Energy for Sustainable Development 32 (2016) 31–39

Contents lists available at ScienceDirect

Energy for Sustainable Development

The role of air tightness in assessment of building energy performance: Case study of Lithuania

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ARTICLE INFO

Article history:
Received 30 January 2014
Revised 10 February 2016
Accepted 10 February 2016
Available online xxxx

Keywords:
Infiltration
Blower door
Air tightness
Energy consumption

ABSTRACT

The aim of this work was to evaluate the reliability of building energy performance methodology and to determine the significance of the building air tightness.

This paper presents a study on the significance of the building air tightness for 27 single-family detached houses, which were built in Central Lithuania during 2007–2011. Results of the field study and calculations indicated that air tightness of A class buildings corresponded to regulation requirements, ACH50 ≤ 0.6 (air changes per hour at a 50 Pascal pressure difference between interior and exterior). There was a large variation in respect of B and C class buildings. The 90% confidence interval of ACH50 value was between 4.17 and 8.05. The results showed that Lithuanian buildings of B and C energy performance class were not sufficiently tight. The average the air change rate, when air pressure of 50 Pa was present, was 2 times higher than the regulatory value (ACH50 = 3 air change per hour). This work presents the ACH50 values' distribution according to the qualifying indicator *Cq* for A, B, C class buildings. Part of the presented ACH50 values of B class buildings are close to the value applicable to C class buildings. When air tightness of the buildings is evaluated, B energy performance class buildings can turn out to be C class.

Results of an existing building's energy performance calculations are reliable only after verifying that the building is air tight. Otherwise, the actual heating energy consumption in buildings can significantly differ from the value calculated as per regulations if air tightness is ignored.

Introduction

The common energy policy was developed by the European Union (EU) because of high dependence on energy supply from non-EU countries and reducing greenhouse gas emissions growth (European Commission, 2000). The primary energy consumption is related to buildings, which represents approximately 40% of all energy consumption in Europe. According to the requirements of European Parliament and The European Parliament and Council issued Directive 2010/31/EC (known as the Energy Performance Building Directive) requiring substantial reduction of building energy consumption by the end of 2020. The directive will require all new buildings to be zero-energy, i.e., they must generate the same amount of energy on site as they consume. According to Directive 2010/31/EC, certification is mandatory for Member States (Andaloro et al., 2010; Groh, 2014).

In order to fulfill requirements of the Directive 2010/31/EC for the reduction of energy consumption, national requirements have been developed by European countries for building envelope thermal properties and calculation methodology to determine the energy performance of buildings. Each European country has a methodology to determine a building's energy efficiency: BREEAM (Building Research Establishment Environmental Assessment Method) in Great Britain; LEED (Leadership in Energy and Environment Design) in the USA; HQE (High Environmental Quality) in France; MINERGIE in Switzerland; PASSIVHAUS in Germany; HB BEAM in Hong Kong; CASBEE (Comprehensive Assessment System for Building Environmental Efficiency) in Japan; and TOTAL QUALITY in Austria. All methods have one purpose—to minimize the use of energy consumption, although they may propose achieving it in different ways (Stankovic et al., 2014; Czako, 2012; Alberini et al., 2013; Malmqvist et al., 2011). They differ by type of buildings and the climatic area, minimum thermal requirements and indexing of certification (Gonzalez et al., 2011; Tronchin and Fabbri, 2010). Primary energy consumption, final energy consumption, or CO_2 emissions are applied in these methodologies as metrics (Gualberti et al., 2014; Feist et al., 2005; Smeds and Wall, 2007; Jaraminienė, 2008; Venckus et al., 2010).

