Dependencies of heat transmittance through the ventilated wall system on thermal conductivity of connectors crossing thermal insulation layer

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\textbf{Abstract.} The ventilated facade systems are widely used for improvement of energy efficiency and reducing of heat losses of newly built buildings and for existing buildings. To reduce the influence of point thermal bridges on heat transfer through the ventilated facades, previously often used aluminium alloy connectors as a change to stainless steel and reinforced plastic connectors. Different thermal characteristics of connectors using in ventilated facade systems, significantly influence the heat transfer coefficient of building’s walls. Previous empirical calculations of the heat transfer through ventilated facade walls with different connectors according to standard methodology and numerical modelling showed significant differences in results, therefore experimental research with the fragments of the ventilated facade systems were carried out using a guarded hotbox method.

The aim of this experimental research was to analyse the heat flows through the ventilated wall system with different kind of heat-conductive connectors. Expanded polystyrene foam ($\lambda \approx 0,031 \text{ W/(m}\cdot\text{K})$) was used as thermal insulation material, thickness 300 mm, and three types of heat-conductive connections were installed: aluminium alloy ($\lambda \approx 160 \text{ W/(m}\cdot\text{K})$), stainless steel ($\lambda \approx 17 \text{ W/(m}\cdot\text{K})$) and glass fiber reinforced plastic ($\lambda \approx 0,23 \text{ W/(m}\cdot\text{K})$).

The measurements in the guarded hotbox were useful for analysis of differences in results according to the standard and numerical calculations methods. The experimental studies showed that the results are very close to the numerical simulation results. The empirical calculation method gave similar results to the other two methods, except in the case of highly heat-conductive connectors.

\textbf{1 Introduction}

According to the Energy Performance of Buildings Directive of European Commission, Member States have to set up minimum energy performance requirements for new buildings and for existing ones that undergo major renovation [1]. Consequently today newly built and renovated buildings must meet high energy efficiency requirements. The

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ventilated facade systems are used for both the newly built buildings as well as for the renovated buildings.

In cold climate zones, it is very important to evaluate correctly the influence of point thermal bridges on the heat transfer through ventilated facade systems. The heat-conductive connectors, which cross the thermal insulation layers, have a thermal conductivity that can sometimes be over 4000 times higher than the thermal conductivity of thermal insulation material. A lot of research was carried out to investigate the reduction in heat transmittance of wall constructions due to the influence of linear and point thermal bridges [3-7]. Theodosiou et al. found that the disregard of point thermal bridges in cladding systems of facades could lead to significant underestimation of actual heat flows what can account for 5 % to almost 20 % of the total heat flows through the building envelope [4].

Composite connectors, which combine metal and less heat-conductive materials, are used in the external ventilated wall to reduce heat loss through the walls envelopes instead of metal connectors. Song et al. investigated a few of composite connectors. His study showed that the composite connectors could reduce overall heat losses through the envelope of wall up to 68 % comparing with the conventional metal connectors [8].

There are three options for evaluating the impact of heat conductive connectors on heat transfer. The most commonly used standard methodology is EN ISO 6946:2017 [10], according to which calculates the change in heat transfer coefficient of the structure due to impact of connectors. The influence of thermal bridges can also be assessed using numerical methods [9]. Ji et al. [11] calculated the effective thermal conductivity \( \lambda_e \) of the insulation system with different anchors by using a numerical simulation method. Authors chose different materials of anchors (nylon, steel, stainless steel and aluminium alloy) and different sizes of the anchors (16 mm\(^2\), 36 mm\(^2\), 64 mm\(^2\), 100 mm\(^2\) and 144 mm\(^2\)]. The results showed that the use of the anchors has great negative influences on the effective thermal conductivity \( \lambda_e \) of the insulation system. The effective thermal conductivity \( \lambda_e \) increases with the increase of anchor properties, such as its density, size, thermal properties and length [11]. For example, the use of aluminium alloy anchors in mineral wool insulation system increases \( \lambda_e \) from 0.04 W/(m·K) to 0.1007 W/(m·K), which results in the increase of building energy consumption of 7.4% [11]. The most realistic method of estimating the influence of heat conductive connectors on total thermal transmittance of wall is the measurement of real-size construction fragments by the hotbox method described in standard EN ISO 8990:1999 [12].

