Using CFD software for the evaluation of hygrothermal conditions at wall-window perimeters

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Abstract. This article evaluates the results of heat and moisture analyses for areas adjacent to a window, mounted in various ways to an external wall. The parameters for the window were assumed to be constant. The calculations were focussed on evaluating the effect of installing a window in a wall and the influence of the wall's construction on the quality of the microclimatic conditions in the contact zone of these two components. The following variables were analysed: a partition without insulation, a partition with thermal insulation, with additional expanding tape and with additional aerogel mat. Each the variable was additionally diversified with respect to the location of the window within the wall. The influence of the material used for the load-bearing wall layer was also analysed in the simulations. The variables were modelled using CFD (computational fluid dynamics) software. For all variables, the cumulative value of heat flux and linear thermal transmittances were calculated. Additionally, distributions of the 0 isotherm were determined and the fRsi temperature factors were calculated. These results have been thoroughly analysed to determine the most beneficial solution that provides optimal thermal insulation and reduced risk of mould. Our findings can help ensure the maintenance of an ideal microclimatic conditions and reduced energy wastage in the contact zone of windows with external walls.

1. Introduction

One of the requirements of energy-efficient buildings is the airtightness of the building envelope and any possible contact zones of the components. Ensuring proper airtightness and thermal insulation requires, among other things, the appropriate joining of the windows with the wall. Insufficient amount of attention given to these details may reduce the benefits of installing well-insulated windows in walls meeting the requirements for thermal transmittance U. Wrong product installation can also result in the occurrence of air leakages and thermal bridges. In the energy balance of buildings, in addition to heat losses due to air leakages, thermal bridges play an important role. While the modern construction and material solutions for building partitions and window frames contribute to the reduction of heat loss, their joining in sensitive areas still remains vulnerable. Therefore, more attention should be paid to the methods of joining windows with partition walls in order to minimize its effect on heat loss.

A similar problem was already discussed in article [1]. The article assessed the influence of the window frame location in the window opening on the reduction of the effects of thermal bridges. Five different wall constructions with two windows of different thermal transmittance U values were studied. The results of the thermal simulations demonstrated that the window location has a decisive influence on the amount of cold bridge energy loss. For each type of wall, optimal window location was found. In some cases, placing the windows in the most energy efficient location reduced the linear thermal...
transmittance by more than 50%. Within the studied window locations, the temperature on the inner surface of the windowpane groups was weakly dependent of the window location.

Variant installation of windows in ceramic wall also evaluated in [2], using simulations generated by the THERM software. The results showed a consistent reduction of up to 75% of linear thermal transmittance as a result of moving the window from the internal to the external position.

In turn, the paper [3] presents the results of studies on the airtightness of the window-wall interface in 13 different installation variants. The obtained results proved that it is possible to obtain very high performance using the polyurethane foam, hermetic membranes, plywood frame and plaster and seal. The authors conclude that in locations where good airtightness is required, mineral fibre, partial polyurethane filling and plaster without seal should be avoided.

The work [4], on the other hand, analyses the influence of windows located in the lintel area. Six installation variants were investigated. The resulting $\psi$ values and the $f_{bld}$ were assessed. The study confirmed the importance of the window position in the improvement of thermal properties and the avoidance of condensation in this area.

The authors of [5] focused on the influence of the material of the lintel beam and its design on the heat flow through exterior wall with a window. Such beams are used as supporting elements in the installation of windows in the thermal insulation layer. The study analysed temperature distribution in the wall, the $0^\circ$C isotherm gradient and the possible occurrence of condensation inside the wall. Based on the results of numerical analysis and experimental tests, it was found that moving the window towards the insulation layer using a mounting element made of high-performance materials and increasing the thickness of the insulating layer in the outer wall eliminates the risk of condensation.

An important element of the study is also the solution applied in the window frame construction. Numerical CFD simulations, this time only for the window frame, were presented in paper [6]. The study demonstrates the two-dimensional numerical method for the evaluation of the thermal behaviour solely of the framework.

Other research concerning minimization of windows thermal bridges were described in [7] and [8]. In the research [7], a new innovative insulating coating which can be used to limit thermal bridge effects was evaluated. In addition, the authors computed the cooling/heating load coming from the windows offset thermal bridges of a typical French house before and after adding the insulating coating.

The authors of [9] demonstrated an application of the quantitative infrared thermography technique to evaluate the heat losses through windows thermal bridges. This kind of research can be a proper way to confirm CFD simulations. Other thermal imaging measurements analysis were presented in [10].

