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The Comparison of a Numerical and Empirical Calculation of Thermal Transmittance of Ventilated Facade with Different Heat-Conductive Connections

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The energy efficient buildings are priority these days. The building energy efficiency requirements are increasing and thicker thermal insulation layer is used for building envelopes in order to achieve these high requirements. Ventilated facades are often used for the construction of public buildings, whose thermal insulating layers are crossed with connections made from steel or aluminium alloy, whose influence on the heat transfer through the construction is high. Looking for less heat-conductive materials for connections, it has been observed that different calculation methods give different results of heat transfer, depending on characteristics of materials for thermal insulation and connections. In order to find out the reasons for these differences, calculations of ventilated walls with various connections were carried out.

The heat transfer through the wall with connections crossing thermal insulating layer could be calculated in two ways. The first way is simpler and was often used earlier - this is the calculation of the heat transfer coefficient increase depending on type and geometry of connection using the formulas presented in the standards. A more precise calculation method is the calculation of the heat transfer coefficient of wall with connections using two - dimensional and three - dimensional heat transfer modelling computer software (heat flow analyses). The use of these two calculations methods shows the differences of results of the heat transfer through ventilated walls.

For both calculations, the fragments of ventilated walls with connections made from aluminium alloy (λ - 160 W/(m·K)), zinc coated steel (λ - 50 W/(m·K)), stainless steel (λ - 17 W/(m·K)) and glass fiber reinforced plastic (λ – 0.23 W/(m·K)) were created. Calculations have shown that the heat transfer coefficient calculated for walls with zinc coated and stainless steel connections using different methods

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varies by 29 %, for walls with glass fiber reinforced plastic connections – by 0.4 % and for walls with aluminium alloy connections - by 130 %.
The main aim of this paper is the investigation of reasons of different calculations results according to numerical and empirical calculations methods. When the causes of discrepancies are found, empirical formulas can be corrected.

Keywords: heat-conductive connections, point thermal bridges, thermal insulation, ventilated facade systems.

Introduction

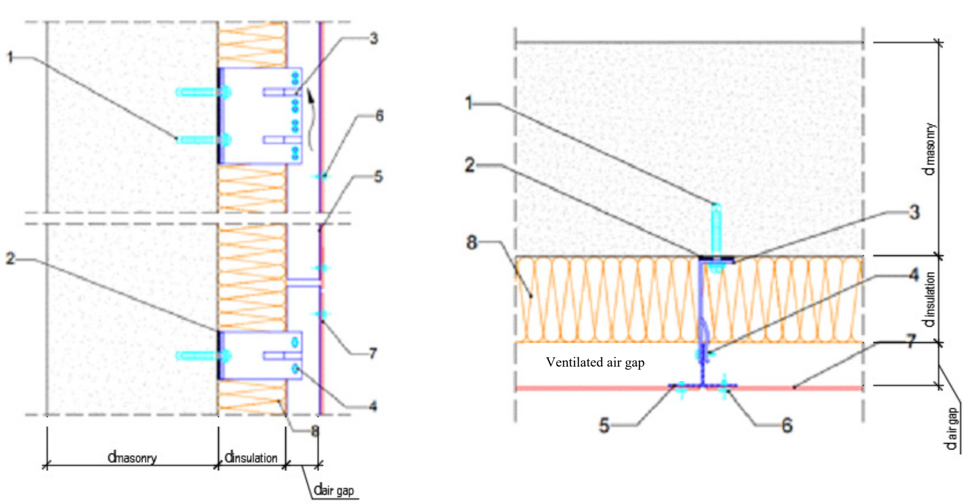
Energy use in residential and commercial buildings represents about 40% of the European Union's (EU) total final energy consumption and CO2 emissions (European Commission, 2008). This is the main reason for the higher requirements of the energy efficiency of buildings. Therefore newly built buildings must be designed as energy efficient buildings today in Lithuania as in other EU countries. The main tasks for reducing heat losses of buildings are improvement of the insulating properties of building envelopes, reduction of influence of thermal bridges, increase of airtightness of buildings, the use of efficient ventilation systems and others.

