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AURELIJA STONKUVIENĖ

INVESTIGATION OF HEAT FLOW THROUGH THERMAL INSULATION LAYERS WITH HEAT-CONDUCTIVE CONNECTORS

SUMMARY OF DOCTORAL DISSERTATION

TECHNOLOGICAL SCIENCES, CIVIL ENGINEERING (T 002)

Kaunas
2021

KAUNAS UNIVERSITY OF TECHNOLOGY

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This doctoral dissertation was prepared at Kaunas University of Technology, Institute of Architecture and Construction, Laboratory of Building Physics, during the period of 2016–2020.

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AURELIJA STONKUVIENĖ

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INTRODUCTION

Relevance of the Research

Improving the energy efficiency of buildings is a relevant challenge for reducing consumption of fossil energy and carbon emissions. Heat losses in energy-efficient buildings are significantly lower than in previously constructed buildings; thus, their envelopes are insulated with thicker layers of thermal insulation materials. While the heat losses of the uninsulated or poorly insulated buildings were high, less attention was given to the accuracy of calculation of the heat transfer through building envelopes, as this did not significantly affect the result of the calculation of the total energy consumption of the building. When the energy consumption of energy-efficient, near-zero energy buildings has decreased several times over the last decade, the insufficiently accurate estimates of heat loss through envelopes can lead to unreasonably higher amounts of thermal insulation and other building materials and more powerful and expensive building engineering systems. This hinders the development of energy-efficient construction and limits the use and improvement of thermal insulation systems, which thermal properties are calculated by unreliable methods. These thermal insulation systems as well include building facade with metal connectors crossing thermal insulation layers, which significantly increase their heat transfer, which is calculated by the standard empirical formula (LST EN ISO 6946:2017). A significant differences of up to 1.5 times were found, comparing the heat transmittance coefficients calculated by the approximate empirical formula and experimentally measured wall structures with connectors, especially with high thermal conductivity rectangular connectors. The estimated heating energy demand of the energy-efficient residential building decreases on average from 12 kWh/m^2 to 6 kWh/m^2, when 3D numerical modelling method is used instead of the standard empirical procedure for the calculation of heat transmittance coefficient of walls with ventilated insulation systems. However, at the design stage of buildings, especially when choosing building insulation schemes, the approximate standard method for calculating the heat transmittance coefficient is often used due to its simplicity and low labour costs. It is an important task of the system of building energy efficiency increase to improve this calculation method by increasing the accuracy and reliability.

Aim of the Dissertation

The aim of the dissertation is to investigate the heat flow through thermal insulation layers crossed by heat-conductive connectors and clarify this dependence on the geometric and thermal characteristics of the layer's materials.

Objectives

1. To analyse the methods of calculation and measurement of heat transfer through thermal insulation layers with heat-conductive connectors and the reasons for the differences in the obtained results.

2. To investigate the heat transfer through thermal insulation layers with connectors of various geometrical and thermal characteristics experimentally.

3. To determine the quantitative indicators of the influence of thermal conductivity and geometrical characteristics of connectors on heat transfer through facade systems by numerical calculation method.

4. To adjust the standard equation for calculating the heat transfer coefficient of structures with heat-conductive connectors, according to the results of experimental investigations and numerical calculations.

5. To check the reliability of the corrected empirical calculation procedure, comparing the obtained results with the officially published results of measurement and calculation of the heat transfer coefficients of the facade systems, to prepare recommendations and restrictions for the application.

Methods of the Research

The experimental investigations of heat flows through thermal insulation layers of building facade systems with heat-conductive connectors were performed by measuring heat transfer by applying "hot box" method (ISO EN 8990) with the additional use of temperature sensors near the connectors. The quantitative indicators of the influence of thermal conductivity and geometrical characteristics of the connectors on heat transfer through thermal insulation layers were determined by modeling the heat transfer of the wall fragments in 3D space using the computer program HEAT3.0, based on the calculation of temperature fields by finite element method. The adjusted calculation equations were checked by comparing the obtained results with the results of analogous studies published by the other authors and the heat transfer coefficients of the facade systems presented in the technical literature.

Scientific Novelty of the Research

1. The reasons for the differences in the results of experimental measurement and calculation of facades with heat-conductive connectors using the standard equation were investigated: the conditions of heat exchange of the connector with the construction environment are not evaluated in the equation.

2. The dependencies of intensity of the heat flow through the wall structure with and without air gap depending on the thickness of the thermal insulation layer and the thermal conductivity of metal connectors were determined.

Practical Relevance of the Dissertation

1. A revised approximate methodology for the calculation of heat transfer through structures with thermally conductive connectors is recommended for the selection of wall insulation systems at the design stage of buildings. The application of this methodology significantly reduces the calculation costs and, taking into account the determined limitations, gives an average of ± 6%. errors compared to 3D numerical modelling.

2. For the improvement of energy efficiency of building insulation systems, the possibility of heat exchange of the joint with the internal and external environment of the thermal insulation layer must be reduced first, because then, the impact of thermal and geometrical characteristics of the joint crossing the thermal insulation layer is significantly reduced. It is recommended to use this trend in the development of composite connectors, the material of the central part of which may be selected primarily according to their mechanical and technological properties, and the heat transfer of the insulated structure is reduced by using low-conductive or additionally insulated fixing parts of the connectors.

Statements Presented for the Defense

1. The dependence between the thermal conductivity of the connectors and the increase of heat transfer through the thermal insulation layer with these elements is not direct: the higher is the thermal conductivity of the connectors, the smaller part of heat transfer through the connectors must be included in the total value of heat transfer, because heat transfer through connectors crossing the thermal insulation layer is limited by the heat input and output area of the connectors.

2. As the thickness of the thermal insulation layer with heat-conductive connectors' increases, the effect of the connectors on the overall heat transfer does not change significantly, especially when using aluminium alloy connectors with the highest thermal conductivity, and even less with less thermally conductive steel or stainless steel connectors.

Scientific Approbation of the Dissertation

Four scientific articles on the topic of the dissertation have been published in periodicals, one of them with a citation index included in the Web of Science database, one without the citation index included in the Web of Science database, two without the citation index included in the Index Copernicus International database. The results of the research have been published in three international scientific conferences.

Structure of the Dissertation

The dissertation consists of the following parts: an introduction, three chapters, general conclusions, bibliography, a list of scientific publications and appendices.

The full version of the thesis contains 101 pages featuring 41 figures, 13 tables, 28 formulas and a list of 127 references.

1. LITERATURE REVIEW

Today, newly constructed buildings and renovated old buildings are properly insulated and meet high energy efficiency requirements in Lithuania and Europe. Heat loss through energy-efficient building wall accounts about 20% of a building's total heat loss. When calculating the total heat loss of a building, not only heat loss through envelopes is estimated, but also through thermal bridges, through which heat easily moves from the inside of the building to the outside environment. The smaller part of total heat loss accounts, for example, heat loss through the walls, the more significant the influence of linear and point thermal bridges in wall structures and accurate calculation of them.

The connectors made from aluminium alloy, steel or stainless steel and crossed the thermal insulation layer are much more heat-conductive (sometimes even over 7,000 times greater) than thermal insulation material. These metal connectors develop the point thermal bridges, because the heat flow through them is much more intense than through the insulation material. Sometimes the influence of the point thermal bridges is not evaluated on the heat loss of building walls, assuming that unfavourable impact is not significant. However, more and more research is being done recently in order to determine the significance of the effect of point and linear thermal bridges on the heat losses through building structures or the increse of heat transfer facade constructions (Ilomets, Kuusk, Paap, Arumagi, & Kalamees, 2017; Sadauskiene, Ramanauskas, Seduikyte, Dauksys, & Vasylius, 2015; T. Theodosiou, Tsikaloudaki, Tsoka, & Chastas, 2019; T. G. Theodosiou & Papadopoulos, 2008; T. G. Theodosiou, Tsikaloudaki, Kontoleon, & Bikas, 2015; Zalewski, Lassue, Rousse, & Boukhalfa, 2010). Theodosiou et al. (T. G. Theodosiou et al., 2015) has determined that a neglect of point thermal bridges in ventilated facade created to be metal connectors is the main reason for underestimating the actual heat flow through these wall constructions, which can reach 5–20%. Sprengard and Holm (Sprengard & Holm, 2014) investigated the influence of thermal bridging on thermal conductivity value of vacuum insulated panels (VIPs). Researchers established up to 65% increased equivalent thermal conductivity of VIPs concerning the impact of the thermal bridging. Berardi and Akos (Berardi & Akos, 2019) investigated the change in the wall structures insulated with aerogel-enhanced blankets thermal resistance by increasing the number of steel connectors per m². They found that the thermal resistance of wall structure with 3 anchors per m² reduce up to 15% and up to 45% with 6 anchors per m², compared to the wall structure without connectors (Berardi & Akos, 2019). Moreover, the researchers have found solutions how to decrease the heat losses through the building envelope using heat-conductive connectors, such as using composite connectors made of metal and plastic (J. H. Song, Lim, & Song, 2016; S. Y. Song, Yi, & Koo, 2008) or connectors with low thermal conductivity, such as glass fibre reinforced plastic (Arregi, Garay-Martinez, Astudillo, Garcia, & Ramos, 2020; Ji, Zhang, He, Liu, & Qu, 2017; T. Theodosiou, Tsikaloudaki, & Bikas, 2017; T. Theodosiou et al., 2019; Woltman, Noel, & Fam, 2017).

