ISSN 2029–9990 JOURNAL OF SUSTAINABLE ARCHITECTURE AND CIVIL ENGINEERING 2013. No. 3(4)
DARNIOJI ARCHITEKTŪRA IR STATYBA

Diagnostics and Problems Analysis of Buildings Air Tightness

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crossref http://dx.doi.org/10.5755/j01.sace.3.4.4375

Constantly increasing prices of energy and rising heating costs are forcing inhabitants of multifamily apartment houses and individual houses to think about savings of heating costs and improvement of living conditions as well. Air tightness is one of the most important factors influencing comfortable, energy efficient living environment. During winter time, air movement forms because of the pressure difference between outside and inside air. Air moves from the higher to the lower pressure zone, i. e. cold outside air penetrates to the room through the lower parts of the walls, and finally when it warms up, it goes out of the premises through the upper parts of the construction. The higher of uncontrolled air circulation is present in the premises, i.e. the more of cold air penetrates into the room, the higher energy consumption is required for heating. These energy losses can be reduced by increasing air tightness of the buildings. The aim of this research is to investigate the most common places of the buildings' leakage and the causes of it.

Keywords: *infiltration, blower door, ventilation, air leakage, energy.*

1. Introduction

About 40 % of EU energy is consumed for buildings, it becomes an important issue to talk about. According to the requirements of European Parliament and Council Directive (Directive 2010/31/ES), energy consumption of buildings should be significantly reduced, and no later than 31st of December, 2020, all new buildings should be zero energy. However, constantly increasing prices of energy resources and heating costs are forcing residents of multifamily apartment houses and individual houses to think not only about reduction of the heating expenses, but about improvement of their living conditions as well. In order to achieve this aim, not only thermal properties of building envelopes should be improved, but proper selection of technological solutions should be made in order to ensure the quality of building insulation work and air tightness. Indeed, air tightness, in conjunction with other complex solutions of the building, reduces heating costs, increases thermal comfort, and ensures a healthy environment and durability of the building (Pan, 2010), (Kalamees et al. 2010), (Sfakianaki et al. 2008), (Becker, 2010), (Kovanen et al. 2009), (Matrosov et al. 2007), (Feist et al. 2005), (Smeds and Wall, 2007), (d'Ambrosio Alfano et al. 2012).

During winter time, air movement is formed through the leaky places of the building because of the pressure difference between outside and inside air. Air moves from the higher to the lower pressure zone, i. e. cold outside air penetrates to the room through the lower parts of the walls, and finally when it warms up, it goes out of the premises through the upper parts of the construction. Leakage of the building negatively affects humans' well-being: air movement is felt during the cold season because of the large temperature difference between the envelope surface and the indoor air temperature; and blow of cold air is felt, which requires more heating energy (Kauppinen and Siikanen, 2011).

Another negative factor resulting from the leakage of the building is the risk of appearance of condensation and mold on the surface of the envelope. Other researchers have founded, that process of mold growth on the interior surfaces of the building envelope might start when the relative humidity (RH) near the surface is 80% and more. It is okay, while indoor RH can be in the range of 50%–70%. When the surface temperature decreases, RH near the surface increases and at the same time the process of condensation and mold growth continues (K. F. Nielsen et al. 2004) (L. Bellia,2003). Also, studies have shown that mold growth commences for air leakage greater than 0.1 Litre/m^2·s (M. Nofal and K. Kumaran, 2010).

The aim of this research is to investigate the most common places of the leakage of buildings'; to analyze the reasons of insufficient air tightness; and to determine possibilities of appearance of condensation and mold on the inner surfaces of the envelopes.

2. Methods

2.1. Thermographic survey

For this study, different types of newly constructed or renovated buildings were selected, whose technical characteristics are presented in table 1.

Thermographic survey was performed in order to identify defective parts of the investigated buildings. Qualitative detection of thermal irregularities in building envelopes (LST EN 13187) based on Infrared method was used for this purpose. This survey was carried out with infrared camera „ThermaCAM B640“, which creates electrical signals according to the infrared wavelength and intensity. Electrical signals are compared with temperature etalon and temperature of the measured surface is calculated.