According to review of literature, the influence of thermal bridges on building's heat losses can be achieved from 5% to 39 % (Quinten and Feldheim 2016, Ilomets et al. 2016, Al-Sanea and Zedan 2012). Correct design of thermal bridges is significant, because inefficiency solutions can be a cause of much higher heat losses of buildings. This is evidenced by the many studies carried out (Cappelletti et al. 2011, Misiopecki et al. 2018, Ge et al. 2013, Levinskyte et al. 2016).

Today ventilated facade system (Fig. 1.) is often used for renovated and also for newly built buildings, which have higher requirements of energy efficiency. The steel, which is used as connectors in ventilated facade systems, has a thermal conductivity that may be over 1500 times higher than the thermal conductivity of insulating material. It has been shown that ignoring the effect of the steel connectors can lead to an over-estimate of the thermal resistance up to 50%, depending on the details of the construction (Gorgolewski 2007). Zalewski et al. (2010) quantified heat losses by thermal bridges in prefabricated building walls. The study showed the relative importance of the thermal bridges in the wall with steel frame increased by 26% comparing to wall without thermal bridges. For this reason point thermal bridges through heat-conductive connections in ventilated facade systems are also very significant and have to be correctly evaluated.

Fig. 1

Example of ventilated facade system (plastic anchors are used to fixing of thermal insulation) (www.plantas.lt/file/repository/AK_lt(plantas).pdf 2018)



1– anchors; 2– thermal break; 3 – heat-conductive connections; 4 –screws;
5 –T profile; 6 – screws; 7 – external panel; 8 – thermal insulation+ wind barrier

The value of the point thermal bridge in ventilated facade systems depends on several parameters: the thickness and thermal conductivity of the thermal insulation material, the thickness and thermal conductivity of the load bearing layer of the wall, dimensions and the thermal conductivity of heat-conductive connections. Also the thermal breaks are often used in practice, because they minimise the heat transfer between the heat-conductive connections and the load bearing wall. Theodosiou et al. (2015) analysed thermal bridging on cladding systems and made calculations of this system with the thermal breaks and without them (Fig.2.). The results of that study showed that the thermal break cannot provide a fully efficient measure against increased heat flow concentrated around the anchors penetrating the load bearing wall (Theodosiou et al. 2015) as it is seen in Fig.2 (b).

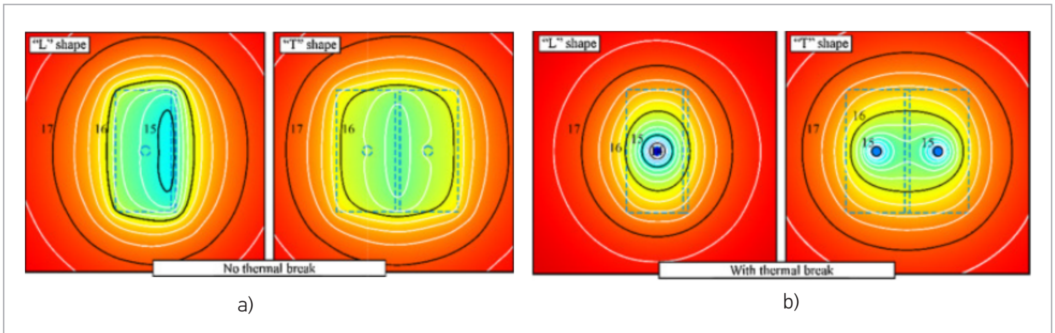


Fig. 2

The effect of braket type in the temperature distribution at the junction among the bracket with the substrate, in the case of (a) no thermal break and (b) thermal break existence (Theodosiou et al. 2015)