The influence by the metal connectors created point thermal bridges on heat transmittance through the wall structures can be estimated using different techniques. The most commonly used are: the standard approximate empirical calculation procedure, 3D numerical simulations or experimental measurements. The most realistic and reliable method is the experimental measurement. The steady-state heat transmittance and the heat flow through the wall fragment could be measured by using the guarded hot box (GHB) facility in laboratory. This experimental GHB test method is validated by the standard EN ISO 8990 (1999). Wakili and Tanner (Ghazi Wakili & Tanner, 2003) have adapted the GHB and numerical simulation methods analysing the differences of heat transmittance of wall structure made from hollow porous clay bricks. They determined a low difference of U-values, only up to 7% by different methods. Martin et al. (Martin, Campos-Celador, Escudero, Gomez, & Sala, 2012) have investigated the thermal bridges of a pillar in dynamic and steady-state conditions using the GHB. The difference between the measured and simulated results did not exceed 8%. More similar investigations were carried out comparing the results of the thermal characteristics of building envelopes obtained by the experimental GHB and numerical methods (Asdrubali & Baldinelli, 2011; Gao, Roux, Teodosiu, & Zhao, 2004; Kus, Ozkan, Gocer, & Edis, 2013; Manzan, De Zorzi, & Lorenzi, 2015; Sala, Urresti, Martin, Flores, & Apaolaza, 2008).

The numerical simulation method involves many advantages. This method is regarded a standardized method validated by the EN ISO 10211 (2017). The software's of numerical simulation tools are multifunctional and allows to simulate thermal bridges of any construction type. The heat transfer through the structure can be evaluated in several aspects such as heat flow through construction, temperature distribution, linear and point thermal transmittance etc. The results can be presented in numerical form and graphical form, which allows more precise analysis of each situation. Taylor, Counsell and Gill (Taylor, Counsell, & Gill, 2014) demonstrated the supplementary practice of modelling and thermography in the actual context by evaluating thermal bridges in building envelope construction. The authors (Taylor et al., 2014) concluded that combining a couple of methods confirm the strengthening of diagnostic and analytical stages in the process of thermographic investigation. Capozzoli et al. (Capozzoli, Gorrino, & Corrado, 2013) conducted a sensitivity analysis on 36 thermal bridges using the numerical method, including the most typical junctions of the building envelope. More similar research were carried out using numerical modelling (Aguilar, Solano, & Vicente, 2014; Deque, Ollivier, & Roux, 2001; Ge & Baba, 2017; Quinten & Feldheim, 2016; S. Y. Song et al., 2008; Viot, Sempey, Pauly, & Mora, 2015), in that it is a convenient, reliable, fast, widely applicable and uncomplicated method.

The numerical calculation method is validated by the standard EN ISO 10211 (2017). According to the standard the coefficient of point heat transmittance is calculated using the equation:

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

where L_{3D} is the thermal coupling coefficient obtained from 3D calculation of the 3D component separating the two environments under consideration, U_i– the thermal transmittance of the 1D component i separating the two environments under consideration, A_i– the area over which the value U_i applies, Ψ_j– linear thermal transmittance, l_j– the length over which the value Ψ_j applies, N_j– the number of 2D components, N_i– the number of 1D components.

The easiest and simplest method to estimate the influence of point thermal bridges is the empirical approximate procedure in accordance with the standard EN ISO 6946 (2017). The empirical equation from the standard allows calculating the correction to the thermal transmittance due the impact of point thermal bridges. First of all, this procedure calculates the total resistance R_{tot} of all layers of the building envelope; then, the thermal transfer U_0 without connectors is found from the previously calculated R_{tot} value, and the value of the correction of the thermal transmittance due to the influence of connectors is added (Eq. 2, Eq. 3).

$$U = U_0 + \Delta U_c, \tag{2}$$

$$\Delta U_c = \alpha \cdot \frac{\lambda_c \cdot A_c \cdot n_c}{d_1} \cdot \left(\frac{R_1}{R_{tot}}\right)^2, \tag{3}$$

where $\alpha = 0.8$ if the connector fully pierce whole insulation layer, $\alpha = 0.8 \times \frac{d_1}{d_0}$ in the case of the recessed connector, λ_c– thermal conductivity of the connector (W/(m·K)), n_c– the number of heat-conductive connectors per m², A_c– the cross-sectional area of one connector (m²), d_0– the thickness of the insulation layer holding the connector (m), d_1– the length of the connector penetrating the insulation layer (m), R_1– the thermal resistance of the insulation layer pierced by the connectors (m²·K/W), R_{tot}– the total thermal resistance of the structure ignoring any thermal bridging.

This approximate procedure is a simple, express and appropriate method for designers, engineers, architects and other users. Nevertheless, the previous investigations showed importantly different results of heat transmittance of wall structures obtained by the standard approximate procedure and numerical calculations, especially when high heat-conductive connectors are used. Significant differences of heat transmittance of facade systems with heat-conductive connectors obtained by the approximate empirical procedure and 3D numerical calculation method as well as the characteristics, having the most important influence on the facade heat transfer such as thermal conductivity of connectors, thickness and thermal conductivity of thermal insulation material, were determined and published (Levinskytė, Bliūdžius, & Kapačiūnas, 2018). Santos et al. (Santos, Goncalves, Martins, Soares, & Costa, 2019) have evaluated the heat transmittance of lightweight steel-framed (LSF) walls using four approaches: experimental measurements applying the heat flow meter (HFM) method; 3D numerical simulation using ANSYS software; 2D numerical simulation using THERM software; analytical estimation according to the standard EN ISO 6946 (2017) procedure. The research showed a conducive performance of the empirical approximate procedure regarding simple LSF walls. However, the main disadvantage of the research was the use of only one material frame without comparing with other frame materials. Analysing the LSF walls, Gorgolewski (Gorgolewski, 2007) has determined the impact of heat-conductive metal connectors in accordance with the standard EN ISO 6946 (2017) and creating the finite element model by numerical simulation method. The correction of thermal transfer of wall ΔU_c was calculated 0.0077 W/m²·K due to the impact of stainless-steel ties by the standard approximate procedure and 0.008 W/m²·K by the numerical method. The researcher asserted that the empirical equation (Eq. 3) was sufficient for evaluating the influence of connectors crossing the thermal insulation layer; however, the results of these two methods were not compared when changing the material of connectors.

In order to demonstrate the practical significance of the application of the standard approximate empirical procedure for the thermal performance of a building, a typical 9-storey apartment building was selected, and its heat loss through the walls (wall area $2170\ m^2$) was calculated using the NRG5 energy performance certification computer program. The heat transmittance of walls with aluminium alloy connectors ($\lambda c = 160\ W/m \cdot K$) was calculated in the first case, according to the standard approximate procedure, and in the second case, using 3D numerical modelling. In the first case, the heat loss per 1 m² wall area was calculated $11.94\ kWh/(m^2 \cdot years)$, in the second case, $5.82\ kWh/(m^2 \cdot years)$. This difference results in about 30% higher energy consumption for heating the building. Since point thermal bridges in the facade systems of multi-apartment residential buildings are usually identical, their impact on the thermal characteristics of such buildings will be similar to the calculated for the selected typical multi-apartment building.

