Implications of Model Complexity for the Simulated Thermal Behavior of a Casement Window

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Abstract. Windows have been a subject of interest for research in building industry due to their multifaceted and significant implications for indoor environmental quality and energy use. In this context, the present contribution explores the retrofit opportunity toward retrofit of casement windows via application of vacuum glazing. The first scenario included conductive and convective heat transfer processes. The second, more detailed scenario took, in addition, the effects of (long-wave) radiation phenomena into account. The main objective of the present contribution is thus to contrast the results obtained from primarily conductive and convective computations with those that involve a detailed coupled conductive, convective, and radiation simulation. The study benefits from a CFD (Computational Fluid Dynamics) model to evaluate the airflow patterns (temperature and velocity) within the window's interstitial space by assuming isothermal boundary conditions. Based on simulation results, the thermal performance of the retrofitted casement window (with vacuum glass applied as external pane) can be compared to the conventional construction. Thus, benefits in terms of reduced energy use and surface condensation risk can be documented.

1. Introduction

Energy consumption associated with buildings has a considerable impact on the environment [1]. Building sector consumes 35.3% of final energy demand [2]. There is a need to consider passive design options (e.g., building construction, orientation, and envelope) more carefully and to enhance indoor air quality by energy-efficient means [3]. Regarding thermal insulation of windows, designers should consider special attention toward improving the pertinent properties of the frame and glazing [4].

A large number of windows in central Europe originating from the middle of the 19th century to the middle of the 20th century are double layered, so called box type windows (casement windows, or, in German: "Kastenfenster") [5]. The cavity of box type windows is not sealed like an IG (Insulating glass) unit, and it is formed not by small spacer bars but with the distance between two layers of sashes. In order to reliably estimate the heat transfer intensity through a box window, the consideration of the convective and radiative heat transfer in the cavity and conduction in the solid bodies of the frame is necessary [6]. Recent studies suggest that traditional casement windows can be thermally retrofitted by installing vacuum glazing instead of float glass in external or internal wings. Thereby, the focus of the studies was predominantly on conductive heat transfer and applied thermal bridge analysis of the conventional and retrofitted casement windows [7].

Numeric heat transfer for analysing multi-pane windows' thermal performance (which basically has focused on free convection in the cavity) has been studied in previous research [4, 8, 9, 10]. There are
also few studies on conduction and convective heat flow in casement windows. However, the effects of (long-wave) radiation phenomena have not be sufficiently addressed.

In this context, this paper includes an investigation of the coupled conductive, convective, and radiative heat transfer through a casement window. Thereby, three scenarios are considered, namely a conventional casement window construction, one with vacuum glazing installed in the inner layer, and one with the vacuum glazing in the outer layer. The analysis was performed using the commercially available ANSYS FLUENT 19.1 CFD code [11]. The two-dimensional steady-state analysis resulted mainly in computed temperature and velocity fields for winter conditions.

2. Methodology

Accurate consideration of material properties and boundary conditions is essential for obtaining reliable thermal performance results [4]. To address the mentioned research objectives, a conventional casement window with interstitial space of 150 mm and two operable wings (see schematic illustration of Figure 1 for the retrofit case with vacuum glazing in the external wing) was used for two-dimensional heat transfer analysis. Table 1 summarizes the thermal conductivity of the window components. The conductivity assumptions are based on the setup of the SYNERGY glass [7,12].

![Figure 1. The schema of the casement window (retrofitted with application of vacuum glazing at the external wing)](image)

| Table 1 | Thermal conductivity assumptions (in W.m$^{-1}$.K$^{-1}$) of the constitutive elements of the selected casement window (see Figure 1) |
|-------------------|----------------------------------------------------------------------------------|
| 1. Window putty | 0.375 | 2. Lime glass | 1 | 3. Wooden frame | 0.11 | 4. Mineral insulation | 0.045 | 5. Window seal | 0.3 | 6. Silicon | 0.24 | 7. Glass | 1 | 8. Vacuum layer | 0.000975 | 9. Edge seal | 1 |

Vacuum glazing construction involves heat strengthened low-e vacuum glass with two 4 mm-thick glass panes, a 0.15 mm thick vacuum layer, 8 mm edge sealing, outside and inside radius of stainless support pillars of 0.30 mm and 0.15 mm respectively. Support pillars were assumed to be spaced on a 40 mm grid [7].