2. Materials and methods
This article focuses on the solution for the installation of windows in the sill area. The analysis of the solution of this critical zone was performed using the numerical CFD modelling which, as a rule, is used for the simulation of stationary and non-stationary thermal processes [11]. The analysed interface was modelled two-dimensionally. 10 cases were considered presented in figure 1 and figure 2.

Options were diversified in terms of window location in the wall, i.e. in the external face of the wall (variants a) and in the centre of the wall (b). All variants assumed that the window had thermal transmittance equal to 0.830 (W/m$^2$·K). The coefficient $U$ of the concrete 24 cm thick wall was 3.310 (W/m$^2$·K), while total coefficient $U$ of the partition with an extra layer of 15 cm thick foam amounted to 0.218 (W/m$^2$·K).

The simulation included the following variants:
– variant 1 – wall without insulation, windows installed using assembly foam,
– variant 2 – wall without insulation, windows installed using expanding tape, application of aerogel mat on the outside,
– variant 3 – wall with insulation, windows installed using assembly foam,
– variant 4 – wall with insulation, windows installed using expanding tape, application of aerogel mat on the outside,
– variant 5 – wall with insulation, windows installed using styrofoam mould.
Figure 1. The diagrams of walls variants without thermal insulation.

Figure 2. The diagrams of walls variants with thermal insulation.

The computational model was dimensioned in accordance with the [12] standard. In all variants, the same internal $\theta$ temperature of +20°C and external $\theta_e$ temperature equal to -16°C were assumed. The adopted surface resistance of the boundary layer for the outer surface was 0.04 m²·K/W and 0.13 m²·K/W for interior surfaces, while for determining temperatures necessary for the calculation of the temperature factor $f_{Rsi}$ the $R_{si}$ resistance was increased to 0.25 m²·W/K. The horizontal boundaries of the model were identified as adiabatic.
3. Results and discussion
The results obtained were: total heat flux $Q$ [W], thermal coupling coefficient $L^{2D}$ [W/m·K] and temperatures in all three set points of the partition wall shown in figure 1. The third point was placed 15 cm from the bottom of the window sill. The obtained results are collected in table 1 and in figure 5.

Table 1. The total energy of each variant and the thermal coupling coefficients.

| Variant   | $Q$ [W] | $L^{2D}$ [W/m·K] |
|-----------|---------|-----------------|
| Variant 1a | 0.1384  | 3.843           |
| Variant 1b | 0.1365  | 3.791           |
| Variant 2a | 0.1348  | 3.745           |
| Variant 2b | 0.1345  | 3.736           |
| Variant 3a | 0.0274  | 0.760           |
| Variant 3b | 0.0294  | 0.818           |
| Variant 4a | 0.0272  | 0.756           |
| Variant 4b | 0.0286  | 0.795           |
| Variant 5a | 0.0276  | 0.768           |
| Variant 5b | 0.0281  | 0.781           |

The $Q$ values point to clear differences in the variants without wall insulation (variants 1 and 2) compared to insulated walls (variants 3, 4, 5). A more than fivefold reduction in heat flux in favour of the thermally insulated walls was observed. This had its impact on the values of the linear thermal transmittance $\psi$ [W/m·K]. Figure 3 shows the extent of the influence of the window location and the methods applied for the insulation of this zone.

Figure 3. The linear thermal transmittances of the tested variants.

In the case of the first two variants with non-insulated walls and very well thermally insulated windows, it was shown that the use of a short strip of aerogel mat contributes to obtaining better linear thermal transmittance values (negative values of the coefficient $\psi$). In these cases we observe larger losses of heat due to transmittance through walls than in the case of thermal bridges.
In variants 3, 4 and 5, the installation of the window in the insulation layer (variants a), resulted in a reduction of the coefficient \( \psi \) compared to the values obtained in case of centrally positioned windows (b). The most evident influence of the window location was demonstrated in variant 3, where the use of foam more than doubled the values measured. The application of the styrofoam mould under the window sill also proved to be a beneficial option (variant 5). However, the best solution was the use of expanding tape and aerogel mat which, in case of the window being installed in the insulation layer, provided the lowest value of the parameter \( \psi \) compared to solutions proposed in variants 3 and 5.

As a result of the simulations performed, charts showing temperature distribution in the analysed variants were obtained. The example temperature distribution for variants 3a and 3b is shown in figure 4.

![Figure 4. The example temperature distribution for variants 3a and 3b.](image-url)

In turn, figure 5 shows the temperature values for the three critical points in the window-wall interface in the area of the window sill and the wall. In the case of the first two variants, notably the lowest temperatures in all three analysed areas were obtained. In the worst case, the wall surface temperature was even close to 0°C (V1a and V1b). It was demonstrated once again that the application of aerogel mat and expanding tape contributes to the increase of temperatures in all three evaluated points.