The accuracy of the device is 2 % or 2 °C. The infrared camera converts thermal heat radiation to the color image, i. e. thermogram, which is used to detect building envelope's defects.

All thermographic investigations were made during the winter period. The difference between the indoor and the outdoor air temperature was at least 20 °C. In order to determine the risk of the condensation and mold growth, thermographic survey was carried out under natural conditions, without the additional pressure difference.

In order to investigate air leakages places, thermographic investigations were carried out twice. First, to determine the normal situation, the surface temperature measurements were performed without any additional pressure difference. Next, to determine the main air leakage places, the 50 Pa negative pressure under the envelope was set with fan pressurization equipment. After the infiltration airflow the surface temperatures were measured with the infrared camera from the inside of the building.

The average temperatures on the inner surfaces of the envelopes, captured in thermograms (thermographic measurements were performed under natural conditions, without pressure difference), were compared with the normative temperatures of the measured surface, in order to determine if identified temperature changes were normal.

Normatyve internal surface temperature (θ_{siN}, °C) is calculated according to the Eq. 1:

$$\theta_{siN} = \theta_i - \frac{\theta_i - \theta_e}{R_t} \cdot R_{si}; \qquad (1)$$

where: θ_i – indoor temperature, °C; θ_e – outdoor temperature, °C; R_t – thermal resistance of the envelope (m^2·K/W); R_{si} – normative thermal resistance of the internal surface (m^2·K/W).

The indoor temperature of the buildings was selected as θ_i = 20°C and this corresponds to the requirements set of the hygienic norm (HN 42:2004). When thermographic investigations is performed, in order to acquire the trusted results the difference between indoor and outdoor temperature should be $(\theta_i - \theta_e) \geq 20°C$. Normative thermal resistance of the internal surface (R_{si}, m^2·K/W) is presented in STR 2.05.01:2005: for walls and windows R_{si} = 0.13 (m^2·K/W), for roof R_{si} = 0.10 (m^2·K/W). The thermal transmittances of the investigated residential houses are presented in Table 1. These values are converted into the total thermal resistance of the envelope R_t (m^2·K/W).

2.2. The temperature factor at the internal surface

In order to determine, whether captured changes of the envelope's inner surface temperature have influence on the harmful water sorption of the surface, including the possibility of the formation of mold, the temperature factor at the internal surface was calculated. The temperature factor at the internal surface (f_{Rsi}) was calculated according to the European Standard ISO 13788:2001 (Eq. 2).

$$f_{Rsi} = \frac{\theta_{si} - \theta_e}{\theta_i - \theta_e}; \qquad (2)$$

where: θ_{si} – measured internal surface temperature, °C; θ_i – indoor temperature, °C; θ_e – outdoor temperature, °C.

While calculating the temperature factor at the internal surface (f_{Rsi}), the outdoor temperature (θ_e, °C) corresponds to monthly mean value, in the city of Kaunas in January (RSN 156-94 1995) and is equal to -5.2 °C. For calculations of the risk of surface condensation on low thermal inertia elements such as, for example, windows and their frames, the mean annual minimum temperature on a daily basis is selected. The coldest daily temperature in Kaunas city, at 92 % of integral recurrence, is equal to -27 °C.

The temperature factor at the internal surface (f_{Rsi}) is calculated when average temperature of the whole surface is determined by the thermographic investigations. The calculated value (f_{Rsi}) was compared with the design temperature factor at the internal surface ($f_{Rsi.N}$).

In order to determine hydrothermal processes that take place only on the surface of the envelope (that directly depends on the envelope's surface temperature) ($f_{Rsi.N}$)

Table 1. *Technical characteristics of investigated buildings*

Type of the building walls	The number of investigated buildings	Construction year	Thermal transmittance of the investigated residential houses U, W/(m^2·K)		
			Walls	Roofs	Windows
Framework	12	2002–2009	0.16–0.20	0.16–0.18	1.4–1.9
Precast reinforced concrete blocks	50	1961–1993	0.18–0.21	0.14–0.18	
Masonry	25	1961–2010	0.16–0.20	0.16–0.20	
Timber	8	2000–2010	0.20–0.30	0.18–0.24	
Monolithic concrete	6	1997–2009	0.18–0.22	0.16–0.21	

the calculations adopting design values that corresponds to ISO 13788:2001 and STR 2.05.01:2005 requirements were carried out. The obtained results should meet the requirement: $f_{Rsi} \geq f_{Rsi,N}$.