Theodosiou et al. (2017) also had been making the research about thermal bridging effect on ventilated facades. Authors analysed the influence of heat-conductive connections type on point thermal transmittance, calculated by finite element method using 3-D simulation software. In calculations different types of heat-conductive connections were used: two geometrical dimensions (full height and half height, as shown in Fig.1.) and three different heat conductivity materials (synthetic – λ=0.20 W/(m·K), steel – λ=65 W/(m·K), chemical – λ=0.09 W/(m·K)) and also fragments of wall with thermal break and without them. As it can be seen from Fig. 3, the effect of the connections of all types increased in the cases of the full height connector without bracket and the high thermal conductivity of the material of load bearing wall. This figure also shows how the chemical connections, compared to others types of connections, can influence the decrease of the heat transfer through the insulated wall. The contribution of dimensions of connector to point thermal transmittance in all investigated cases is close to 10% (Theodosiou et al. 2017).

Sadauskiene et al. (2015) developed a simplified methodology for evaluation of influence of point thermal bridges created by aluminium alloy connections on energy performance of walls insulat-

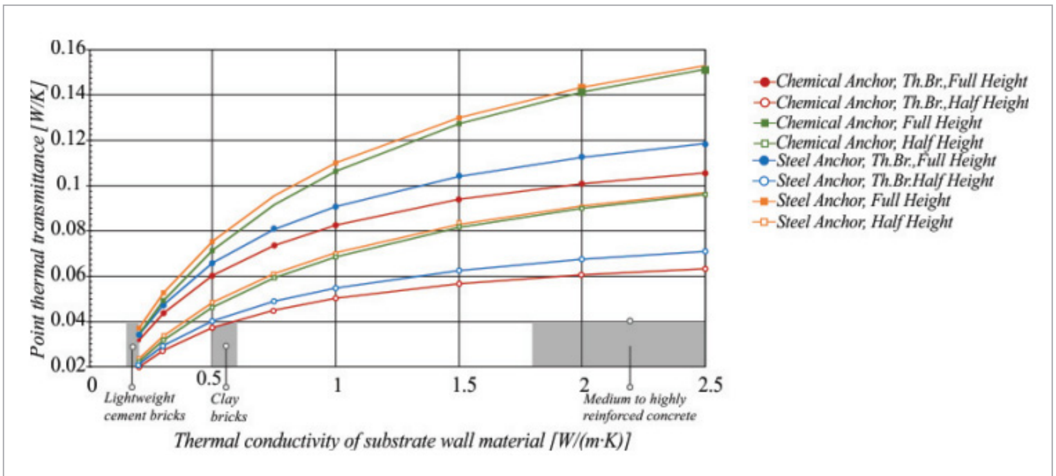


Fig. 3

Point thermal transmittance (x-value) as a function of connector material for various wall materials and for both examined connectors sizes (Theodosiou et al. 2017) ed according to Passive House requirements. Their investigation showed that the highest influences on the point thermal transmittance (x, (W/K)) and thermal transmittance (U, (W/m²·K)) of the entire wall are the thermal conductivity of the material of load bearing wall and the thickness of the insulating layer. The thermal transmittance of the entire wall depending on these options may differ up to 35% (Sadauskiene et al. 2015).

The general functional dependency may be expressed as follows (Sadauskiene et al. 2015):

$$\chi = f(\lambda_L, d_L, \lambda_T, d_T) \tag{1}$$

λ_L - thermal conductivity of the material of load bearing wall, W/m·K; d_L - thickness of the load bearing wall, m); λ_T - thermal conductivity of thermal insulating material, W/m·K; d_T - thickness of the thermal insulating layer, mm.

A system of equations was produced by authors (Sadauskiene et al. 2015):

$$\chi = \begin{cases} 0.038 + 0.014\ln(\lambda_L), & 0.1 \le \lambda_L \le 1 \\ 0.034 - 0.025 d_L & 50 \le d_L \le 500 \\ 0.032 - 0.093\lambda_T & 0.030 \le \lambda_T \le 0.040 \\ 0.025 + 0.022 d_T & 100 \le d_T \le 200 \end{cases} \tag{2}$$

The solution of this system gives a mathematical expression according which the point thermal transmittance could be calculated with aluminium alloy connections:

$$\chi = 0.041 + 0.014\ln(\lambda_L) - 0.025 d_L - 0.016\lambda_T + 0.022 d_T \tag{3}$$

The authors claim that a simplified calculation using the empirical relationship is a sufficiently precise (95%).