The results of previous studies showed that the results of standard and numerical calculations differ significantly, especially when using highly heat conductive aluminium alloy connectors. Therefore, the aim of this study was to compare the results of calculation and measurement and to clarify the reasons for the differences in calculation result.

2 Methodologies

2.1 The empirical calculation method

Calculating the heat transfer coefficient \( U \) of walls fragment, according to the empirical calculation method, the total resistance \( R_T \) of all fragment layers is calculated, from which the thermal transmittance \( U_0 \) without mechanical fasteners is found and the correction of the thermal transmittance due influence of heat-conductive connectors according to Eq.2 is added:

\[
U = U_0 + \Delta U_f
\] (1)
According to the standard EN ISO 6946:2017 [10] the correction to the thermal transmittance is given by:

\[ \Delta U_f = \alpha \cdot \frac{\lambda_f A_f n_f}{d_1} \cdot \left( \frac{R_1}{R_{tot}} \right)^2 \]  

(2)

Where: \( \alpha = 0.8 \) if fastener fully penetrates the insulation layer; \( \alpha = 0.8 \times \frac{d_1}{d_0} \) in the case of recessed fastener; \( \lambda_f \) – thermal conductivity of the fastener (W/(m·K)); \( n_f \) – the number of fasteners per m²; \( A_f \) – the cross-sectional area of one fastener (m²); \( d_0 \) – the thickness of the insulation layer containing the fastener (m); \( d_1 \) – the length of the fastener that penetrates the insulation layer (m); \( R_1 \) – the thermal resistance of the insulation layer penetrated by the fasteners (m²·K/W); \( R_{tot} \) – the total thermal resistance of the component ignoring any thermal bridging.

### 2.2 Numerical calculation method

A more precise calculation of the impact of mechanical fasteners can be obtained by the numerical calculation method validated by standard EN ISO 10211:2017 [9]. Using 3-D finite-difference numerical simulation software HEAT3 (version 6.1.0.0) two models of wall fragment with the same dimensions are designed: with heat-conductive connections and without them. The heat flow through each model is calculated by HEAT3 program and the difference between them indicates the amount of heat flow due to the influence of the connectors. This procedure represents the equality of the standard EN ISO 10211:2017 [9]:

\[ \chi = L_{3D} - \sum_{i=1}^{N_i} U_i \cdot A_i - \sum_{j=1}^{N_j} \Psi_j \cdot l_j \]  

(3)

where \( L_{3D} \) – the thermal coupling coefficient obtained from 3-D calculation of the 3-D component separating the two environments being considered; \( U_i \) – the thermal transmittance of the 1-D component \( i \) separating the two environments being considered; \( A_i \) – the area over which the value \( U_i \) applies; \( \Psi_j \) – linear thermal transmittance; \( l_j \) – the length over which the value \( \Psi_j \) applies; \( N_i \) – the number of 2-D components; \( N_i \) – the number of 1-D components.

Then the correction to the thermal transmittance is given by:

\[ \Delta U_f = n_f \cdot \chi \]  

(4)

Where: \( n_f \) – the number of fasteners per m².

### 2.3 Experimental “Hotbox” method

Experimental measurements were carried out using the guarded hotbox method. The guarded hotbox consisted of a cold chamber, a hot chamber and a metering box. A test specimen is installed between the cold chamber and the hot chamber. The procedure of measurements is validated against the standard EN ISO 8990:1999 [12]. The air temperature of the cold chamber was set to 0° C, and the temperature of the hot chamber was set to 20° C.
2.4 Parameters of wall fragments for theoretical and experimental research