2.3. Statistical analysis

Statistical analysis was made using Stjudent statistics with significance of $\alpha = 0.05$ in order to determine statistical significance of calculated mean value of f_{Rsi} and $f_{Rsi,N}$. Statistical significance of the results is presented by p value: $p < 0.01$ – highly significant, $0.01 \geq p \geq 0.05$ – significant, $0.05 \leq p \leq 0.1$ – close to significant, $p > 0.1$ – not significant.

3. Results

3.1. Thermographic survey

Thermographic survey was performed in order to determine the main causes of heat losses in buildings. It revealed defects related to poor quality of installation work and improper decisions.

Improper insulation or the absence of insulation at all in the socle part of the building was a very frequent case identified in different types of tested buildings. The example of the improper insulation is presented in Fig. 1. The temperature of basement wall external surface (brick house) was -2.8 °C (point 1), while the temperature of building wall at point 2 was -10.6 °C. As temperature difference is about 8 °C, it is expected, that a significant part of the heat is radiated through the base to outdoors. The insulation of the basement might be not effective.

The other insulation defects, such as leaky windows (point 3) or gaps near the roof (point 4) can be identified using the same thermogram (Fig. 1). All these defects are result of poor quality of insulation work and improper application of technological solutions while uniting different building elements.

The second thermogram (Fig. 2) shows leaky places between wall and roof junction, through which the heat flows from indoors to outdoors (points 2 and 3). Taking into consideration the distribution of surface temperatures of the building elements, the probability of heat losses is quite high. Poor quality of joints between these elements goes throughout the perimeter of the building as quality of roof and wall junction's thermal insulation and air tightness is not solved.

Thermal properties at different points (points 1 and 4) of the same wall are different (Fig. 2). As the upper parts of the wall are conductive to heat, it is quite probable, that the insulation layer is not of the proper thickness and the occurrence of empty places might appear in some places as well (point 4). Joints of the insulation panels are visible, and as compact thermal insulation layer without air gaps is not ensured during the insulation process, it allows air movement. When thermographic survey was carried out from inside of the building (Figure 3), it was observed that significant part of heat is lost through the poorly sealed building corners. The third thermogram clearly identifies defects between wall and floor junction. The maximum wall surface temperature θ_{si} = 20 °C, and the minimum temperature at the corner of wall and floor junction θ_{si} = 5.5 °C. As the temperature difference is about 14 °C, it is likely, that condensation processes will take place in this problematic place, and conditions for mold growth will be created. Temperature distribution of the timber's house internal corner is presented in Figure 4: at the corner it is -3.3 °C, and wall surface temperature is 17.3 °C. Temperature difference is 20 °C. Water condensation at this corner will result into ice.

The thermographic survey of the buildings show, that it is more difficult to ensure tightness in light construction buildings compared with the massive ones. Air-permeable insulation materials are used for this type of buildings. In order to ensure thermal insulation properties, a proper wind barrier membrane is needed.

The following defects were observed during the survey of carcass houses: leaky junctions of building elements, air gaps or blisters resulting from the improper tension of the wind insulation membrane, unfixed places after damages resulting during the mounting process. All these wind insulation defects alouded air infiltration, which significantly increased building heat losses.

Other identified defects are related to the insulation quality of walls in carcass houses: mineral wool boards or mats are not properly installed, longwise air channels are formed near the empty cavities around the studs (point 1, Fig. 6). As a result, convectional heat transfer is activated, too large thermal bridges are present next to the framing elements.