Nowadays the composite connectors or glass fibre reinforced plastic connectors crossing the thermal insulation layers are often used in practice in order to reduce the negative effect of point thermal bridges in wall structures. However, the metallic connectors made from aluminium alloy, steel or stainless steel are also usually used in facade structures. A review of recent research revealed a lack of investigations evaluating the thermal conductivity of the connectors, although it is an important characteristic influencing the point thermal bridge's impact on the thermal transmittance through building envelopes. "Recent studies or standards have not mentioned that the standard approximate procedure is only applicable for stainless steel connectors, and the results of the corrected thermal transmittance coefficient are the most compatible with the numerical and experimental results. Therefore, in order to adapt this empirical calculation method to all materials of connectors, the main purpose of this research is to examine the equation used for the approximate procedure and suggest correction of this equation, backed up with the determined dependencies" (Stonkuviene, Bliudzius, Burlingis, & Ramanauskas, 2021).

A detailed research of wall constructions with heat-conductive connectors allowed to determine the main reason for a significant difference between the values of heat transmittance evaluated by approximate calculation procedure and other experimental or numerical simulation methods. The standard approximate procedure assesses the total heat flow that can pass through the connectors without any restrictions, although newer research has shown that the heat flow is limited by the ability to take the heat from the indoor environment and give away this amount of heat to the outside environment. This means that the amount of heat passing through the connector depends on the heat input and output area of the connector. The dependencies of the intensity of heat flow through the wall structure on the thickness of the thermal insulation layer and the thermal conductivity of metal connectors are very significant as well.

2. RESEARCH METHODOLOGY

2.1. Graphic algorithm of the research

The research on ventilated facade systems with heat-conductive connectors was performed according to the algorithm, which is shown in Fig. 2.1.

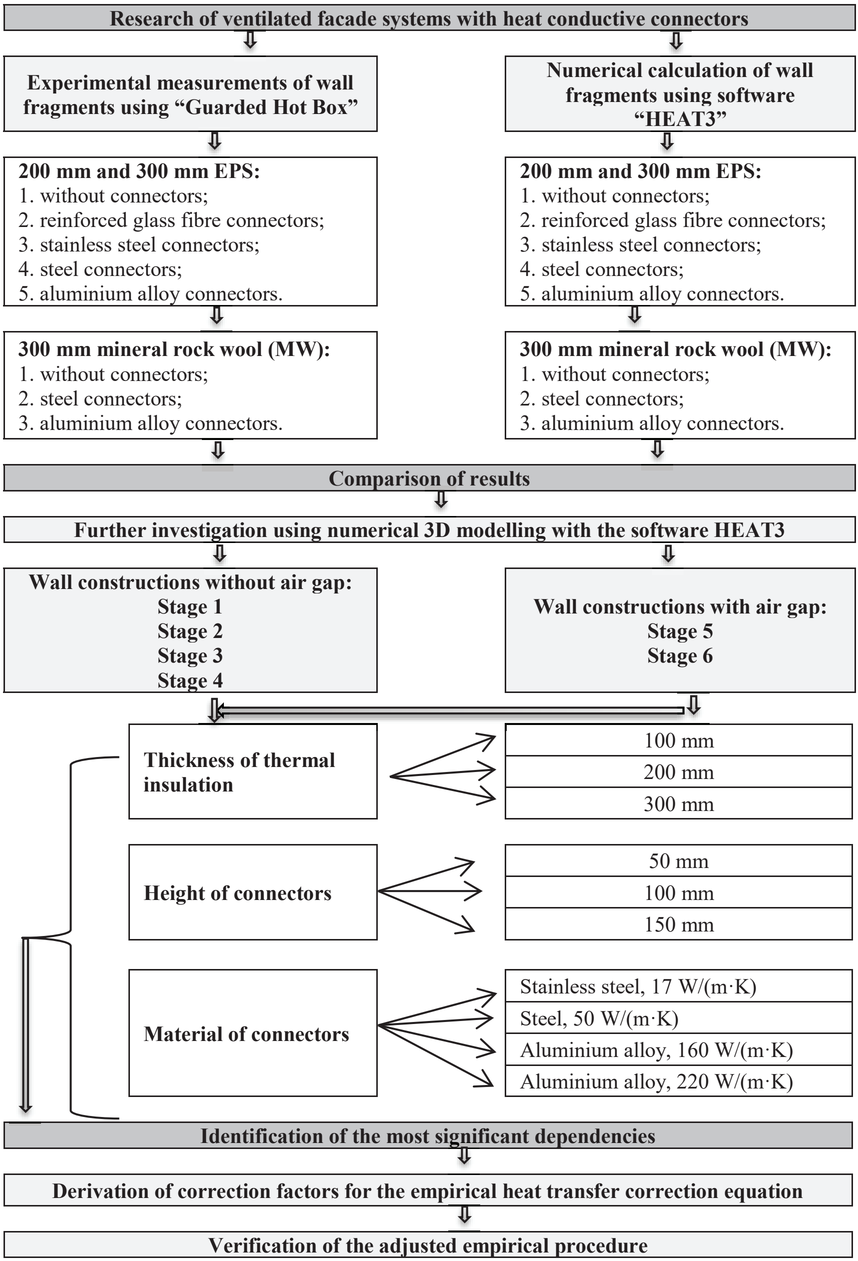
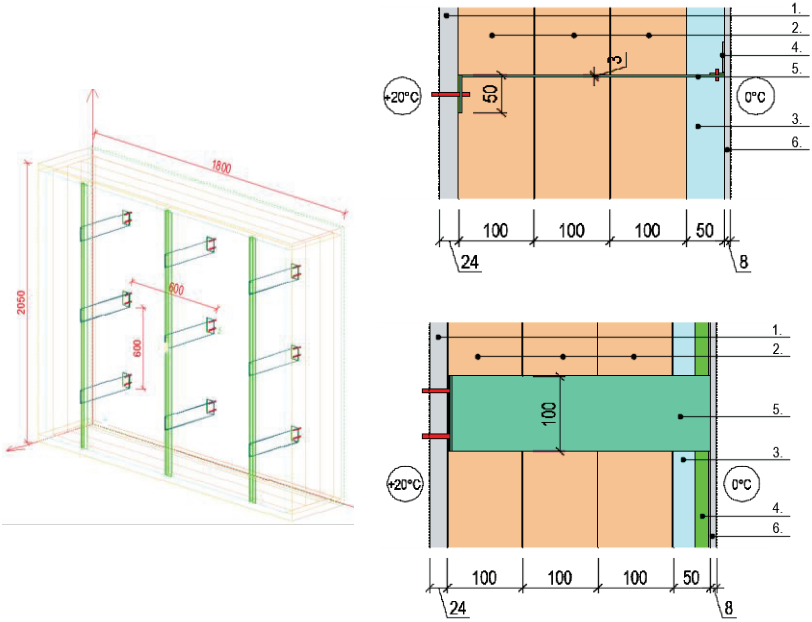


Fig. 2.1. Graphic algorithm of the research

2.2. Geometric model of wall fragment with heat-conductive connectors

Experimental and theoretical research was carried using a created geometric model of a ventilated wall fragment with heat-conductive connectors. The geometric view of the wall model is shown in Fig. 2.2. The dimensions of the wall fragment are selected according to the dimensions of the test equipment "hot box" partition opening into which the samples are mounted: height 2050 mm, width 1800 mm. The thickness of the wall fragment varies depending on the thickness of the thermal insulation layer, i.e., from 282 mm to 382 mm.



(a) (b)

Fig. 2.2. Wall fragment with heat-conductive connectors: a) 3D model view, b) top and side view

2.3. Materials

Table 2.1 shows the materials selected for the model creation of the wall fragment. Material numbers in Table 2.1 match the numbers in Fig. 2.2.