Experimental and theoretical researches were carried out with thickness 300 mm of thermal insulation layer from expanded polystyrene foam ($\lambda = 0.031 \text{ W/(m} \cdot \text{K)}$). The thermal insulation material is crossed by “L” shape connectors made from aluminium alloy ($\lambda = 160 \text{ W/(m} \cdot \text{K)}$), stainless steel ($\lambda = 17 \text{ W/(m} \cdot \text{K)}$) and glass fiber reinforced plastic ($\lambda = 0.23 \text{ W/(m} \cdot \text{K)}$). The thickness and height of all heat-conductive connectors are the same – 3 mm and 100 mm respectively. The length of connectors depends on thickness of thermal insulation layer. The structure and dimensions of the fragment are shown on the Fig. 1.

![Fig. 1. Fragment of wall: a) 3D model; b) side view; c) photo of sample preparation](image)

Dimensions of the whole fragment are: height – 2050 mm, width – 1800 mm, thickness – 382 mm. There 2.78 pcs of connectors were used per 1m². A total nine connectors of “L” shape are installed across the fragment area using 600 mm step. All edges of fragment are guarded with 50 mm thickness polystyrene foam ($\lambda = 0.034 \text{ W/(m} \cdot \text{K)}$).

3 Results

Calculations and measurements results by three methods are shown in Table 1. The research showed that, using connectors with lower heat conductivity, the difference between values of heat transmittance of wall is not significant. However, the biggest difference of heat transmittance is noticeable in the calculations by the empirical method with aluminium alloy connectors, which have the highest thermal conductivity. In this case, the value of heat transmittance by the empirical method is almost two times higher than by hotbox and numerical methods. The calculated correction to the thermal transmittance of wall fragment with aluminium alloy connectors also indicated the highest difference comparing with other two methods.
Table 1. Calculations and measurements results of heat transmittance by three different methods

| Material of connectors | Hotbox method          | Numerical method         | Empirical method          |
|------------------------|------------------------|--------------------------|----------------------------|
|                        | $U$, W/(m²·K) | $\chi$, W/K | $\Delta U$, W/(m²·K) | $U$, W/(m²·K) | $\chi$, W/K | $\Delta U$, W/(m²·K) | $U$, W/(m²·K) | $\Delta U$, W/(m²·K) |
| Without connectors     | 0.105              | -                 | 0.098                    | -                   | 0.100              | -                 |
| Glass fiber reinforced plastic | 0.103          | -0.0006   | 0.0002                   | 0.099              | 0.0005             | 0.0004           |
| Stainless steel        | 0.123              | 0.0074       | 0.0205                   | 0.125              | 0.0109             | 0.0302           |
| Aluminium alloy        | 0.201              | 0.0401       | 0.1114                   | 0.200              | 0.0417             | 0.1159           |

Fig. 2 shows temperature distribution and intensity of heat flow through the models with aluminium alloy (a, b) and stainless steel (c, d) connectors. Analysing the fields of temperature it was observed that using aluminium alloy connector much lower temperature reached the inner surface of wall than using the stainless steel connector. The intensity of heat flow through the aluminium alloy connector was almost four times higher than through the stainless steel connector.

The heat flows through the specimen and through the one connector are shown in Table 2. Comparing the values of heat flow through the specimen by the experimental hotbox method and numerical 3-D calculation method, the difference is up to 5% between them. It means that simulation models of wall fragments were created with very close conditions to the real fragments used in experimental measurements. In order to analyse the reasons of very significant differences in results, the values of the heat flow through the one connector were calculated for each case. These results clearly showed tendency that the more conductive connectors are used, the higher amount of heat flow dissipates to the boundary layers. It means that heat flow does not go only through the connector, how the empirical method evaluates. The tendency is also visible in the Fig. 2. (a, c). For that reason, the heat transfer from heat-conductive connector to thermal insulation material should be analysed additionally.