It is very common, that electrical outlets are made near corners which are not properly sealed (Fig. 5 and 6) and a cold air flow is felt through them. The surface temperature at the electrical outlet place (point 1) is 4 °C lower than at the corner of walls (point 2) and 8 °C lower than the inner wall surface temperature (point 3). The leaky electrical outlets and wind barrier membrane are often found in carcass houses. Figure 6 identifies that. The temperature of improper sealed corner's surface is 9.6 °C (point 3), and it is higher than the temperature of electrical outlet's surface (8.3 °C, point 2), while wall surface temperature is 16.8 °C (point 4).

The main heat losses usually are through the windows and external doors (Fig.7 and 8). The main causes for this are poor quality of installation of windows and external doors, and insulation tapes or insulation foams which have lost its thermal insulating properties. Fig. 7 shows, that due to the unqualified installation of windowsill, excessive thermal bridges appear at the bottom part of the window, where temperature is negative (-2.2 °C, point 2). Conditions for the condensation processes, mold growth or even icing are created at the window and windowsill junction. At the places of thermal bridges with unfavorable circumstances, not only water vapor condensation but also frost (at negative temperatures) or mold (when condensation is present for longer period) can occur (Ramanauskas *et al.* 2005).

A poor quality door installation example is presented in Fig. 8. The surface temperature at point 1 and 3 are lower by 10 °C compared with door surface temperature at point 2. The reason of appearance of thermal bridges at this place is that the door cannot be closed tightly enough because of the improper adjustment during installation. The surface temperature at point 5 is 4.5 °C, the reason for appearance of thermal bridges at this place is mounted lock.