To study the temperature and velocity fields in the casement window, we assumed no infiltration in the interstitial space as well as the following boundary conditions was considered for the indoor and the
outdoor space; the reference indoor and outdoor temperatures are assumed to be 20 °C and -10 °C respectively. Special attention must be paid regarding convective heat transfer coefficient assumptions [13, 14, 15, 16]. In this study, we used the calculation procedure described in DIN EN ISO 10077-1 [17] and the included internal and external convective heat transfer coefficients of 7.7 and 25 W.m⁻².K⁻¹.

To investigate the thermal performance of the casement window, the following steps were undertaken:

1. Generating the geometry model
2. Settings of boundary conditions (indoor and outdoor temperatures) and material properties.
3. Numeric Simulation (using ANSYS FLUENT 19.1 CFD code)
4. Post-processing of simulation results.

The following CFD settings were applied to address the mentioned research objectives:

The applied CFD code uses a control-volume method to solve the coupled heat and fluid flow equations [18]. The computational approach [19] involved two-dimensional, steady-state, double precision calculation with temperature dependent thermophysical properties for the fluid (air), constant properties for solid materials, incompressible ideal gas model for the buoyancy forces, the SIMPLE (Semi-Implicit Model for Pressure-Linked Equations) pressure based solver, the Pressure Stagging Option (PRESTO) scheme (to find the pressure values at the cell faces), the Quadratic Upstream Interpolation for Convective Kinetics (QUICK) scheme for the momentum. Shear Stress Transitional (SST) k-ω turbulence model is suggested to simulate turbulent natural convection in a differentially heated 2D cavity [20, 19]. Discrete ordinates method (DOM) was deployed as it is reported [21] to provide better accuracy in radiative energy transfer modeling in CFD simulations. In this study the internal emissivity of the glass is assumed to be 0.94.

Due to a highly complex geometry, as well as coupled airflow and heat transfer modeling, a very fine grid had to be formed, resulting in a total number of grid elements of 34453.

3. Discussion and results

The window glazing and frame have a considerable effect on the temperature distribution and also on the U-value of the window. In previous research, measurements and a two-dimensional numerical solution have been used to ascertain the thermal bridge effects of windows' edge seals and frames on the temperature distribution along the height of the inner glazing [7].

We conducted heat transfer simulation (conduction, convection, and radiation) of the base case (conventional construction) as well as retrofit versions with installed vacuum glazing in the exterior and interior window wing. The temperature factor at the internal window wing \( f_{Rsi} \) was determined using Equation 1 [22]:

\[
f_{Rsi} = \frac{\theta_{si}-\theta_{e}}{\theta_{i}-\theta_{e}}
\]

\( \theta_{si} \) = temperature at the internal surface at the point with the lowest temperature
\( \theta_{i} \) = the internal temperature,
\( \theta_{e} \) = the external temperature

Table 2 summarized the computed minimum inside surface temperatures and the associated temperature factor values for the three scenarios considered. These results suggest that the retrofitted casement window exceeds the minimum temperature factor value \( f_{Rsi}= 0.71 \) according to the applicable regulation in Austria [23]. However, application of vacuum glazing to the internal wing is not recommended as it results with very low cavity temperatures and increases condensation risk. The calculated \( f_{Rsi} \) values in the inside of the cavity are higher when the window is retrofitted externally. (0.76 versus 0.23).
Figure 2 compares the computed temperature distribution patterns for the aforementioned simulated scenarios. The results of the detailed heat transfer are consistent with previously published results [7]. They suggest that the application of vacuum glazing can significantly reduce the heat transfer rates. Specifically, the external wing retrofit option appears to be a suitable retrofit option given higher surface temperatures and the associated reduction of condensation risk.

### Table 2. Comparing minimum inside temperatures and temperature factors for different types of the window

| Window type                        | Minimum inside surface temperature [°C] | Temperature factor $f_{Rsi}$ |
|------------------------------------|----------------------------------------|------------------------------|
| Conventional casement window       | 7.67                                   | 0.59                         |
| Window with retrofitted internal wing | 13.34                                   | 0.77                         |
| Window with retrofitted external wing | 16.16                                   | 0.87                         |

Figure 2. Temperature distribution in the casement window: (a) original construction; (b) retrofitted external wing; (c) retrofitted internal wing.

