of all of the topics listed earlier far exceeds the possible scope of a single doctorate thesis. The work needs to be divided into smaller, manageable parts in a suitable order. The goal of this thesis is to make the first steps along this road, by focusing on questions of thermal transmittance, thermal bridging and heat balance calculations.

2. Summary of scientific findings

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. 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 texts, nor are there any references given to the research works they were based on.

An analysis of the models and a detailed literature survey reveals that the main assumptions are, that:

- the heat transfer in glazing cavities is approximatively one-dimensional,
- the natural convection in 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.

Published in Bakonyi and Becker [2] and Bakonyi and Dobszay [6] I have reached the following conclusions:

I. a) With a detailed survey of the relevant literature I have shown what the implicit simplifying assumption in the fenestration thermal calculation standards are. With identifying their source in the primary literature I could determine their intended range of validity.

I. b) I have demonstrated that in the cavities of double-skin box type windows, merely due to their different cavity thickness and vertical aspect ratio range, a radically different natural convection flow regime is encountered (a turbulent boundary layer flow instead of a laminar conduction regime flow) which lies outside the validity range of the standardize fenestration thermal models.

[1] EN 410 [8], 673 [9], 1077-1 [10], 1077-2 [11]
[2] ISO 15099 [15], NFC 100-2010 [19]

I have performed a simple 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. Using a CFD model, validated based on measurement results found in the literature, I performed a large parameter study to create 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. The temperature stratification in the core of the cavity was also investigated.

In Bakonyi and Dobszay [7] I have published the following results:

II. a) By fitting a new set of empirical equation 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)

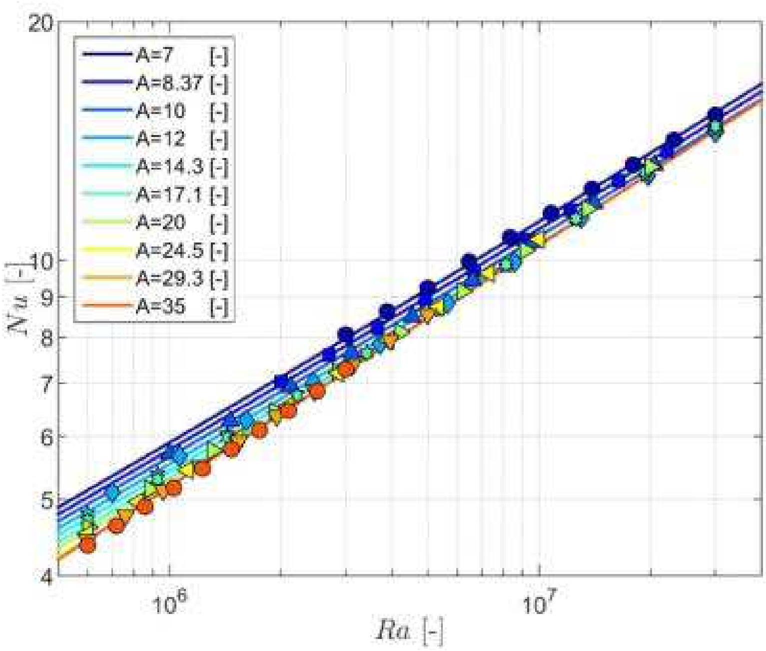

Fig. 1. – the new Nusselt number correlation (derived for the large cavities of double-skin box type windows) compared to parameters study datapoints it is based on

II. b) By studying the dimensionless temperature field in the cavities of box type windows it can be concluded that they constitute a transition point between near-rectangular and high 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). I summarized the results of the study in a new correlation for the vertical temperature stratification:

$$f = 0.5 + 0.8963 \cdot b + 0.0159 \cdot b^2 - 1.5771 \cdot b^3 - 0.0341 \cdot b^4 + 5.2452 \cdot b^5 ...$$
$$-0.0238 \cdot Ar \cdot b - 0.0010 \cdot Ar \cdot b^2 + 0.1176 \cdot Ar \cdot b^3 + 0.0025 \cdot Ar \cdot b^4 - 0.1282 \cdot Ar \cdot b^5$$
$$b = \left(\frac{y}{H} - 0.5 \right)$$

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

The model in the study was then extended to the whole glazing system (the glazing consisted of typical 3 [mm] thick float glass panes) 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 asses the condensation resistance of box type windows. Therefore:

II. c) I have stated that the standard fenestration heat transfer models that rely on only one-dimensional calculation for quantifying the heat transfer and temperature field in glazing systems and neglect the temperature stratification can not be used for assessing the condensation resistance of double-skin box type windows as they can not predict minimum surface temperatures.

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 in the standard fenestration models and 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 a 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.