Lithuania also has a regulation—STR 2.01.09:2005 "Energy Performance of Buildings. Certification of Energy Performance," which defines requirements for energy certification of buildings. Buildings

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http://dx.doi.org/10.1016/j.esd.2016.02.006

Nomenclature

ACH50 air changes per hour at an indoor-outdoor pressure difference of 50 Pascals. Air change is air flow rate normalized by building interior volume.
Q_{sum} total annual energy consumption of the building was calculated total heating requirement at reference temperature conditions, kWh/m^2·year
Q_{vent} calculated energy consumption for ventilation, kWh/m^2·year
Q_{env} heat losses through building envelope, kWh/m^2·year.
Q_{d1} calculated heat losses due to entrance door opening, kWh/m^2·year. Infiltration is not included in this calculation. The calculations are based on assessed opening frequency, area, and type of door.
Q_{inf} calculated heat losses due to over norm infiltration through windows and external doors, kWh/m^2·year
Q_e calculated heat gains in building due to solar radiation, kWh/m^2·year
Q_i calculated heat gains due to internal heat sources, kWh/m^2·year
Q_E assumed electricity consumption based on typical electricity consumption, kWh/m^2·year. It is given by heat suppliers of individual cities of Lithuania.
$Q_{h.w}$ assumed energy consumption for domestic hot water, kWh/m^2·year, based on typical water consumption and hot water system design
$\eta_{h.s.}$ efficiency coefficient of building heating system, by parts of units
η_r calculated efficiency coefficient of mechanical ventilation with heat recovery system, by parts of units.
$A_{wd.sum}$, $A_{d.sum}$ total areas of windows, roof windows, skylights or other transparent partitions and entrance doors, m²
A_p building heated floor (used in calculation of all Q values given above), m^2
$A_{n.v.}$ building heated floor area, with natural ventilation system, m^2
A_r building heated floor area, with mechanical ventilation and heat recovery system, m^2
A_m building heated floor area, with mechanical ventilation and no heat recovery system, m^2
K air penetration value of windows, roof windows, skylights or other transparent partitions and entrance doors, m^3/(m^2·h). The value is determined through laboratory testing and specified in regulation STR 2.01.09:2005.
v_o Assumed amount of external air for ventilation. For single family house, the value is set by regulation at 0.7 m^3/(m^2-h).
v_1 amount of external air infiltration through the entrance door due to opening, m^3/(m^2·h)
$\theta_{i.w}$ Assumed indoor temperature. Set by regulation at 20 °C.
θ_{si} temperature of ceiling surface, °C
C_q the value of qualifying indicator. Building's energy performance class is determined according to the value of qualifying indicator C_q
Φ_r output of the electrical part of mechanical ventilation with heat recovery system, W. If mechanical ventilation with heat recovery system is absent $\Phi_r = 0$.
Φ_m output of the electrical part of mechanical ventilation with no heat recovery system, W. If the mechanical ventilation with no heat recovery system is absent $\Phi_m = 0$.

Subscripts
N regulatory value, which is approved by the Ministry of Environment of Lithuania (STR 2.01.09:2005)
R reference value, which is approved by the Ministry of Environment of Lithuania (STR 2.01.09:2005), which are statistically determined according to results of 50 buildings.

can be classified as belonging to one of 7 classes: A, B, C, D, E, F, or G (Table 1.). Class A is at the top and such a building is very energy efficient, with low energy consumption, while class G refers to a building with poor energy efficiency. The energy performance class of a building is determined according to the value of the qualifying indicator C_q. The energy performance class of buildings built after 2006 must not be lower than C. Beginning in 2013, only A class buildings are permitted. The energy performance class of existing buildings after major renovation must not be lower than D (Maldonado et al., 2011).

Regulation STR 2.01.09:2005 mentions that the requirement of air tightness is applied for buildings of energy performance class A (Table 1). A concept of A class buildings in Lithuania has the same meaning as Passive House in EU. Passive houses are characterized by extremely low transmission and infiltration losses in combination with high efficiency heat recovery ventilation systems. The passive house standard specifies an air tightness ≤0.6 air changes per hour (ACH50) measured using a standard blower door test at pressure difference of 50 Pa between inside room air and the outside ambient air. The value of ACH 50 shows infiltration, i.e., the uncontrolled flow of air from outdoors to indoors through leaks (unplanned openings) in a building envelope. The intentional introduction of outside air can be categorized as either mechanical ventilation, or natural ventilation. Mechanical ventilation uses fans to drive the flow of outside air into a building. This may be accomplished by pressurization (in the case of positively pressurized buildings), or by depressurization (in the case of exhaust ventilation systems). Natural ventilation is the intentional passive flow of outside air into a building through planned openings (such as louvers, doors, and windows).