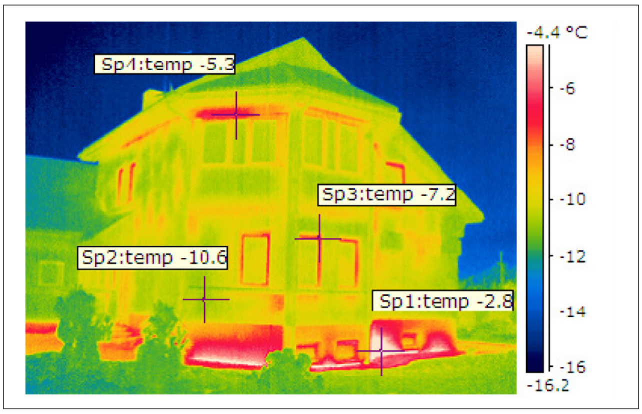

***Fig. 1.** Distribution of building socle surface temperatures*

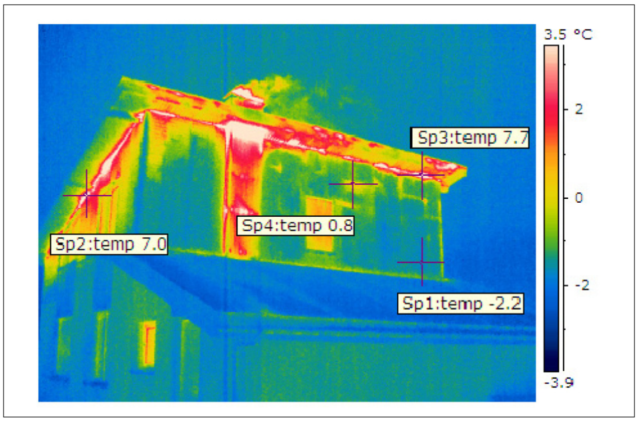

***Fig. 2.** Defects at wall and roof junction*

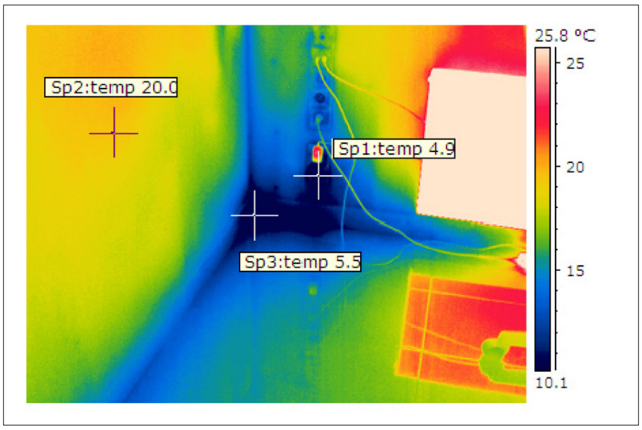

***Fig. 3.** Wall and floor junction at the corner of the building*

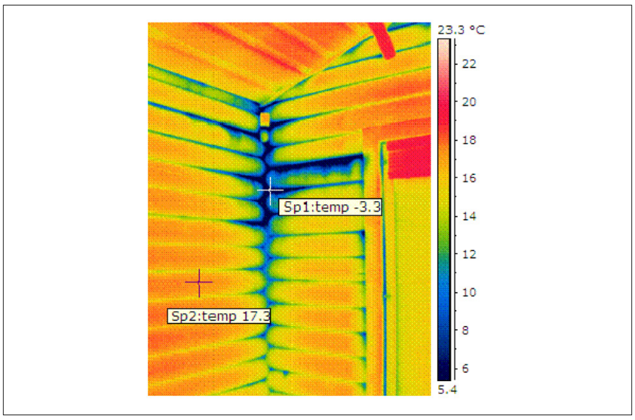

***Fig. 4.** Defect at the internal corner of the timber building wall*

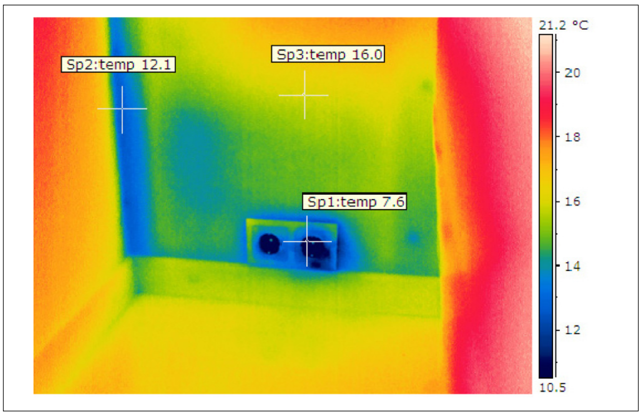

***Fig. 5.** Poor quality electrical installation*

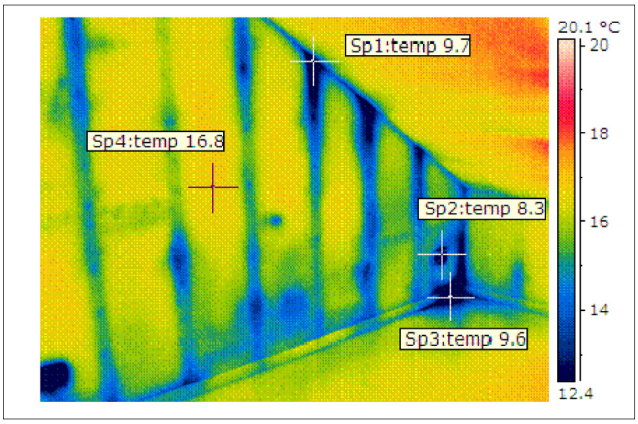

***Fig. 6.** Leaky places of the* carcass houses

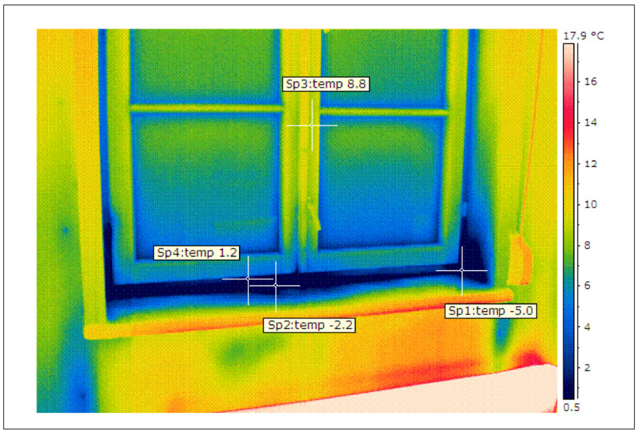

***Fig. 7.** Leaky windows*

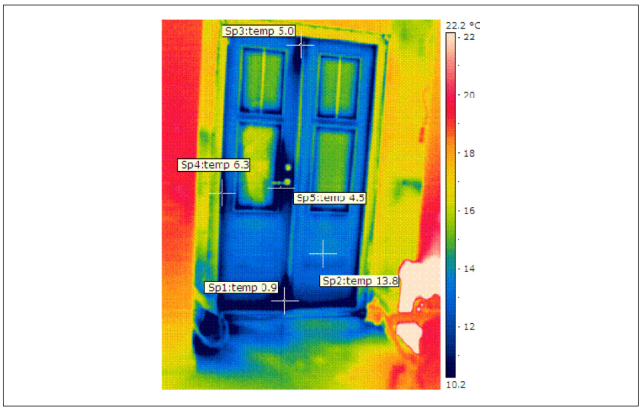

***Fig. 8.** Leaky doors*

Table 2. *The average surface temperature values*

Type of the building	Average surface temperatures identified during the s urvey θ_{si}, °C with 95 % confidence interval			Average calculated normative surface temperature, θ_{siN} °C		
	Walls	Roofs	Windows/doors	Walls	Roofs	Windows/doors
Framework	7–9	17-19	5–11	19.41	19.57	14.76
Precast reinforced concrete blocks	10–14			19.38	19.60	
Masonry	13–15			19.41	19.55	
Timber	4–6			19.18	19.47	
Monolithic concrete	14–16			19.34	19.55	

During buildings' air tightness assessment, normative surface temperatures were compared with the average values of the whole surface identified during the thermographic survey in order to determine whether surface temperature changes identified during the thermographic survey are significant. Investigation and calculation results are presented in table 2.

The investigation and calculation results (Table 2) show that the average surface temperatures identified during the thermographic survey θ_{si} (°C) are lower than the average calculated normative surface temperatures θ_{siN} (°C). While assessing statistical significance, it can be stated, that there was a statistically significant difference ($p = 0.034$) between the average indoor surface temperatures identified during the investigation and the calculated ones.