Table 2.1. The materials selected for the creation of a geometric model of external ventilated wall with heat-conductive connectors

No.	Material	Thickness, mm	Thermal conductivity $\lambda, W/(m \cdot K)$
1.	Cement–sawdust plate	24	0.27
2.	Thermal insulation layers: EPS/MW	100	0.031/0.034
3.	Air gap	50	0.144
4.	Aluminium alloy profile for fastening	3	160
5.	"L" shape heat-conductive connectors: aluminium alloy/steel/stainless steel/reinforced glass fibre	3	220/50/17/0.23
6.	Cement–sawdust plate	8	0.27

Two different thermal insulation materials were chosen for experimental measurements and theoretical simulation of wall structures: mineral wool (MW) and expanded polystyrene foam (EPS). The investigations of heat transmittance of wall fragments were carried out with two thicknesses of thermal insulation materials: 200 mm and 300 mm. MW is a fibrous compressive insulation material that ensures tight contact between the thermal insulation material and the connector. EPS harder material and do not have so tight contact with the connector comparing to the MW. The measured and calculated heat transfer values of wall structure may differ from each other if thermal convection takes place in the thermal insulation material, it means the air movement will be possible in air-permeable mineral wool or cracks between the EPS. On purpose to avoid the influence of convection, MW with air permeability of $42 \cdot 10^{-6}\ m^3/(m \cdot s \cdot Pa)$ was chosen for the research, and EPS plates were carefully cut by adjusting them to the connectors and to each other.

The suppliers of materials intended for connectors' production supplied the data of the materials' thermal conductivity and these data were besides checked in the chemistry manuals. The calibrated HFM apparatus was used in order to determine the thermal conductivity values of the thermal insulating materials. The measurements were carried out in laboratory according to the standard EN 12667 (2002). The accuracy of thermal conductivity measurement is between 1.25–1.73%, whereas it was calculated using the standard procedure.

Nine "L" shape connectors (Fig. 2.3) of each material, three vertical "L" shape aluminium alloy profiles, thermal breaks and steel screws were used for the creation of wall fragment.

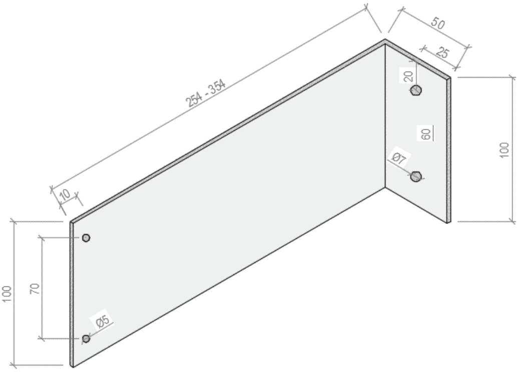


Fig. 2.3. "L" shape connector's preparation scheme

2.4. Test conditions

The experimental research and numerical simulation of wall fragments with heat-conductive connectors were carried out in stationary conditions. The temperature regime was set at 20 °C inside of construction and 0 °C outside of construction. When measuring constructions in the "hot box", the most commonly used outdoor temperature is 0 °C. The 0 °C outdoor temperature is close to the average temperature of the heating season; during the measurement, the average temperature of the sample becomes +10 °C, which corresponds to the conditions used by the heat flux meter apparatus measuring the thermal conductivity of the materials. The ambient conditions in the laboratory were as well kept constant: temperature 23±2 °C, relative humidity 50±5%.

"In order to compare the numerical calculation and experimental "hot box" measurement results, the air gaps were evaluated as not ventilated during the numerical calculation and experimental measurement. The temperatures of all surfaces of fragment were measured in "hot box" using thermocouples, and, having heat flow value, the thermal conductivity of the air gap layer was calculated. After that, this conductivity was used in 3D numerical calculation for simulation of air gap. In this way, similar air gap conditions were created for the evaluation of the impact of connectors on heat transfer through the wall fragment" (Stonkuviene et al., 2021).

The research was not focused on the comparison to real life conditions of air gap ventilation in the facade systems. Ventilated and not ventilated air gaps have different influence on the final result of heat transmittance of wall fragment. In order to compare these values, one sample of wall fragment (300 mm EPS with aluminium alloy connectors) was measured without external finishing layer (8 mm cement-sawdust plate). In this way, the ventilated air gap was simulated in "hot box". The thermal resistance of the wall fragment with not ventilated air gap was measured $R = 4.7791\ m^2 \cdot K/W$. The thermal resistance of the wall fragment with ventilated air gap was measured $R = 4.3754\ m^2 \cdot K/W$. Thus, the difference between the values is about 8%. The ventilation of air gap does not change the main dependencies of heat flow through thermal insulation systems with heat-conductive connectors. In accordance with the requirements of standard EN 6946 (2017), the approximate procedure is applied to facade systems without air gaps as well as with ventilated or non-ventilated air gaps. The presence or absence of an air gap and its ventilation are evaluated by calculating the thermal transfer coefficient U_0 without connectors (Eq. 2). The effect on the ΔU_c is estimated by calculating R_{tot} (Eq. 3).

2.5. Detailed analysis of approximate procedure

2.5.1. Physical meaning of heat transmittance equation

According to the approximate procedure, the thermal resistance of the structure without connectors is calculated first. Then, the heat transfer through the connectors is calculated and corrected by the ratio $\left(\frac{R_1}{R_{tot}}\right)^2$ and the coefficient of 0.8. The heat transmittance through walls with connectors using Eq. 2 is calculated as a sum of the heat transmittance of the same wall without a connector and the heat transmittance resulting due to the connector's influence (Fig. 2.4), which is described by Eq. 3.

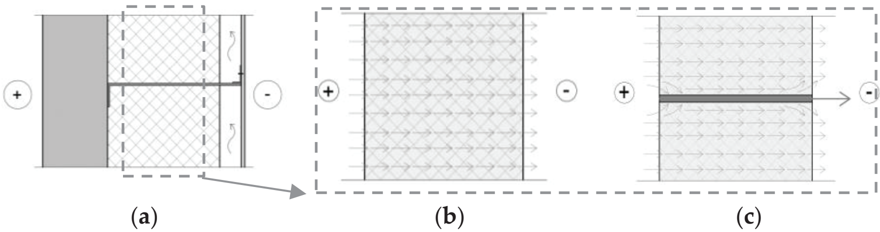


Fig. 2.4 Heat flow through the thermal insulation: a) whole wall structure, b) without a connector, c) with a connector

The member of Eq. 3: $\frac{\lambda_c \cdot A_c \cdot n_c}{d_1}$ describes the heat transmittance through the element, which has an area $A_c \cdot n_c$. The heat transmittance of the connector U_c can be written as below:

$$\frac{\lambda_c}{d_1} = U_c; \tag{4}$$

then, the member of the Eq. 3 can be rewritten:

$$\frac{\lambda_c \cdot A_c \cdot n_c}{d_1} = U_c \cdot A_c \cdot n_c. \tag{5}$$

"Using the approximate procedure, the heat transmittance through the connector is corrected by two coefficients: 0.8 (when the connector crosses the layer of thermal insulation) and $\left(\frac{R_1}{R_{tot}}\right)^2$. The coefficient 0.8 has unknown physical meaning, because it is not clear why such a coefficient is applied and how it was obtained. Maybe, it was determined for some specific geometry or material of the connectors, but this information is not mentioned in the standard or other literature. The ratio $\left(\frac{R_1}{R_{tot}}\right)^2$ shows how the heat transmittance through the connector varies depending on the square of the ratio between the thermal resistances of the thermal insulation layer and the whole construction without connectors. This factor approaches 1 when the thermal resistance of the thermal insulation layer is close to that of the whole construction and has little effect on the heat transfer through the connector. The factor parabolically decreases when the thermal resistance of the load-bearing layer (base wall) increases. This means that the heat transmission through the connector passing the thermal insulation layer is smaller when there is a lower impact of the thermal insulation layer on the overall thermal insulation of the wall structure" (Stonkuviene et al., 2021).

2.5.2. Stages in the correction of approximate calculation procedure

In order to establish the physical meaning and eligibility of coefficient 0.8 for the correction of heat transfer, a new coefficient a is introduced. The ratio between the correction of heat transmittance due the effect of the connectors ΔU_c calculated by using the 3D calculation method and the heat transfer coefficient of the connector calculated empirically by the connector material's thermal conductivity and the cross-sectional area is indicated with equation:

$$a = \frac{\Delta U}{U_c \cdot A_c \cdot n_c \cdot \left(\frac{R_1}{R_{tot}}\right)^2}, \tag{6}$$

where U_c is the heat transmittance of the connector, $(W/m^2 \cdot K)$; A_c – the cross-sectional area of one connector, (m^2); R_1 – the thermal resistance of the insulation layer penetrated by the connectors, $((m^2 \cdot K)/W)$; R_{tot} – the total thermal resistance of the component, ignoring thermal bridging, $((m^2 \cdot K)/W)$.