Analysis of literature showed that evaluation of point thermal bridges in ventilated facade systems with heat-conductive connections is multiparametrical and often quite complicated, especially when there is no possibility to use 3-D simulation software. In this case, a simplified calculation methodology (Sadauskiene et al. 2015) can be used, which is based on the requirements of the standard EN ISO 10211 (2017). However the review of literature did not reveal the situation of using of two standard calculation methods and differences between the results according to them. Therefore, the main purpose of this study is to analyse the two standard calculation methods when different heat conductivity connectors are used and determine the reasons of different results between these methods.

Methodology

The standard calculations methods

There are two standard ways to calculate the heat transfer through fragments of buildings envelopes when heat conductive connections are used. The three dimensional nature of the point thermal bridge effect on thermal performance of ventilated systems require a detailed calculation approach in order to take into account the complex geometry and the great differences in thermo physical properties of adjacent materials (Theodosiou 2017). According to the EN ISO 10211 the temperature distribution within, and the heat flow through a construction can be calculated if the boundary conditions and constructional details are known. Therefore the geometrical model is divided into a number of adjacent material cells, each with a homogenous thermal conductivity. The effect of mechanical fasteners can be assessed by calculations in accordance with EN ISO 10211 (2017) in order to obtain the point thermal transmittance, x, due to one fastener calculated according to EN ISO 6946. The correction to the thermal transmittance is given by:

$$\Delta U_f = n_f \cdot \chi \tag{4}$$

where: n_f– the number of fasteners per m². χ the point thermal transmittance, are determined by:

$$\chi = L_{3D} - \sum_{i=1}^{N_i} U_i \cdot A_i - \sum_{j=1}^{N_j} \Psi_j \cdot l_j \; ; \tag{5}$$

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; Ψ_j – linear thermal transmittance; l_j *the length over which the value* Ψj *applies;* N_j *– the number of 2-D components;* N_i *– the number of 1-D components.*

The standard EN ISO 10211 (2017) explains modelling conditions and calculation method of the heat transmission coefficients. So using 3-D simulation software HEAT3, which is validated against the standard EN ISO 10211 (2017), the model of envelope fragments was created. The model was 600 mm wide and 600 mm high with one "L" shape heat-conductive connection in the middle. The model was split into finite elements. Maximum numerical cells N_i = 45 were applied in x-direction, y-direction and z-direction. Then boundary conditions were attributed to the internal surface and the external surface of the wall fragments. According to the EN 6946 (2017) thermal resistance of internal surface is 0.13 (m²·K)/W and the same thermal resistance value 0.13 (m²·K)/W of surface located in front of the ventilated air gap. Temperature difference through the fragment was 1 K. After calculations, the heat flow through the envelope fragment was obtained and using that value the heat transfer coefficient U was calculated.

The standard EN ISO 6946 (2017) provides an approximate method that can be used for elements containing inhomogeneous layers, including the effect of metal connectors, by means of a correction term (EN ISO 6946 2017). The correction to the thermal transmittance is given by:

$$\Delta U_f = \alpha \cdot \frac{\lambda_f \cdot A_f \cdot n_f}{d_1} \cdot \left(\frac{R_1}{R_{tot}}\right)^2 \tag{6}$$

where: α = 0.8 if fastener fully penetrates the insulation layer; $\alpha = 0.8 \times \frac{d_1}{d_0}$ in the case of recessed fastener; λ_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..

The calculation method according to EN 6946 (2017) does not estimate the influence of steel screw fastening the "L" shape connection to the load bearing wall layer. For calculation of the heat transfer coefficient of envelope fragment, according to this method, the total resistance of all fragment layers is calculated and the correction of the thermal transmittance according to Eq.6 is added.