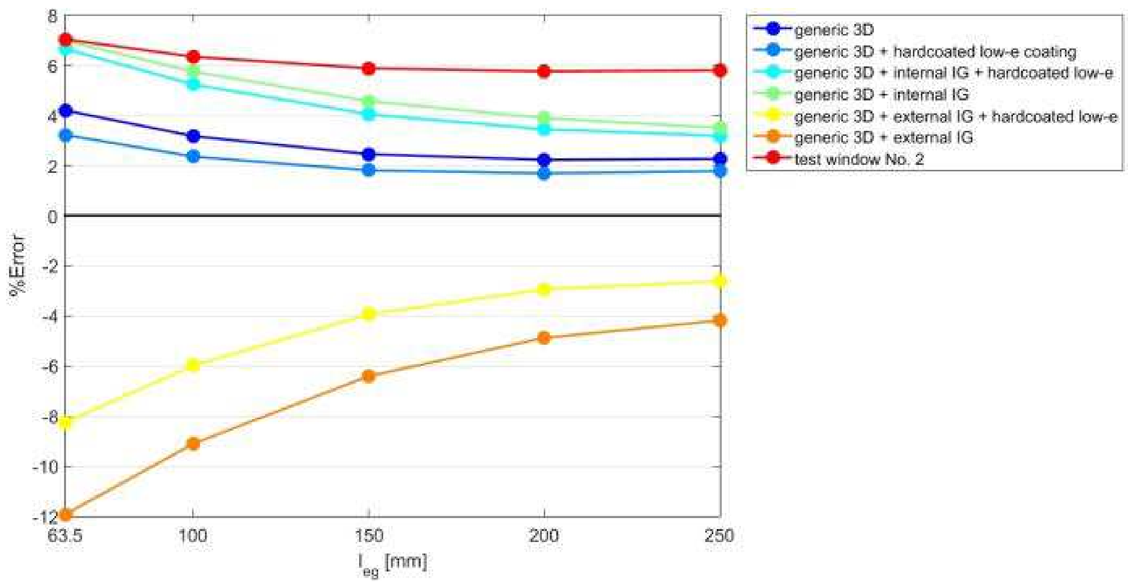

Fig. 2. – %Error in Uw between 2 and 3D calculation for box type windows with different glazing systems, investigated as a function of leg (the width of the edge-of-glass area)

I summarized my findings as[3]:

III. a) I performed a comparative study of standardize conduction-only fenestration thermal transmittance models with 3D thermal and 3D CFD/conjugate heat transfer models for a set of generic and a realistic box type window geometries, with the help 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 the fullness of even the 2D heat flow and results in large errors when compared to 3D thermal calculations. I concluded that the edge-of-glass are 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.

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

- ***the NFRC 100-2010 / ISO 15099 based standard calculations can predict overall thermal transmittance with an accuracy of only ±10%,***
- ***the 3D thermal simulations are generally closer to the CFD results as even the improved 2D calculations,***
- ***that the NFRC 100-2010 / ISO 15099 based standard calculation tends to overpredict thermal transmittance***
- ***the NFRC 100-2010 / ISO 15099 based calculation method 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 difference in calculated thermal transmittance with hard coated low-e glazing in the internal or external position, which is only predicted by CFD simulation, highlights the importance of three-dimensional infrared radiation effects that are neglected by the standard models.***

[3] The publication for these findings has not been finalized jet

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. 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 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 [8] 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 [1], Bakonyi and Dobszay [3] and Bakonyi and Dobszay [5] and can be summarized as follows:

IV. a) I have demonstrated a new method that is capable to calculate 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 proposed new simplified thermal bridge correction method I have demonstrated that in order to create truly general simplified wall thermal bridge correction methods, without sacrificing accuracy, account of the window-to-wall installation thermal bridge must not be taken in the wall’s thermal bridge correction, but must instead be incorporated into $U_{w,inst}$, the window thermal transmittance coefficient in the installed state. I made the modification to the new proposed method for al three building types mentioned above, and demonstrated the possible reduction in the number of influencing parameters and overall complexity .

In Bakonyi and Dobszay [4] I published the results of my investigations into the area of fenestration heat balance calculations in historic buildings with box type windows. These 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 test requirement.

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 on the experiences gained with the program, the experiences of the introduced design project and the results of the detailed sensitivity analysis I created a new proposed design methodology for refurbishment projects of valuable historic windows. 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

I would like to thank all of my colleges for their help and support in creating this thesis, with special thanks to my supervisor Dr. Gábor Becker, and Dr. Gergely Dobszay.

I would also like to thank Dr. János Várfalvi and Tamás Orbán for their generous help in performing a hygrothermal monitoring of a box window in the university building, which although did not fit into the scope of this work, nevertheless helped to start me in my research and will be the subject of future publications.

I am also obliged to Dr. Árpád Veress at the Budapest University of Technology and Economics' Department of Aeronautics, Naval Architecture and Railway Vehicles for his advice and support with the CFD simulations.

I would also like to thank Imre Papp and Péter Sólyomi at the ÉMI Minőségellenőrző Innovációs Nonprofit Kft. for the access to their Building Constructions laboratory, and their patience and untiring help in the hot box measurements. For the test windows, materials and manufacture of the hot box apparatus for these measurements I am also grateful to Károly Vigh and the entire Hofstädter Kft. For the financial support of the measurements I thank the ODOO+ project (a "SolarDecathlon versenyen eredményes BME ODOOprojekt további hasznosításának vizsgálata " c. projekt, illetve az azt támogató „Új Széchenyi Terv ED_13-1-2013-0005 programja" keretében).

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