The refinement of the empirical calculation procedure is performed in stages by changing the geometrical parameters of the structure and the characteristics of the thermal insulation layer. Fig. 2.5 demonstrates the location of the connectors in the cross-section of wall fragments, which were simulated with 3D numerical software.

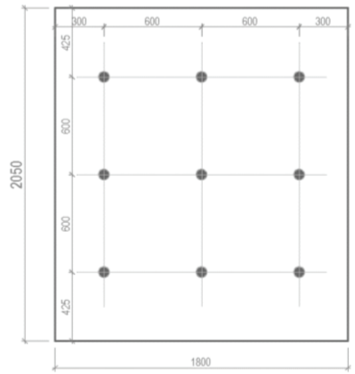


Fig. 2.5. Scheme of connectors' locations in simulated wall fragments (units in mm)

In order to determine the parameters that have the most significant effect on the heat transfer of the structure and the dependencies on them, the simplest structure was analysed first, where the thermal insulation layer is crossed by heat-conductive connector. Subsequently, the additional structural layers were added, and their effect on the heat flow was analysed. Six wall constructions with more and more elements with and without air gaps were selected and investigated according to the algorithm presented in Fig. 2.1 with the 3D numerical calculation method. The investigation is divided into stages according to the wall fragment structures schemes, which were described in the publication by A. Stonkuviene et al. (Stonkuviene et al., 2021):

"Stage 1. Thermal insulation layer crossed by the straight heat-conductive connector;

Stage 2. Thermal insulation layer crossed by the bended heat-conductive connector;

Stage 3. Thermal insulation layer crossed by the bended heat-conductive connector fixed to the load-bearing layer;

Stage 4. Thermal insulation layer crossed by the bended heat-conductive connector fixed to the load-bearing and finishing layers;

Stage 5. Thermal insulation layer crossed by the bended heat-conductive connector extended through the air gap;

Stage 6. Thermal insulation layer crossed by the bended heat-conductive connector extended through the air gap and fixed to the load-bearing and finishing layers".

The wall structures of each stage were investigated by using 3D numerical simulation software. The calculations were performed by setting the standard temperature regime: 0 °C outside the structure; 20 °C inside the structure.

3. RESEARCH RESULTS

3.1. Comparison of results of numerical simulation and experimental measurements

The investigated wall fragments were simulated using 3D finite-difference numerical modelling software HEAT3 (version 6.1.0.0). The uncertainty of numerical simulation is contingent on the geometry of the model elements, density of the chosen numerical mesh and uncertainty measurement of the material's thermal conductivity. The mesh density for models was picked according to the HEAT3 software developer's recommendations for evaluating the heat transmittance through the structures with heat-conductive connectors.

The comparison of results of experimental measurements and numerical simulation confirms the reliability of numerical calculation method in all cases. The comparison of heat transmittance values of external wall specimens obtained by the experimental measurements and numerical calculation method is presented in Fig. 3.1.

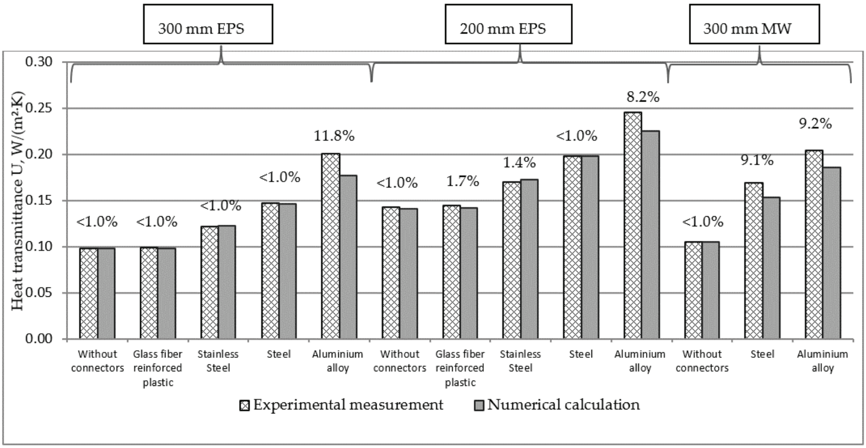


Fig. 3.1. Comparison of heat transmittance obtained by the experimental and numerical calculation methods

"The largest difference between the measured and calculated heat transfer coefficients was 11.8%, when the sample was equipped with aluminium connectors, whose thermal conductivity is over seven thousand times larger than the thermal insulation material EPS" (Stonkuviene et al., 2021). The ideal case of a wall fragment with connectors crossing the thermal insulation layer is created by using numerical calculation method, because all connectors' surfaces have the ideal contact with the thermal insulation layer. This ideal case is impossible to ensure in practice, because micro air gaps are formed between the connectors and thermal insulation material, which have an impact on the heat exchange and lead to arising differences between the results obtained by the experimental measurements and numerical calculation.

As shown in Fig. 3.1 the differences between the calculated and measured heat transmittance values of structures with lower thermal conductivity connectors fall within the extended uncertainties' limits that are set for the measuring device. The measurement extended uncertainty values of thermal resistance were calculated for each case of the sample: 1.69–2.46% for wall samples of 300 mm with EPS, 1.64–1.92% for wall samples of 200 mm with EPS, 1.72–2.23% for wall samples of 300 mm with MW. The confidence level of extended uncertainty values is 95%.

The MW material has better contact with the connector, therefore smaller differences were determined between the results of thermal performance of measured and simulated wall fragments with MW thermal insulation. Nevertheless, the lower homogeneity of the structure of thermal insulation material's also affects the final result. The effect of the contact between the thermal insulation material and the connector's surface on the heat transmittance through the wall fragments was confirmed, whereas larger differences were obtained at higher thicknesses and longer connectors of the investigated fragments. Furthermore, MW material is more than 120 times more air permeable than EPS; thus, this factor can be important reason of the difference between the first and third groups of measured and simulated results (Fig. 3.1). Based on the results of the comparison of experimental and numerical methods, it has been found that the influence of connectors with extremely low thermal conductivity coefficients and similar to plastic can be underestimated for heat transfer through a ventilated wall structure. Given that the measured and calculated values of the heat transfer coefficient of walls without connectors do not differ by more than 1%, it can be stated that the experimentally measured and numerically calculated values of heat transfer coefficients of walls with thermally conductive connectors are equivalent in practice of heat loss assessment of buildings. In addition, the results of this study have shown that the differences in the structure and thermal conductivity of thermal insulation materials do not have a significant effect on the heat transfer through wall structures with heat-conductive connectors. Larger temperature gradient as well did not have significant influence on the results. One of the wall fragments (with 300 mm MW and steel connectors) was measured in two temperature regimes: 0 °C/20 °C and -15 °C/20 °C. The first temperature regime gave $R=5.6618\ m^2{\cdot}K/W$ and the second $R=5.5381\ m^2{\cdot}K/W$. The difference between the values is about 2%. Consequently, based on the results of this study, it was decided to perform further theoretical investigations of ventilated wall fragments by the method of numerical modelling using EPS thermal insulation.

3.2. Application of correction factor a to wall constructions with connectors of different thermal conductivity

Summarizing the results of the analysis of heat flows through various wall structures and the calculation of correction factors, the mathematical expressions of the average coefficients a have derived, which directly depend on the length of the connectors. The average values of the coefficients a were obtained for each case of connectors of different thermal conductivity and for two cases of wall constructions, i.e., with and without an air gap.

3.2.1. Simplified application of coefficient a to wall constructions without air gap

The coefficient a for the investigated constructions may be calculated using the following equations that were described in publication by A. Stonkuviene et al.:

"$a = 1.8 \cdot L$ – for stainless steel connectors ($\lambda_c = 17, W/(m \cdot K)$), (7)

$a = 0.7 \cdot L$ – for steel connectors ($\lambda_c = 50, W/(m \cdot K)$), (8)

$a = 0.25 \cdot L$ – for aluminium alloy connectors ($\lambda_c = 160, W/(m \cdot K)$), (9)

$a = 0.2 \cdot L$ – for aluminium alloy connectors ($\lambda_c = 220, W/(m \cdot K)$), (10)

where L is the connector's length (thickness of thermal insulation)" (Stonkuviene et al., 2021).