Parameters of elements of wall fragments for empirical calculation and numerical simulation

Since the thickness and conductivity of thermal insulation are some of the most significant parameters for value of point thermal transmittance, this calculation is carried out in accordance with two methodologies by changing these parameters. The ventilated facade systems with four different thermal conductivity connections were chosen for the calculations (Fig.4.). The conductivity of glass fiber reinforced plastic connectors is 0.23 W/(m·K), stainless steel connectors – 17 W/(m·K), zinc coated steel connectors – 50 W/(m·K), and aluminium alloy connectors – 160 W/(m·K). "L" shape connectors were chosen, because that shape is commonly used in practice. The thickness of all kind of these connectors was 3 mm, width – 100 mm, a part connected to wall – 50 mm. Total length of the connector through the insulation layer was in accordance with the thickness of the thermal insulation layer. There were used 2.78 pcs of connectors per 1m² in calculations. Also four thicknesses of thermal insulation were used: 200 mm, 300 mm, 330 mm and 400 mm. Two types of thermal insulation materials were chosen with different thermal conductivity: 0.036 W/(m·K) and 0.040 W/(m·K). The load bearing wall was the same in all cases. The thermal conductivity of load bearing wall was 0.7 W/(m·K) like ceramic brick masonry and the thickness of this wall was 250 mm. Finishing layer on the inner side of the envelope was 15 mm thick plaster with thermal conductivity 0.882 W/(m·K). All other fastening elements like screws in the ventilated facade system were steel elements (λ=50 W/(m·K)). They were simulated as square cross section elements (7 mm x 7 mm), whereas only square elements could be drawing in HEAT3 software.

All of calculations were performed in two cases. The first of them was with thermal break between load bearing wall and connectors, and the second one without thermal break. Thermal conductivity of that break was 0.17 W/(m·K). Dimensions of thermal break are the same like base of "L" shape connections (50 mm x 100 mm) with 5 mm thickness.

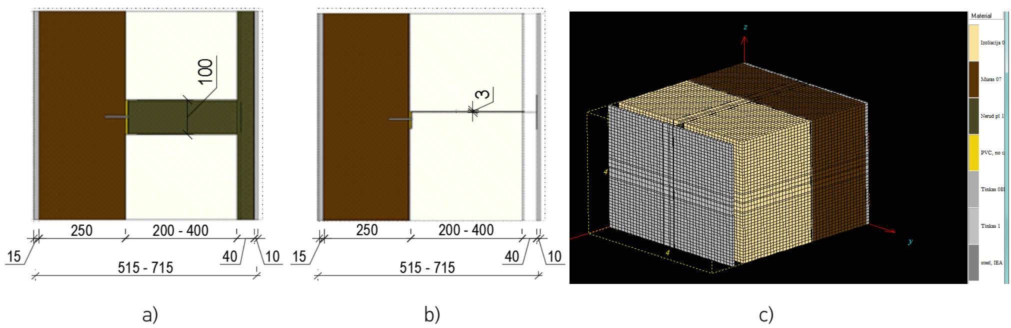


Fig. 4
Fragment of ventilated facade system: a) side view; b) top view; c) 3D model

Results

The influence of thermal break

The use of the thermal break between the load bearing wall and the heat-conductive connections is a quite good way to reduce heat flows through the envelope. Using the glass fiber reinforced plastic connections the difference in results of 3-D with thermal break and without them is almost equal to zero (0.0–0.3 %), using the stainless steel connections that difference is up to 0.9 % and steel connections – up to 5.5 %. Difference in results of 3-D calculations of ventilated facade system fragments with different thermal conductivity insulation and aluminium alloy connections with thermal break and without them varies from 4.8 % to 5.7 %. The biggest difference in the results is obtained with the highest heat conductivity connectors – aluminium alloy fasteners: using the thermal break, U=0.195 W/(m²·K), without the thermal break - U=0.207 W/(m²·K). According to the EN 6946 (2017) method the influence of the thermal break could not be evaluated, consequently only numerical calculations can be compared.