In other variants, the obtained temperature values for the second (under the sill) and the third point (on the wall surface) were similar. The effect of window location on the obtained temperature was observed. While the installation of the window in the insulation layer is conducive to the increase of temperatures in these two points, in the first point (on the frame surface) it leads to lower temperature values in relation to the values of the variants where the window was installed in the wall layer.
Another important aspect in the diagnosis of the interface elements of buildings is also the assessment of the risk of surface condensation and the development of mould. Table 2 shows the obtained temperature values in point 1 (according to figure 1a). On this basis, a boundary value for humidity was determined that meets the dew point condition and the value of the $f_{Rsi}$ temperature factor. The results show that the use of adequate insulation in the window installation area by the windowsill increases the temperature in point 1: in the best scenario, even by 9°C. At the same time, it ensures maintaining the temperature factor at a sufficiently high level and above the critical value of 0.72 [13]. This condition is not met solely by the variant 1, in which no insulation in the area of the thermal bridge was used.

What is more, table 2 shows the specified permissible humidity values below which there is no risk of occurrence of condensation based on the dew point temperature. The best results were obtained for the variant 4b, for which the relative humidity would have to exceed 83% in order for the condensation to occur in point 1 within the specified temperature conditions.

**Table 2. The comparison of hygrothermal parameters.**

| Variant | The temperature point 1 [°C] | Boundary humidity that meets the requirements of dew point [%] | $f_{Rsi}$ [-] |
|---------|------------------------------|-------------------------------------------------------------|--------------|
| Variant 1a | 8.04 | 45.92 | 0.67 |
| Variant 1b | 9.25 | 49.84 | 0.70 |
| Variant 2a | 11.27 | 57.05 | 0.76 |
| Variant 2b | 10.67 | 54.82 | 0.74 |
| Variant 3a | 13.74 | 67.09 | 0.83 |
| Variant 3b | 16.84 | 81.85 | 0.91 |
| Variant 4a | 16.52 | 80.21 | 0.90 |
| Variant 4b | 17.06 | 83.00 | 0.92 |
| Variant 5a | 16.08 | 77.99 | 0.89 |
| Variant 5b | 16.77 | 81.49 | 0.91 |

**Figure 5.** The temperature values in the three specified points.
Another important issue is the depth of frost penetration of walls. Data concerning this aspect can be seen in the charts in figures 6 and 7. They present the distribution of the zero isotherms for all the five variants – subdivided to non-insulated (figure 6) and insulated walls (figure 7). Out of all the variants without wall insulation, the most profitable was the variant 2 insulated by means of aerogel mat and expanding tape. The use of such type of insulation significantly shifts the 0°C isotherm towards the negative temperatures.

On the other hand, the 0°C isotherms in the insulated wall variants in all cases show that the freezing area is in the insulation layer. The comparison demonstrates the difference between the variants with windows in the insulation layer and the variants with windows in the central area of the wall. The window installation place has, in these cases, a significant influence on the characteristics of the zero isotherm in the window sill area. For the variant 5b using the styrofoam mould, the values are the least profitable.

Figure 6. The isotherm 0°C distributions of variants without thermal insulation.

Figure 7. The isotherm 0°C distributions of variants with thermal insulation.

4. Conclusions
The article discusses the problems concerning the occurrence of thermal bridges located in the window-wall interface at the height of the window sill. The results of the simulation confirmed the importance of finding an appropriate solution to this issue with regard to the location of window frames in the wall and the application of proper insulation materials. The most profitable method of window installation among the analysed cases is the location of the window within the insulation
layer. The paper also shows the positive effect of the application of aerogel mats and expanding tapes which leads to a decrease in the value of the linear heat transfer coefficient. It was demonstrated that the correct location and insulation of windows in the sill area is important for the prevention of condensation and therefore should be subject to assessment. Moreover, attention was drawn to the problems that arise in the installation of windows in walls with insufficient insulation parameters. In this case, improvements can be obtained by using the aforementioned aerogel mats and expanding tapes.

Another important issue for persons creating energy saving plans for buildings is also the source of the adopted values of the linear thermal transmittance $\gamma$. The linear thermal transmittance of the thermal bridge should be determined according to the standard [12] (numerical calculations) or, by approximation, using the tabulated values specified in the standard [14]. However, the tables included in the standard [14] do not feature many cases relevant to the analysed variants as they do not take into account the newest insulation solutions available nowadays for this critical zone. As a result, this can lead to significant inaccuracies in the calculations of heat loss. It is therefore reasonable to perform simulations for such kinds of thermal bridges and to include in the calculations the exact values reflecting the actual solutions applied.

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