In coefficient a equations (7–10), the multipliers were determined by creating matrices according to the coefficients a obtained from the calculation results of constructions in stages 1–4. The values of the coefficient a were divided by the connector length. The calculated values were not uniform; therefore, they were averaged, and for this reason, the corrected calculation procedure is approximate as well. In order to obtain one equation for the calculation of the heat transfer correction factor a using any heat-conductive connectors, the equations for the thermal conductivity of the connectors have derived from the calculated multipliers of the coefficient a (equations 7, 8, 9, 10). The dependency graph is shown in Fig. 3.4.

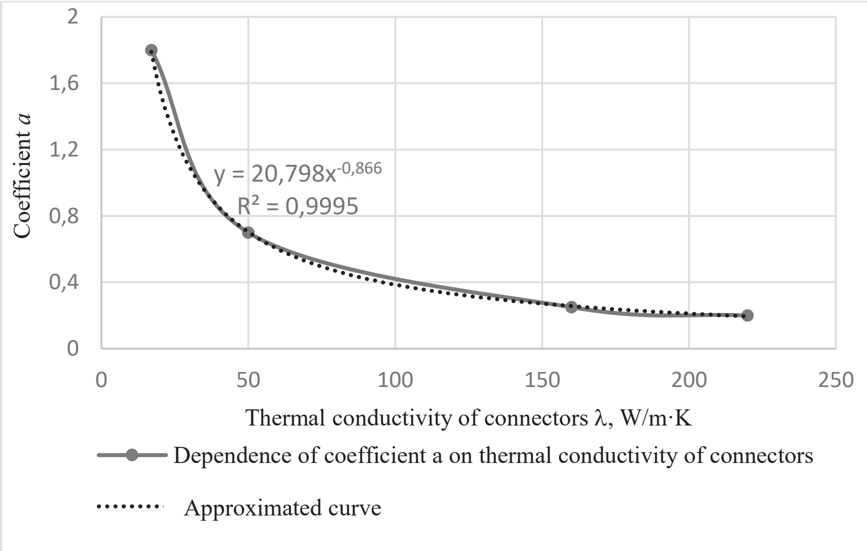


Fig. 3.4. Dependence of coefficient a on the thermal conductivity of connector: the case of construction without air cavity

Then, the coefficient a for wall structures without air gaps can be calculated according to the following equation:

$$a = \frac{20.798}{\lambda_c{}^{0.866}} \cdot L \ . \tag{11}$$

For practical use, the previous equation has been simplified and rewritten as follows:

$$a = \frac{21}{\lambda_c{}^{0.87}} \cdot L \ . \tag{12}$$

3.2.2. Simplified application of coefficient a to wall constructions with air gap

The coefficient a for the investigated wall constructions with air gap may be calculated with some error using the equations that were described in publication by A. Stonkuviene et al. (Stonkuviene et al., 2021):

$a = 3.2 \cdot L$ – for stainless steel connectors ($\lambda_c = 17, W/(m \cdot K)$), (13)

$a = 1.6 \cdot L$ – for steel connectors ($\lambda_c = 50, W/(m \cdot K)$), (14)

$a = 0.75 \cdot L$ – for aluminium alloy connectors ($\lambda_c = 160, W/(m \cdot K)$), (15)

$a = 0.55 \cdot L$ – for aluminium alloy connectors ($\lambda_c = 220, W/(m \cdot K)$). (16)

In equations (13−16), the multipliers were determined by forming matrices according to the coefficients a obtained from the calculation results of the constructions in stages 5–6. As in the case of structures without air gap, the equation for the thermal conductivity of the connectors has derived from the calculated multipliers of the coefficient a (equations 13, 14, 15, 16). The dependency graph is shown in Fig. 3.5.

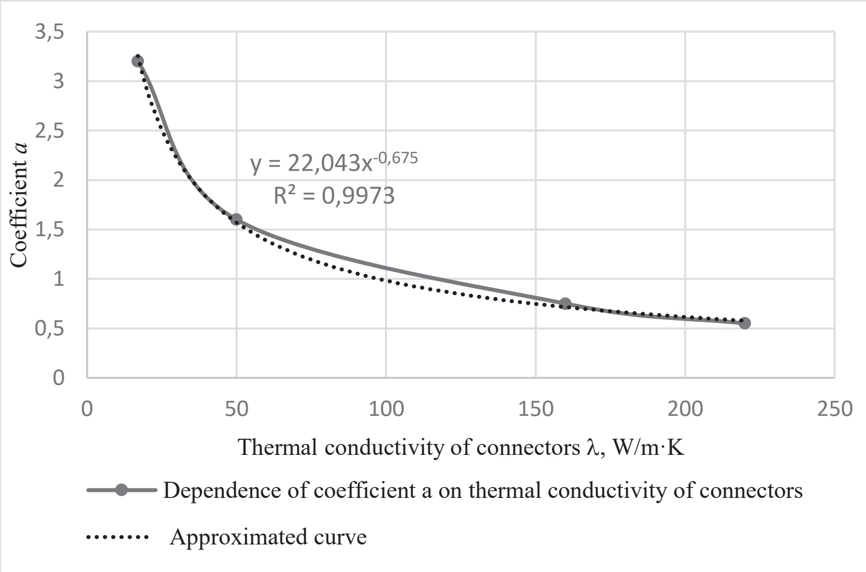


Fig. 3.5. Dependence of coefficient a on the thermal conductivity of connector: the case of construction with air cavity

Then, the coefficient a for wall structures with air gaps can be calculated according to the following equation:

$$a = \frac{22.043}{{\lambda_c}^{0.675}} \cdot L. \tag{17}$$

For the practical use, the previous equation has been simplified and rewritten as follows:

$$a = \frac{22}{{\lambda_c}^{0.68}} \cdot L. \tag{18}$$

After performing the calculations and applying the mathematical steps, the heat transfer correction for the effect of heat-conductive connectors ΔU is calculated according to the following equation using the new correction coefficient a, depending on whether the wall structure is with or without air gap:

$$\Delta U_c = a \cdot \frac{\lambda_c \cdot A_c \cdot n_c}{d_1} \cdot \left(\frac{R_1}{R_{tot}}\right)^2. \qquad (19)$$

3.3. Verification of reliability of corrected empirical calculation procedure

After making corrections to the empirical heat transfer calculation procedure, the corrected empirical procedure was verified by comparing the obtained results with the results of studies published in the scientific literature on heat transfer of ventilated facade systems. For this comparison, two studies were used in which the heat transfer of wall structures was determined using numerical modeling programs. The first study selected for comparison was conducted by the authors T. G. Theodosiou et al. (T. G. Theodosiou et al., 2015) (Table 3.1). The authors investigated the influence of thermal bridges formed in the structures of ventilated facades with steel connectors on the heat transfer. The second selected study was conducted by the authors K. Nowak and A. Byrdy (Nowak & Byrdy, 2019), which as well analyses heat transfer through ventilated facade systems in which thermal insulation layers are crossed by aluminium alloy and steel connectors (Table 3.2).

Table 3.1. The comparison of the heat transmittance of a constructed ventilated wall system with steel connectors by corrected and not corrected empirical and 3D numerical methods

Load-bearing layer	Ventilation of air cavity	Thickness of thermal insulation, mm	U, W/m²·K			Difference %	
			Approx. proc.	Corrected approx. proc.	3D numerical method	3D/ approx. proc.	3D / corrected approx. proc.
Reinforced concrete (*λ=2.4 W/m·K*)	Ventilated	100	0.430	0.299	0.29	48.2	3.2
	Not ventilated	200	0.234	0.175	0.17	37.4	3.2
	Without an air cavity	250	0.189	0.130	0.125	51.0	4.0

The results show minor discrepancies between the corrected approximate procedure and 3D numerical method with up to 4%. For that reason, the corrected equations are applicable and reliable for calculating heat transfer through facade systems with metal connectors.