The influence of thickness of thermal insulation

According to the empirical and numerical calculations of ventilated facade system with thermal insulating material of λ=0.036 W/m·K, the heat transfer coefficient when used aluminium alloy connections is very high compared to the calculation results using other kinds of connectors (Table 1): the heat transfer coefficient U=0.592 W/(m²·K) with thickness of thermal insulation 200 mm and U=0.324 W/(m²·K) with 400 mm. The heat transfer coefficient of envelope fragments with the stainless steel connections respectively – U=0.207 W/(m²·K) and U=0.111 W/(m²·K) and for fragments with the glass fiber reinforced plastic connections – U=0.162 W/(m²·K) and U=0.086 W/(m²·K) respectively. The calculation results showed the influence of different connectors on heat transfer coefficient of ventilated facade system increases when thickness of thermal insulating material is bigger. The increment of heat transfer of ventilated wall depending on thickness of thermal insulation layer and type of connectors, compared to wall without connectors is presented in Fig. 5. The results show the negative trend: the influence of heat conductive connectors increases with increment of thickness of thermal insulating layer.

Thermal insulation		Heat transfer U, W/(m²·K)			
		Heat-conductive connections			
Thermal conductivity λ, W/(m·K)	Thickness, mm	Glass fiber	Stainless Steel	Steel	Aluminium alloy
0.036	**200**	0.162	0.207	0.296	0.592
	400	0.086	0.111	0.160	0.324
0.040	**200**	0.178	0.222	0.309	0.598
	400	0.094	0.119	0.168	0.330

Table 1
The empirical calculations results of the heat transfer coefficient with different thickness of thermal insulation

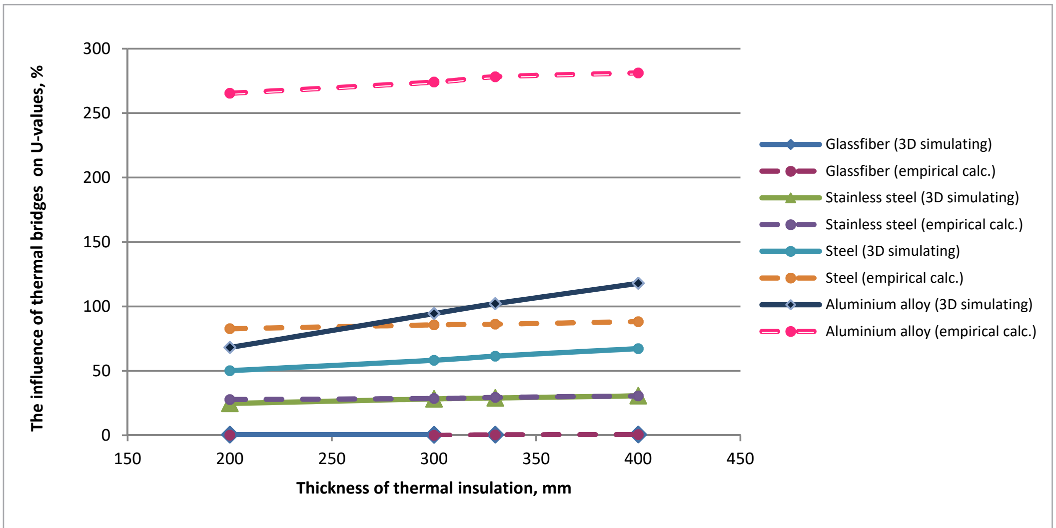


Fig. 5
The influence of the thermal bridges on thermal transmittance of ventilated facade system

The impact of heat conductivity of thermal insulation

The heat conductivity of the thermal insulation is one of the most significant factors to the heat transfer coefficient of envelope. Calculations results of the heat transfer through ventilated facade system without thermal breaks with 300 mm of thermal insulating material and with heat conductivity 0.036 W/(m·K) and 0.040 W/(m·K) are shown in Table 2. For glass fiber connections, the

