Experimental investigation of thermal bridges in building at real conditions

Robert Smusz[1,*], and *Michał* Korzeniowski[2]

[1]Thermodynamics Department, the Faculty of Mechanical Engineering and Aeronautics, Rzeszów University of Technology, al. Powstańców Warszawy 12, 35-959 Rzeszów, Poland
[2]Department of Electrical and Computer Engineering Fundamentals, the Faculty of Electrical and Computer Engineering, Rzeszów University of Technology, al. Powstańców Warszawy 12, 35-959 Rzeszów, Poland

Abstract. In recent time the energy consumption of buildings may be reduced by the application of modern technologies in the construction industry. Modern building materials ensure a reduction of heat losses. However, studies show that thermal bridges may cause up to 30% of the additional heat losses through the building envelope. Therefore, a one key aspect in assessing the real thermal state of buildings is the identification of the heat losses through thermal bridges. The analytical, experimental and numerical methods are used for the assessment of thermal transmittance value of building. In the paper the authors present the experimental research on heat losses through the building under real winter conditions. Infrared thermovision technique has been used to the thermal bridges assessment in situ. IR thermography technique allowed the determination of the influence of thermal bridges on the additional heat losses. For the obtaining the surface emissivity the measurements have been also performed with the use of thermocouples system. Numerical validation of the experimental results has been performed.

1 Introduction

Heat losses through the insulated envelope in modern buildings are mainly due to occurrence of thermal bridges. The heat losses contribute to the increase of energy consumption in buildings. The energy use of residential and commercial buildings contributes about 30% of final energy consumption in the most developed countries. Therefore, energy efficiency in buildings is one of the main objectives to reduce the energy demand.

Research shows that thermal bridges may cause up to 30%-60% of the additional-heat losses through the building envelope. Therefore, a one key aspect in assessing the real thermal state of buildings is the identification of the heat losses though thermal bridges. The heat loss through thermal bridges depends on the linear thermal transmittance. Values of this parameter can be obtained from tabulated values for typical building details based on standards or they can be calculated through a theoretical approach. For theoretical calculations the thermal conductivity and thickness of each material that constitutes the building wall must be known. Numerical simulations and direct measurements are the alternative way for the obtaining the thermal transmittance. But when the internal structure of the building envelope is unknown only measurement is the possible option.

Recently, the infrared thermography technique IR was proposed for the in-situ measurements. The main advantages of this method are non-invasiveness and the possibility of measurements the relatively large surfaces in real time. A review of the IR image analysis methods and the future trends are included in [1]. The authors concluded about usefulness of IR technique for the characterisation of defects in the buildings. Some researchers use IR in their study on an impact of thermal bridges on heat losses. Nardi et al. [2] describes a case study on the basis of the results obtained by IR method on existing building. Experimental results are compared with thermal transmittance given by the standard ISO calculations and heat flow meter measurements. The authors also discuss the advantages and limitations of IR thermography technique. In the next work [3] Nardi et al. presents the results of the study on the effect of three different types of thermal bridges on thermal transmittance. The results have been obtained with the use IR method. The methodology has been validated by numerical simulations. Albatici and Tonelli presents in [4] the theoretic background together with the application of IR technique in three case studies. The results received indicate that the infrared thermography gives a significant data to perform a proper assessment of the building energy performance. Another work by Astdrubali et al. [5] describes a quantitative methodology of the evaluation of thermal bridges in buildings with the use of IR technique. The authors discuss the analytical method and its validation with experimental and numerical analysis.

The main aim of the present paper is the study of the effect of thermal bridges on heat losses through the

* Corresponding author: robsmusz@prz.edu.pl

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building envelope**.** The IR measurement procedure has been applied under real conditions of the building in winter season. For the validation of the results received by IR technique the comparative analysis with the numerical simulation results have been performed.