3.2. The temperature factor at the internal surface

The temperature factor at the internal surface was calculated in order to determine whether the identified surface temperature changes affect the appearance of condensation processes on the surface of the envelope. The calculation results of the temperature factor at the internal surface (f_{Rsi}) and the design temperature factor at the internal surface ($f_{Rsi.N}$) are presented in Fig. 9. The results show, that the temperature factor values at the internal surface $f_{Rsi.}$ are lower than the design temperature factor values at the internal surface $f_{Rsi.N}$, which is equal to 0.95.

While assessing statistical significance of the timber and carcass buildings, it can be stated, that there was a high statistically significant difference ($p < 0.01$) between f_{Rsi} and $f_{Rsi.N}$ values. During evaluation of statistical significance of other investigated buildings, it can be stated, that there was statistically significant difference ($0.01 \geq p \geq 0.05$) between the values of the temperature factor at the internal surface of the building walls f_{Rsi} and the values of the design temperature factor at the internal surface $f_{Rsi.N}$.

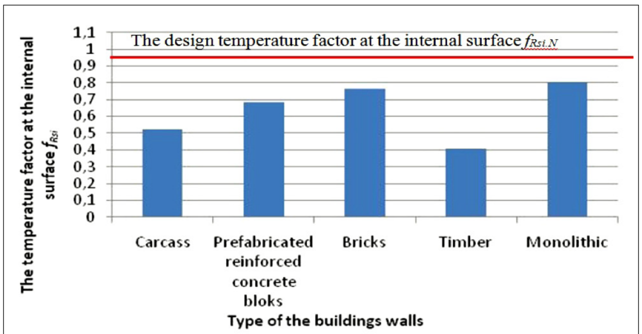

Fig. 9. *The temperature factor at the internal surface of building walls*

There was statistically significant difference ($p = 0.03$) between the values of the temperature factor at the internal surface of building windows f_{Rsi} (0.723) and the values of the design temperature factor at the internal surface $f_{Rsi.N}$ (0.888).

4. Discussion

Summing up the problems of the investigated buildings, it can be stated, that air tightness in buildings statistically depends on the type of insulation, on the installation quality of thermal insulation, the quality of the implemented work and operation of ventilation systems.