Thermal insulation		Heat-conductive connections		Heat transfer U, W/(m²·K)	
Thickness, mm	Thermal conductivity λ, W/(m·K)	Material	Thermal conductivity λc, W/(m·K)	3D simulating (EN 10211)	Empirical calculations (EN 6946)
300	**0.036**	Glassfiber	0.23	0.112	0.112
		Stainless Steel	17	0.143	0.144
		Steel	50	0.177	0.208
		Aluminium alloy	160	0.217	0.419
	0.040	Glassfiber	0.23	0.124	0.123
		Stainless Steel	17	0.154	0.155
		Steel	50	0.194	0.217
		Aluminium alloy	160	0.228	0.425

Table 2
The calculations results of the heat transfer coefficient with different heat conductivity thermal insulation

difference between heat transfer coefficients with different conductivity thermal insulation is about 10 %, it means, reduction of U value is only due to difference of conductivity of thermal insulation material. For stainless steel and steel connectors, this difference is about 8 %, it shows, that the impact of heat conductive connectors relatively increases in more insulated layers. For aluminium alloy connectors, significant differences in calculation results using different methods occur. Then using 3-D simulation, this difference is about 5 %, then empirical calculation – about 10 %. These differences show that 3-D simulation is more reliable because follow the trends of distribution of calculation results of other cases (more significant impact).

Table 3

The 3-D calculations results of the heat transfer coefficient with different heat conductivity connections

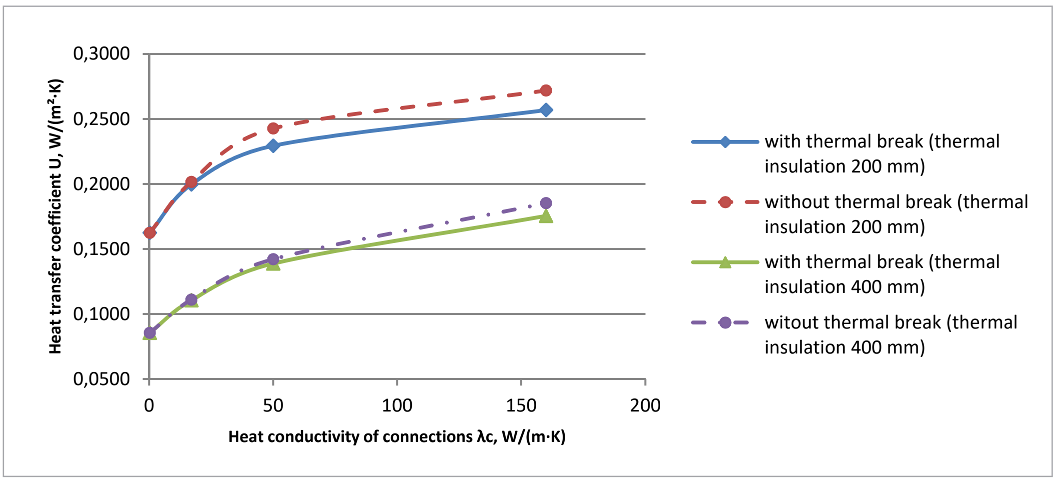
Thermal insulation		Heat-conductive connections		Heat transfer U, W/(m²·K)	
Thickness, mm	Thermal conductivity λ, W/(m·K)	Material	Thermal conductivity λc, W/(m·K)	with thermal break	without thermal break
200	**0.036**	Glassfiber	0.23	0.163	0.163
		Stainless Steel	17	0.200	0.202
		Steel	50	0.229	0.243
		Aluminum alloy	160	0.257	0.272
400		Glassfiber	0.23	0.086	0.086
		Stainless Steel	17	0.111	0.111
		Steel	50	0.139	0.142
		Aluminum alloy	160	0.176	0.185

Different heat conductive connections

It is obvious that using higher thermal conductivity connectors, the values of point thermal bridges (calculated using 3-D method), also increase as the heat transfer coefficient of the envelope (Table 3 and Fig.6). The heat transfer coefficient of the fragment with thermal break decreased 46.4% – 89.9% using different heat conductivity connections when the thickness of thermal insulation was 200 mm and 400 mm. The biggest difference (89.9%) was obtained with glass fiber connections, which have the lowest thermal conductivity. The smallest change in the heat transfer (46.4%) was obtained with the highest thermal conductivity connections – aluminium alloy.