2 Methodology

A thermal bridge is an area of the building structure characterized by the significant different in thermophysical properties comparing to the rest components of the building envelope. Heat losses through thermal bridges in new buildings can reach as much as 30-60% of the building's heat demand [6]. Such large heat losses through thermal bridges are the result of incorrect design and production of the building envelope. The main two negative effects caused by thermal bridges are: the reduction of the wall surface temperature and decreasing of the of thermal comfort and the increase of heat losses through the building envelope. Therefore, an identification of thermal bridges is so important. The typical methodology of calculations of thermal bridges are [7]: numerical calculations based on [8] with accuracy ± 5%, atlases of thermal bridges (±20% accuracy), manual calculations (± 20% accuracy) and reference values– with ± 50% accuracy. An alternative method that can be used to identify thermal bridges is infrared thermography. The main advantage of the infrared thermography is that this technique can be used in-situ analysis.

Thermal bridge is defined by linear thermal transmittance ψ [8]:

$$\psi = L^{2D} - \sum_{j=1}^{K} U_j \cdot l_j \,, \quad (1)$$

where:
$L^{2D} -$ thermal coupling coefficient of the component separating the two environments,
$U_j -$ overall heat transfer coefficient (thermal transmittance) of the j-th one dimensional component, which separate the two environments,
$l_j -$length over which the value U_j applies,
$K -$number of 1D components.
Thus, the quantitative categorisation of thermal bridges is identified by the value of ψ that gives the thermal flux transferred per length and temperature units in steady-state conditions.

The relationship between heat flow rate per meter Φ_l of the linear thermal bridge from the internal environment to the external environment and thermal coupling coefficient is given by the formula:

$$L^{2D} = \frac{\Phi_l}{(T_e - T_i)}, \quad (2)$$

where:
$T_i -$ the temperature of the internal environment,
$T_e -$ the temperature of the external environment.
Based on the numerical simulation it is possible to obtain the thermal coupling coefficient and the linear thermal transmittance.

In the papers [3, 5, 9] the authors defined a new parameter named incidence factor of the thermal bridge I_{tb}, which can be measured by IR technique:

$$I_{tb} = \frac{\sum_{p=1}^{N}(T_i - T_p)}{N \cdot (T_i - T_{w,und})}, \quad (3)$$

where:
$T_p -$ surface temperature along the line from thermal bridge to undisturbed area measured by IR technique,
$T_{w,und} -$ undisturbed surface temperature of the component,
$N -$ number of measuring points (pixels).
The incidence factor is the ratio between heat flow through the component under real conditions (with presence of the thermal bridges) to the heat flow through the component in absence of the thermal bridges.
In the paper [3] the authors showed the relationship between incidence factor I_{tb} and the linear heat transfer coefficient (linear thermal transmittance):

$$I_{tb} = \frac{\psi + \sum_{j=1}^{K} U_j \cdot l_j}{\sum_{j=1}^{K} U_j \cdot l_j} = \frac{L^{2D}}{\sum_{j=1}^{K} U_j \cdot l_j} \quad (4)$$

The correlation (5) makes it possible to calculate the incidence factor based on numerical simulations.

3 IR experiment

A new single-family house completed in 2017 has been examined in the present study. The investigated building was fabricated in traditional technology. Infrared thermographic technique for the measurement in situ of the structural corner thermal bridge and undisturbed area of the walls was carried out. Thermal image of the structural thermal bridge is shown in Fig.1. The building examined has a masonry of bricks coated with an insulating layer of polystyrene positioned on the external side of the structural brick frame. The thickness and the thermal conductivity of components of the multilayer wall are included in Table 1. The calculated value of thermal transmittance of the external walls based on standard [10] was equal U = 0,251 W/(m^{2}K).

Table 1. External wall of the examined building.

No.	Layer	Thickness, cm	Thermal conductivity, W/(m·K)
1	Concrete plaster	1.5	0.820
2	Brick wall	29	0.365
3	Insulation-polystyrene	12	0.040

The IR measurements have been performed with the use of the camera manufactured by FLIR with the microbolometer. A spectral range varied from 8 μm to 14.0 μm.