Table 3.2. The comparison of the heat transmittance of ventilated wall system construction with aluminium alloy connectors by corrected, not corrected empirical and 3D numerical methods

Load-bearing layer	Ventilation of air cavity	Thickness of thermal insulation, mm	U, W/m²·K			Difference %	
			Approx. proc.	Corrected approx. proc.	3D numerical method	3D/ approx. proc.	3D/ corrected approx. proc.
Reinforced concrete (*λ=1.7 W/m·K)*	Ventilated	200	0.546	0.253	0.265	105.9	4.6
Cellular concrete (*λ=0.10 W/m·K)*	Ventilated	200	0.310	0.164	0.165	87.8	0.5

The results of comparing the heat transfer of wall structures with aluminium alloy connectors also demonstrated minor discrepancies between the corrected approximate procedure and 3D numerical method with up to a 5%. This consequently verifies the reliability of the corrected procedure for calculating the correction of heat transmittance due the impact of connectors.

3.4. Limitations and recommendations on the practical application of corrected approximate procedure

The corrected approximate calculation procedure can be used to calculate the heat transfer coefficient of facade systems with and without air gap. The air gap in wall structures may be ventilated or non-ventilated. The following limitations and recommendations shall be met when applying the corrected approximate calculation procedure for heat transfer through a wall structure with metal connectors. The following limitations and recommendations were as well presented in publication by A. Stonkuviene et al. (Stonkuviene et al., 2021):

- The determined dependencies must be applied separately to structures without air gap and with air gap, which may or may not be ventilated. Using an approximate procedure, the impact of air gap ventilation is evaluated by calculating the heat transfer coefficient of the structure without connectors.
- Polymeric and fibrous thermal insulation materials may be used for the thermal insulation layer, but their air permeability and method of installation must ensure the absence of air movement inside the material causing thermal convection. Disregarding this requirement will result in convective heat exchanges between the connector and the air, moving inside the thermal insulation layer, and it will have a significant effect on the calculation result.

- Although the influence of the connector's cross-section area on the coefficient was found to be insignificant, the investigation was performed only with rectangular connectors of 50–150 mm high and 3 mm thick that are most commonly used in facade systems; therefore, the adjusted procedure can be applied only to rectangular connectors of close dimensions.
- The corrected approximate procedure could not be applied to structures with lower than 100 mm thickness of thermal insulation layers, where the effect of the connector is felt throughout the thickness of the whole thermal insulation layer. In this case, the heat exchange scheme between the connector and the environment changes, and significant errors are possible.
- The determined dependencies, as well as the whole approximate procedure, are not applied to the structures with a thermal resistance of the load-bearing layer greater than or equal to the resistance of the thermal insulation layer. The value of the ratio $(\frac{R_1}{R_{tot}})^2$ (Eq. 3) becomes very small; therefore, the value of ΔU decreases significantly. This can lead to large errors of calculation results, because the entire thermal insulation layer with the connector is in a lower temperature environment that changes the heat exchange of the connector with the external environment.

DISCUSSION

The inaccurate standardized calculation method is still used for heat transmittance calculation of facade systems with heat-conductive connectors in practice. The overestimation of heat transmittance of the facade system limits the use of them in energy-efficient construction. Newly build energy-efficient, near-zero energy or renovated apartment buildings could use thermal insulation systems with heat-conductive connectors more often if the heat transmittance coefficient was evaluated correctly: heat loss [kWh/(m²·year)] through the external wall with aluminium alloy connectors of the apartment building will be more than 2 times smaller, compared to the one calculated by the standard approximate procedure and corrected approximate procedure. In the same case, the energy consumption for heating the building [kWh/(m²·year)] increases by about 30%, when not corrected empirical procedure was used for the calculation of the heat transmittance through the wall structures. Consequently, it is obvious that the investigations of heat flow through facade systems with heat-conductive connectors are relevant and still insufficient; therefore, a detailed research in this field is inevitable in order to allow using the insulation systems with heat-conductive connectors for the construction of energy-efficient building without exceeding the thermal insulation materials and the power of building engineering systems.

Highly heat-conductive aluminium alloy connectors are not recommended for buildings that must meet high energy-efficiency requirements. Newly determined dependence between the thermal conductivity of the connectors and the increase of the heat transfer through the thermal insulation layer with these elements allow to refute the mentioned recommendation. It has been found that the conditions of heat exchange of the connector with the construction environment must be evaluated by assessing the impact of heat-conductive connectors on the heat transmittance. Only the most commonly used "L" shape connectors were investigated in this study; therefore, a greater diversity of connectors will be investigated in further studies.

GENERAL CONCLUSIONS

1. Metal connectors crossing the thermal insulation layers of building facade systems create point thermal bridges that significantly increase the heat transfer. The use of a standard approximate empirical procedure to calculate the heat transfer coefficients of point thermal bridges on a building facade can increase the energy consumption for the building heating by 30%; therefore, a more accurate determination of the thermal properties of these bridges is an important task for improving the energy efficiency assessment system of buildings.
2. The experimental research of wall fragments with heat-conductive connectors using the "hot box" method confirmed the reliability of the 3D numerical modelling method for detailed studies of heat transfer through facade systems with and without air gaps.
3. The main disadvantage of calculating the heat transfer coefficient of facades with heat-conductive connectors using the standard equation is that the equation does not evaluate the conditions of heat exchange between the connector and the construction environment.
4. The relationship between the thermal conductivity of the connectors and the increase of heat transfer through the thermal insulation layer with the connectors is not direct: the higher is the thermal conductivity of the connector's material, the lower amount of the heat flux through the connector must be included in the overall heat transfer of the wall. This ratio depends on the surface area of the connector through which the heat enters from the internal environment to the connector and from the connector outside.
5. As the thickness of the thermal insulation layer of the facades increases, the effect of the highest thermal conductivity aluminium alloy connectors on the total heat transfer does not change significantly, and the effect of lower thermal conductivity steel or stainless steel connectors even decreases. This determined trend provides additional opportunities for the use of facade insulation systems with heat-conductive connectors in high energy efficiency buildings.
6. The values of heat transfer coefficients of facade systems calculated by the adjusted approximate procedure differ from the values calculated by other scientists by the 3D numerical modelling method by no more than 5%. Given the limitations of the application, the revised calculation equation can

be used for the empirical calculation of the heat transfer through wall structures with heat-conductive connectors for practical purposes.

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LIST OF SCIENTIFIC PUBLICATIONS ON THE SUBJECT OF THE DISSERTATION

Publications in the Master List of Institute of Scientific Information (ISI)

Indexed in the Web of Science with Impact Factor

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REZIUMĖ

Disertaciją sudaro įvadas, 3 skyriai, baigiamosios išvados, cituojamos literatūros bei disertantės mokslinių darbų sąrašas ir priedai. Bendra disertacijos apimtis 101 puslapis, kuriuose yra 41 paveikslas, 13 lentelių ir 28 formulės. Rengiant disertaciją buvo panaudoti 127 literatūros šaltiniai.

Darbo tikslas – ištirti šilumos perdavimą per termoizoliacinius sluoksnius su šilumai laidžiomis jungtimis ir išaiškinti šilumos srautų priklausomybę nuo jungčių geometrinių ir šiluminių charakteristikų.

Pirmajame skyriuje pateikiama mokslinės literatūros, straipsnių, standartų, techninių reglamentų ir kitų šaltinių apžvalga. Šiame skyriuje analizuojamas vėdinamų fasadų sistemų naudojimo aktualumas, privalumai, trūkumai bei jų šilumos perdavimo vertinimo metodai ir skirtingais metodais gaunamų žymių šilumos perdavimo rezultatų skirtumų problematika.

Antrajame skyriuje pateikta šilumos perdavimo per termoizoliacinius sluoksnius su šilumai laidžiomis jungtimis skaičiavimo ir matavimo metodika ir tyrimų algoritmo sudarymas. Šiame skyriuje detaliai aprašomas eksperimentinių ir teorinių tyrimų vykdymas: geometrinio sienos fragmento modelio sukūrimas, medžiagų ir kitų konstrukcinių elementų parinkimas bei paruošimas, taikytos tyrimo sąlygos bei tyrimo eiga.