Fig. 6

The effect of the heat conductivity of connections on heat transfer coefficient of ventilated facade system (3-D method)



Moreover, the strangest differences in results were observed between two used calculation methods with the same connectors (Fig.7.). For example, using less heat-conductive connections such as stainless steel the value of the heat transfer coefficient calculated by two methods varied by 3.6%. That difference is small enough to think, that both calculation methods are suitable for the calculation of the heat transfer through the ventilated facade system with heat-conductive connections. However, very big differences were determinated comparing the results when aluminium alloy connections were used. These differences ranged from 70.0 % up to 130.4 %. In all cases the empirical calculation method according to EN 6946 (2017) showed much higher values of heat transfer compared to the method according EN 10211 (2017) using 3-D simulation software.

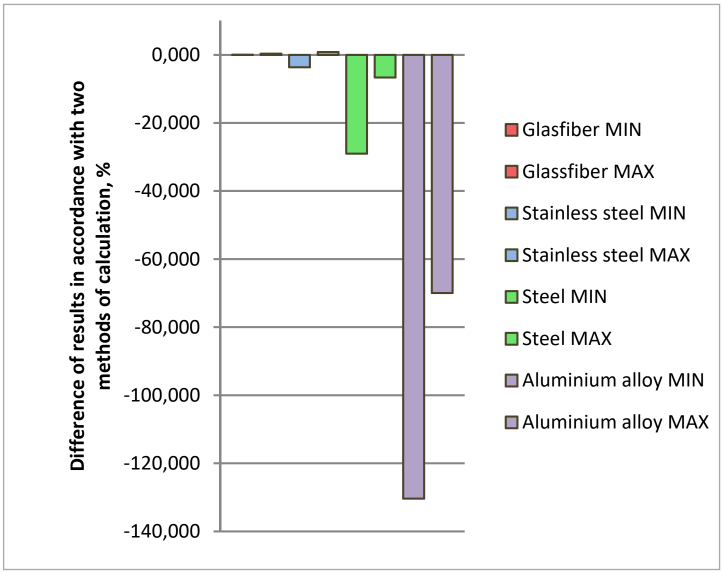


Fig. 7

Minimum and maximum percentage of difference in calculation results using two calculation methods

Conclusions

The results of performed investigations shows, that incorrect evaluating of thermal bridges or ignoring the effect of the metal elements in building thermal insulated constructions could be the reason of reduction of thermal resistance of buildings envelopes up to 30 % with lower heat conductivity metal elements and up to 2.8 times with very high heat conductivity metal elements. Consequently, the impact of heat-conductive connections on heat transfer coefficient of envelope must be evaluated in ventilated facade systems.

The calculation results also indicated:

- the influence of thermal breaks is significant only for insulation systems with steel and aluminium alloys connectors;
- the influence of heat conductive connectors increases with increment of thickness of thermal insulating layer.
- the higher influence of thermal conductive connectors was determined when lower-conductive thermo-insulating materials are used;
- the thermal transmittance of ventilated facade system increases up to 2 times when the aluminium connections are used, so they should not be used for low energy buildings;
- the difference between heat transfer coefficients with different conductivity of thermal insulation show that 3-D simulation is more reliable method for evaluation of point thermal bridges because obtained results follow the trends of distribution of calculation results;
- significant difference in results of the empirical and 3-D calculation method (the calculations with aluminium alloy connections gave even 130 % difference) require to corrected empirical method at least for calculation of the heat transfer through the building envelopes with high thermal conductivity connections such as aluminium alloy connectors.

Whereas, the reason was not clarified why the calculation results using two methods are so markedly different, the experimental research is going to be carried out using a guarded hot box method.

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