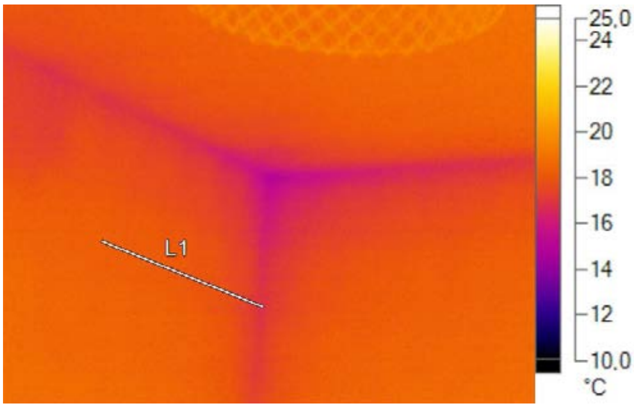

Fig.1. Thermal image of the structural thermal bridge.

Ambient temperature and the relative humidity of the air inside and outside of the building was measured by a Testo 608-H2 thermohydrometer. During the test the temperatures and humidity were equal respectively 21.2°C, 38% and -0.5°C, 98% The reflected (apparent) temperature was determined using the procedure described in [11]. The aluminium foil has been used as a mirror. The reflected temperature necessary for the correct IR measurements has been obtained equal 22°C. Thermal image of thee aluminium foil for determining the reflected temperature is shown in Fig.2.

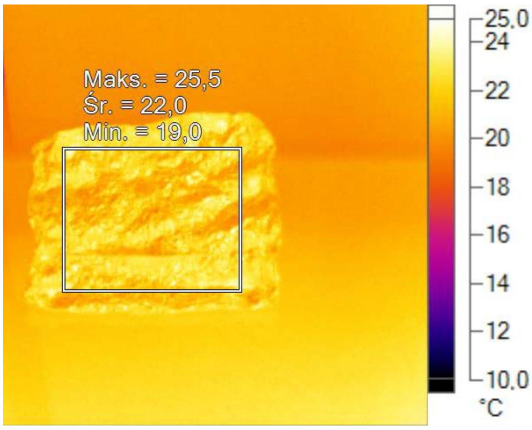

Fig. 2. Evaluation of the reflected temperature.

The emissivity of the internal wall surface was estimated based on the measurement of the wall temperature with the use of K-type thermocouple system. In the case considered thermal emissivity equalled 0.92.

In order to identify of the surface temperature, the imaginary line L1 has been created from thermal bridge to the undisturbed area of the wall, Fig.1. It must be ensured that the length of line L1 must be equal to 1m. The profile of the surface temperature along the line L1 is shown in Fig.3. Asymptotic profile of the temperature shows that the undisturbed surface temperature $T_{w,und}$ is equal to 18.3°C.

In the next step, the incidence factor of the thermal bridge I_{tb} has been calculated according to the formula (3) and its value is equal to 1.10 with estimated uncertainty 18%.

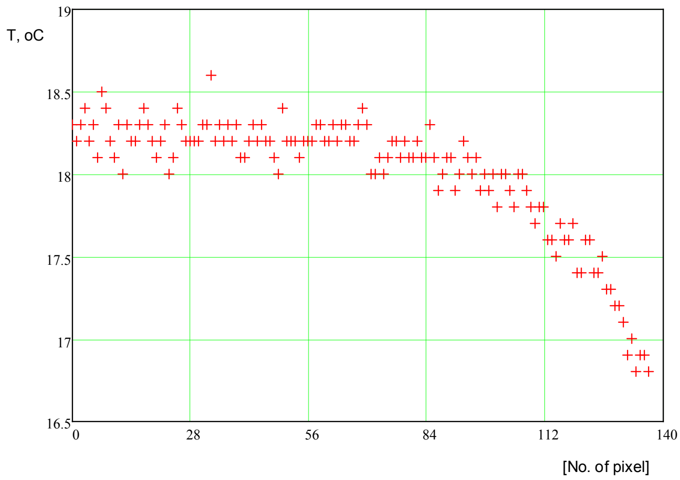

Fig. 3. Wall surface temperature along the line L1.