In order to improve the quality of insulation work and air tightness of buildings, it is necessary to evaluate physical processes taking place between the external and internal sides of the building. During winter time, air flows because of the pressure difference between outside and inside air. Air moves from the higher to the lower pressure zone, i. e. cold outside air penetrates to the room through the untighten places in lower parts of the walls, and finally when it warms up, it goes out of the premises through the uptightness's in upper parts of the construction. Mainly the heat is lost through the roof, as the heat rises up to the upper part of the building and if it is leaky, the warm air penetrates through the cracks and leaky places to outdoors (Fig. 2). Therefore the large amounts of heat losses occur.

At the same time, the air rarefies at the lower parts of the rooms and cold air penetrates into the room through various cracks in floors, doors, walls and windows (Fig. 3, 4, 7 and 8). The higher of uncontrolled air circulation is present in the premises, i. e. the more of cold air penetrates into the room, the higher energy consumption is required for heating.

The other part of heat loses was because of heat loses from radiation and convection, when the heat radiated from the heating devices or transferred by warm air transfers through the walls to outdoor environment (Fig. 1). The air moves indoors between warm and cold surfaces as well. The heat from the higher temperature zone always moves to the place where the temperature is lower. Usually such places are at the corners of the building, windows or defective areas of building envelope, where the thermal resistance is lower. The heat from the indoors by radiation and convection is transferred to the cold inner surfaces of the envelope. However, at low heating in the room and under insufficient heating, cold surfaces of the envelopes are not sufficiently warmed up, and with negative external factors (wind, low temperature) the surfaces continue to cool. As relative humidity rises up, the condensation process begins near the inner surfaces of the envelope because of the decreasing temperature.

The temperature factor at the internal surface shows the probability of appearance of condensation processes inside envelopes and on their inner surfaces. If $f_{Rsi} \geq f_{Rsi,N}$, condition is met, the risk of appearance of condensation and mold growth is very low. However, the investigated cases indicate, that the most typical places of the condensation are at insufficiently air tightened and thermally insulated corners of building walls, windows and doors. The investigation and the results of the calculations show that the highest probability of occurrence of condensation and mold growth is on the window glazing, frame and its mounting perimeter. When new and modern windows with very good thermal insulation properties are installed, moisture can condensate between the window frame and masonry when insulation material consists only from polyurethane mounting foam, and no vapor barrier is applied on the inner side around the window frame. Unprotected polyurethane mounting foam is saturated by water vapor, and therefore thermal insulating properties start to deteriorate. The surface temperature on window frame's fixing points decreases and thermal bridges are formed. There is a possibility of dampness and appearance of the mold on these spots (Fig. 7).

In summary, it can be stated, that the air tightness of new Lithuanian buildings is often not sufficient. Therefore, the heat loses are increasing and inadequate living conditions (mold risk) might take place. The corrosion of the metal fasteners might take place caused by condensation inside the construction. The threat of building stability might appear.

5. Conclusions

The thermographic survey of the investigated buildings: indicated significant differences between the insulated and worse insulated places; the places with highest heat loses have been identified and also the places where thermal bridges are formed; showed weaker areas of the building, where over the time mold, structural cracks or surface finishing defects could appear.

The air tightness of new Lithuanian buildings is often not sufficient. Therefore this increases the heat loses and inadequate living conditions (mold risk) might take place.

This survey revealed the typical leaky places of all types of buildings: junction of the ceiling/floor with the external wall; junction of the partitions with the external wall and roof; penetrations of the electrical and plumbing installations through the air barrier membranes; penetrations of the chimney and ventilation ducts through the air barrier; leakage around and through electrical sockets and switches; leakage around and through windows and doors.

The investigated cases show, that on the statistical assessment of walls, windows and roof with more than 80 % relative humidity of indoor air, condensation is possible near the cool surfaces of the envelope (the RH may be lower). The investigation and calculation results show, that the highest probability of occurrence of condensation is on the window glazing, frame and its mounting perimeter; the lowest probability for condensation is for roof enclosure.

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Received 2013 05 15

Accepted after revision 2013 06 11

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