Figure 3 shows the airflow velocity distribution for two simulation scenarios (original construction and external wing retrofit). Table 3 provides numeric information regarding the cavity mean temperature and air flow velocity for the same scenarios. As it can be seen from Figure 3 and Table 3, application of vacuum glazing to the external wing significantly reduces the mean air velocity and increases the mean air temperature in the cavity.
Table 3. Mean airflow velocity and temperature at the interstitial space between two wings

| Scenario                        | Mean temperature [°C] | Mean Velocity [m s⁻¹] |
|--------------------------------|------------------------|------------------------|
| Conventional window            | 1.03                   | 0.043                  |
| Retrofitted window (external wing) | 14.64                | 0.030                  |

Figure 4 compares the temperature distribution on the inner glass surface of the internal wing for two scenarios (original construction versus retrofitted external wing). Table 4 summarized computed surface temperatures [°C] at selected locations (see Figure 4) on the surface of the inner glass of the inner wing of the casement window for two scenarios. Note that Figure 4 and Table 4 include also – for the window with external wing retrofit – simulation results that do not include the effect of radiation (i.e., consider only conduction and convection).

Figure 4. Temperature distribution on the surface of the inner glass layer of the internal wing for the original and retrofitted (external wing) scenarios. Results are also included for the latter case without consideration of radiative heat transfer.
Table 4. Computed surface temperatures [°C] at selected locations on the surface of the inner glass of the inner wing of the casement window for two scenarios. Results are also included for the latter case without consideration of radiative heat transfer.

| Points | Conventional windows | Retrofitted window (conduction+convection) | Retrofitted window (conduction + convection + radiation) |
|--------|-----------------------|--------------------------------------------|--------------------------------------------------------|
| A      | 2.31                  | 10.55                                      | 13.73                                                  |
| B      | 7.46                  | 16.63                                      | 16.37                                                  |
| C      | 7.83                  | 17.28                                      | 16.69                                                  |
| D      | 8.66                  | 18.34                                      | 17.11                                                  |
| E      | 9.19                  | 18.73                                      | 17.04                                                  |
| F      | 11.89                 | 19.32                                      | 17.33                                                  |

As Figure 4 and Table 4 clearly illustrate, application of vacuum glazing to the external wing significantly increases the window's inside surface temperatures. Generally speaking, retrofitting the window in this way, increases mean cavity temperature and inner glass surface temperature. Moreover, it reduced the mean airflow velocity in the cavity as well as the overall heat loss rate through the construction.

As mentioned before, heat transfer process in casement windows are highly complex, as they involve combined conduction, convection, and radiation. Hence it is necessary to consider fluid flow to find convection effect as well as using either view-factor or raytracing techniques to find radiation effects inside the cavities. However, because of the computational resources and additional modeling efforts required, these simulations are rarely done in fenestration design software tools [24]. To discuss this issue, Figure 4 and Table 4 included also information regarding the temperature distribution on the surface of the retrofitted window scenario (external wing) without the inclusion of radiative heat transfer in the computation. Both models (with and without consideration of radiation) imply the presence of thermal stratification in the cavity due to natural convection. However, considering radiation in the heat transfer simulation results in a more uniform temperature distribution in the whole cavity. As such, the computed minimum indoor surface temperature was higher when the radiation effect was considered, whereas the maximum indoor surface temperature was lower.

Hence, the calculated $f_{RSI}$ values in this study are higher when the radiation effect is considered. (0.84 versus 0.87).

4. Conclusion

In the present contribution we investigated the thermal behaviour of the casement window with application of vacuum glazing as a retrofit option. We conducted heat transfer simulation (involving conduction, convection and radiation) of retrofit scenarios with installed vacuum glazing in the exterior and interior window wing.

The results of the CFD simulations suggest that the application of vacuum glazing to the external wall of a casement window may be the most suitable retrofit option given the computed temperature distribution and condensation risk. In addition, this study highlighted the non-negligible implication of including radiative effects in the simulation. Hence, to obtain more consistent and reliable results, a comprehensive mode of computation may be necessary, involving conductive, convective, and radiative heat transfer processes.

Future efforts are expected to address and remedy the limitations of the present study, namely the restriction to two-dimensional and steady-state computations. Moreover, a larger number of construction options and boundary conditions must be considered.
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