4 Numerical study

In order to verify and validate the experimental results, 2D numerical calculations were carried out. The effect of geometrical thermal bridge was investigated by the use of COMSOL Multiphysics commercial software. The finite element method has been applied. The computational domain was created based on the geometry presented in Fig.4. 17 thousand elements were used in the numerical method.

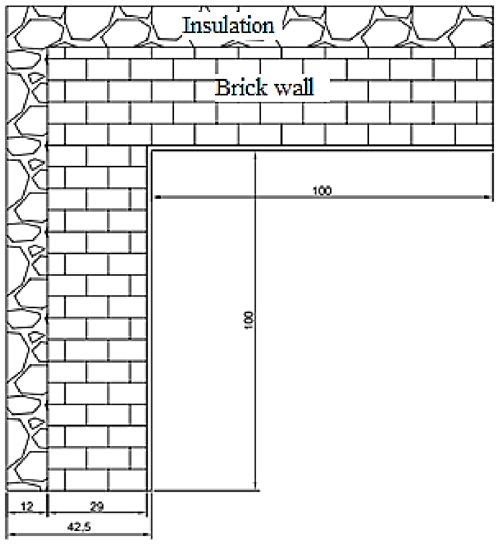

Fig. 4. Geometrical model (all dimensions are in cm).

The computing domain was modelled in accordance with the requirements described in the standard [8] and the domain was meshed by quadrilateral and edge elements with step 0.75 cm.

On the outer and inner sides of the wall, the convective boundary conditions were assumed according to [8, 10]. Based on the numerical simulations, the steady temperature fields and heat flux rate were obtained. The received streamlines, temperature and heat flux in the corner of the wall considered are shown Fig.5.

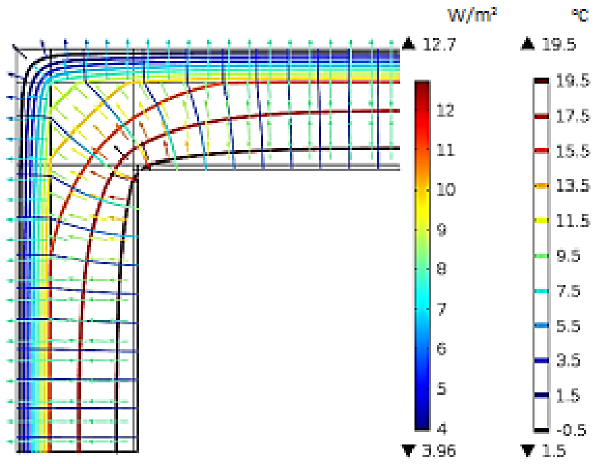

Fig. 5. Streamlines, temperature and heat flux in the wall corner.

Next, basing on the equation (2) the coupling coefficient was calculated. For the case considered $L^{2D} =$ 0.6156 W/(mK). Then, according to the equation (5), the incidence factor was derived $I_{tb} = 1.2$ with uncertainty ± 5%.
Values of I_{tb} received from IR measurements and those from numerical simulations are included in Table 2.

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Method	I_{tb}	Uncertainty, %
IR measurements	1.1 ±(0,2)	18%
Numerical simulations	1.2 ±(0,06)	5%

5 Summary

Recently the energy consumption of buildings may be reduced by the application of modern technologies in the construction industry. Modern building materials ensure a reduction of heat loses. However, studies show that thermal bridges may cause large values of the additional heat losses through the building envelope. Therefore, a one key aspect in assessing the real thermal state of buildings is the identification of the heat losses through thermal bridges. The main three negative effects caused by thermal bridges are: the reduction of the wall surface temperature, decreasing of the of thermal comfort, and the increase of heat losses through the building envelope. Therefore, identification of thermal bridges is so important.
In the paper the authors present the experimental investigations on heat loses through the building under real winter conditions. IR method has been used to assessment the thermal bridges in situ. For the validation of the results received by IR technique the numerical simulation based on finite element method has been performed. On the basis of the results obtained it can be concluded that the quick and easy in situ IR measurements can be applied to evaluate the actual heat losses in building. The results received from IR measurements and based on numerical simulations have a good compatibility.

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