Trečiajame skyriuje pateikiamas eksperimentinių bei teorinių tyrimų rezultatų palyginimas. Eksperimentiniu „karštosios dėžės“ metodu gauti sienų fragmentų šilumos perdavimo rezultatai ir papildomomis termoporomis išmatuotos temperatūros pasirinktuose taškuose šalia šilumai laidžių jungčių palyginimas su skaitiniu metodu suskaičiuota temperatūra atitinkamuose taškuose patvirtino teorinio skaitinio 3D metodo patikimumą, kadangi šiais dviem metodais gautos šilumos perdavimo ir temperatūros minėtuose taškuose vertės skyrėsi nežymiai, todėl toliau šiame skyriuje pateikiami sienų konstrukcijų su oro tarpu ir be jo detalių teorinių tyrimų rezultatai. Įvairių šiluminių ir geometrinių charakteristikų sienų konstrukcijų 3D skaitinio modeliavimo tyrimai padėjo nustatyti pagrindinius parametrus, kurie turi didžiausią poveikį šilumos srautui per fasadų su šilumai laidžiomis jungtimis sistemas. Detalūs teoriniai fasadų su šilumai laidžiomis jungtimis sistemų tyrimai atskleidė, kad ryšys tarp jungties šilumos laidumo ir šilumos perdavimo per termoizoliacinį sluoksnį su jungtimis padidėjimo nėra tiesioginis, kaip vertino standartinė empirinė skaičiavimo procedūra. Atlikti tyrimai taip pat parodė, kad didėjant fasadų termoizoliacinio sluoksnio storiui, didžiausią šiluminį laidumą turinčių aliuminio lydinio jungčių poveikis bendram šilumos perdavimui reikšmingai nesikeičia, o mažesnio šiluminio laidumo plieninių ar nerūdijančio plieno jungčių poveikis netgi sumažėja. Ši nustatyta tendencija suteikia papildomų galimybių fasadų šiltinimo sistemas su šilumai laidžiomis jungtimis naudoti aukšto energinio naudingumo pastatuose. Pagal nustatytas šilumos srauto intensyvumo priklausomybes nuo jungčių šilumos laidumo bei ilgio išvesti nauji pataisos koeficientai α fasadų

konstrukcijoms su oro tarpu ir be jo, kurie pakoreguoja empirinę šilumos perdavimo skaičiavimo procedūrą. Pagal pakoreguotą empirinę lygtį apskaičiuojami sienų su metalinėmis jungtimis šilumos perdavimo rezultatai gaunami labai artimi vertėms, kurias nustatė mokslininkai savo atliktuose tyrimuose, taikydami skaitinio modeliavimo metodą. Laikantis nustatytų taikymo apribojimų, galima teigti, kad pakoreguota empirinė skaičiavimo procedūra yra patikima ir tinkama praktiniam naudojimui.

Sprendžiami uždaviniai

1. Išanalizuoti šilumos perdavimo per termoizoliacinius sluoksnius su šilumai laidžiomis jungtimis skaičiavimo ir matavimo metodikas ir gaunamų rezultatų skirtumų priežastis.
2. Eksperimentiškai ištirti šilumos perdavimą per termoizoliacinius sluoksnius su įvairių geometrinių ir šiluminių charakteristikų jungtimis.
3. Skaitinio modeliavimo metodu nustatyti jungčių geometrinių charakteristikų ir šiluminio laidumo įtakos konstrukcijų šilumos perdavimui kiekybinius rodiklius.
4. Pakoreguoti standartinę konstrukcijų su šilumai laidžiomis jungtimis šilumos perdavimo koeficiento skaičiavimo lygtį pagal gautus eksperimentinio tyrimo ir skaitinio modeliavimo rezultatus.
5. Patikrinti pakoreguotos skaičiavimo lygties patikimumą, gautus rezultatus sulyginant su oficialiai paskelbtais fasadų sistemų šilumos perdavimo koeficientų matavimo ir skaičiavimo rezultatais, parengti naudojimo rekomendacijas.

Mokslinis darbo naujumas

1. Ištirta fasadų su šilumai laidžiomis jungtimis eksperimentinio matavimo ir skaičiavimo, taikant standartinę lygtį, rezultatų skirtumų priežastis: lygtyje neįvertintos jungties šilumos mainų su konstrukcijos aplinka sąlygos.
2. Nustatytos šilumos srauto intensyvumo per sienos konstrukciją su oro tarpu ir be jo priklausomybės nuo termoizoliacinio sluoksnio storio ir metalinių jungčių šilumos laidumo.

Tyrimų metodika

Šilumos srautų per pastatų fasadų sistemų termoizoliacinius sluoksnius su šilumai laidžiomis jungtimis eksperimentiniai tyrimai atlikti matuojant šilumos perdavimą „karštosios dėžės“ metodu (ISO EN 8990), papildomai naudojant temperatūros jutiklius prie jungčių.

Jungčių šiluminio laidumo ir geometrinių charakteristikų įtakos šilumos perdavimui per termoizoliacinius sluoksnius kiekybiniai rodikliai nustatyti modeliuojant sienų fragmentų šilumos perdavimą trimatėje erdvėje, naudojant temperatūrinių laukų skaičiavimo kompiuterinę programą HEAT3.

Pakoreguotos skaičiavimo lygtys patikrintos, gautus rezultatus lyginant su kitų autorių publikuotais analogiškų tyrimų rezultatais ir laboratorijos skaičiavimų ataskaitoje pateiktais įvairių parametrų fasadų sistemų šilumos perdavimo koeficientais.

Bendrosios išvados

1. Pastatų fasadų sistemų termoizoliacinius sluoksnius kertančios metalinės jungtys sukuria taškinius šiluminius tiltelius, reikšmingai padidinančius šilumos perdavimą. Standartinės apytikslės empirinės procedūros taikymas pastato fasado taškinių šiluminių tiltelių šilumos perdavimo koeficientams suskaičiuoti gali 30 % padidinti pastato energijos sąnaudas šildymui, todėl tikslesnis šių tiltelių šiluminių savybių nustatymas yra svarbus pastatų energinio efektyvumo vertinimo sistemos tobulinimo uždavinys.
2. Eksperimentiniai sienų fragmentų su šilumai laidžiomis jungtimis tyrimai „karštosios dėžės“ metodu patvirtino 3D skaitinio modeliavimo metodo tinkamumą išsamiems šilumos perdavimo per fasadų sistemas su oro tarpais ir be jų tyrimams.
3. Esminis fasadų su šilumai laidžiomis jungtimis šilumos perdavimo koeficiento skaičiavimo, taikant standartinę lygtį, trūkumas - lygtyje neįvertintos jungties šilumos mainų su konstrukcijos aplinka sąlygos.
4. Ryšys tarp jungties šilumos laidumo ir šilumos perdavimo per termoizoliacinį sluoksnį su jungtimis padidėjimo nėra tiesioginis: kuo didesnis jungties medžiagos šilumos laidumas, tuo mažesnė šilumos srauto dalis per jungtį turi būti įtraukta į bendrą sienos konstrukcijos šilumos perdavimą. Šis santykis priklauso nuo jungties paviršiaus ploto, per kurį šiluma patenka iš vidaus aplinkos į jungtį ir iš jungties – į išorę.
5. Didėjant fasadų termoizoliacinio sluoksnio storiui, didžiausią šiluminį laidumą turinčių aliuminio lydinio jungčių poveikis bendram šilumos perdavimui reikšmingai nesikeičia, o mažesnio šiluminio laidumo plieninių ar nerūdijančio plieno jungčių poveikis netgi sumažėja. Ši nustatyta tendencija suteikia papildomų galimybių fasadų šiltinimo sistemas su šilumai laidžiomis jungtimis naudoti aukšto energinio naudingumo pastatuose.
6. Fasadų sistemų šilumos perdavimo koeficientų vertės, apskaičiuotos taikant pakoreguotą apytikslę procedūrą, skiriasi nuo kitų mokslininkų 3D skaitinio modeliavimo metodu apskaičiuotų verčių ne daugiau kaip 5 %. Atsižvelgiant į taikymo apribojimus, patikslinta skaičiavimo lygtis gali būti taikoma empiriškai apskaičiuoti sienų konstrukcijų su šilumai laidžiomis jungtimis šilumos perdavimą praktiniais tikslais.

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