![Fig. 2. Temperature distribution (left) and intensity of heat flow (right) with aluminium alloy connector (a; b) and stainless steel connector (c; d)](image-url)
Table 2. Calculations and measurements results of heat flow by different methods

| Material of connectors   | Hotbox method | Numerical method | Empirical method |
|--------------------------|---------------|------------------|------------------|
|                          | Heat flow     | Heat flow        | Heat flow        | Heat flow         |
|                          | through the   | through the      | through the      | through the       |
|                          | specimen Φ, W | one connector Φ | specimen Φ, W   | one connector Φ  |
| Without connectors       | 7.624         | -                | 7.262            | -                |
| Glass fiber reinforced   | 7.521         | 0.001            | 7.296            | 0.0002           |
| plastic                  |               |                  |                  | 0.0007           |
| Stainless steel          | 8.953         | 0.007            | 9.218            | 0.011            |
| Aluminium alloy          | 14.835        | 0.040            | 14.765           | 0.042            |
|                          |               |                  |                  | 0.480            |

4 Conclusions

The results of this study confirmed that numerical calculation method is more accurate than empirical calculation method, calculating heat transmittance through the ventilated wall with heat-conductive connectors. According to the empirical calculation method the difference in results of heat transmittance of wall system with two types of connectors and without connectors were obtained up to 10 % comparing with the results of experiments. That could mean that the simple empirical method is appropriate and sufficiently precise for calculations, but the results with the connectors made of aluminium alloy refuted this assumption, whereas the difference of more than twice was obtained. The distribution of field of temperature is also diverse around the connectors made from different materials. It can be assumed that the empirical method should be corrected for calculations with extremely heat-conductive connectors such as aluminium alloy. For this reason, there is a need to carry out more comparative calculations and experimental measurements with various materials and thickness of thermal insulation and different kind of connectors to analyse heat transfer from the connector to thermal insulation material.

References

1. European Commission. *Proposal for a recast of the energy performance of buildings directive (2002-91-EC)*. (SEC/2008/2865, Brussels, 2008)
2. M. Ciampi, F. Leccese, G. Tuoni. Ventilated facades energy performance in summer cooling of buildings. Solar Energy 75, 491–502 (2003)
3. L. Zalewski, S. Lassue, D. Rousse, K. Boukhalfa. Experimental and numerical characterization of thermal bridges in prefabricated building walls. Energy Conversion and Management 51, 2869–2877 (2010)
4. T. Theodosiou, K. Tsikaloudaki, D. Bikas. Analysis of the Thermal Bridging Effect on Ventilated Facades. Procedia Environmental Sciences 38, 397 – 404 (2017)
5. T. Theodosiou, A. G. Tsikaloudaki, K. J. Kontoleon, D. Bikas. Thermal bridging analysis on cladding systems for building facades. Energy and Buildings 109, 377-384 (2015)
6. S. Ilomets, K. Kuusk, L. Paap, E. Argumagi, T. Kalamees. Impact of linear thermal bridges on thermal transmittance of renovated apartment buildings. Journal of Civil Engineering and Management 23, 96-104 (2016)
7. J. Sadauskiene, J. Ramanauskas, J. Seduikytė, L. Daukšys, M. Vasilius. A Simplified Methodology for Evaluating the Impact of Point Thermal Bridges on the High-Energy Performance of a Passive House. Sustainability 7, 16687–16702 (2015)
8. H. Song, J. H. Lim, S. Y. Song. Evaluation of alternatives for reducing thermal bridges in metal panel curtain wall systems / Energy and Buildings 127, 138–158 (2016)
9. European Committee for Standardization, EN ISO 10211, Thermal Bridges in Building Construction - Heat Flows and Surface Temperatures - Detailed Calculations (2017)

10. European Committee for Standardization, EN ISO 6946. Building components and building elements - Thermal resistance and thermal transmittance - Calculation methods (2017)

11. R. Ji, Z. Zhang, Y. He, J. Liu, Sh. Qu. Simulating the effects of anchors on the thermal performance of building insulation systems / Energy and Buildings 140, 501–507 (2017)

12. International Organization for Standardization, EN ISO 8990:1999, Thermal insulation - Determination of steady-state thermal transmission properties - Calibrated and guarded hot box (1999)