Therefore, today there exists a range of products specially designed to achieve excellent air tightness at given penetrations (Šadauskienė et al., 2014). Besides, the architects are particularly attentive at the design and construction phase to the way the penetrations will be addressed to minimize leakage and thermal bridges. In summary, the severe air tightness requirement (ACH50 ≤ 0.6 air changes per hour) is commonly achieved in these passive houses using similar robust methods and products. In the European climate, adequate thermal insulation and overall air tightness of the building envelope together with energy efficient ventilation are prime requirements (Chel et al., 2015; Wouters and Carrie, 2008).

References argue that this is an important factor in assessing the energy performance of the building (Kalamees et al., 2010; Pan, 2010; Sinnott and Dyer, 2012; Kalamees, 2007; Sfakianaki et al., 2008; d'Ambrosio Alfano et al., 2012; Matrosov et al., 2007; Kovanen et al., 2009; Šadauskienė et al., 2013). The air tightness values are not checked for other classes of building energy performance in Lithuania. The following levels of air tightness of buildings are set according to Lithuanian regulation. Buildings should meet these requirement on design stage; however, when air tightness values are not checked, these values can be much higher than required by the Ministry of Environment of Lithuania (STR 2.05.01:2005) in reality. According to STR 2.05.01:2005, the air change rate ACH50 have to be 3 air change per hour for detached houses without ventilation devices and 1.5 air change per hour for detached houses with ventilation devices.

So, without the checking that the building is air tight, energy performance calculations are meaningless because these estimates do not reflect to the real energy consumption for heating. The aim of this

Table 1
Buildings energy performance classified according Lithuanian national document—STR 2.01.09:2005 "Energy Performance of Buildings. Certification of Energy Performance."

Requirements of regulation STR 2.01.09:2005	Energy performance class						
Existing buildings	A	B	C	D	E	F	G
Existing buildings after major renovation	A	B	C	D			
New buildings	A	B	C				
Level of qualifying indicator C_q	<0.5	0.5 ÷ 1	1 ÷ 1.5	1.5 ÷ 2	2 ÷ 2.5	2.5 ÷ 3	≥3
Level of energy consumption	Very high	High	Moderate	Normal	Low	Very low	Poor
Requirements for air change rate ACH50 (air change per hour)	≤0.6			No requirement			

study was to determine the significance of air tightness of the building for the certification of building energy performance.

Methods

Studied houses

Investigation was carried out in 27 single-family occupied detached houses, constructed during 2007–2011 in Lithuania. Most of the houses were relatively new, built on an average 2–3 years prior to the measurements. The average floor area of the studied houses was 189 m^2; the average volume was 639 m^3.

All investigated buildings were built from bricks or masonry blocks. External walls were insulated with external thermal insulation composite systems (ETICS) or ventilated facade systems. These structures of building envelopes were installed according to technical regulation ETAG 004. Characteristics of investigated buildings are presented in Table 2.

Ventilation systems in the tested buildings were as follows (Table 2):

- system with natural ventilation, when ventilation is caused by wind and gravitational forces.
- mechanical ventilation without heat recovery, when ventilation is caused by the use of exhaust fans.
- mechanical ventilation with heat recovery, when mechanical ventilation is provided with 95% of heat recovery for the heating of outside air.

Table 2
Key building characteristics (other details in the next table).

House	Heated floor area, *A*, m^2	Height of the building *h*, m	Volume V, m^3	Number of exposed facades	Number of levels	Type of ventilation system
1	210.2	6.2	651.6	4	2	Heat recovery
2	190.2	6.6	627.7	4	2	Heat recovery
3	170.1	6.0	510.4	4	2	Heat recovery
4	188.8	6.5	615.4	4	2	Heat recovery
5	200.8	6.0	602.3	4	2	Heat recovery
6	190.0	7.0	665.0	4	2	Heat recovery
7	208.8	6.5	678.6	4	2	Heat recovery
8	201.3	6.5	654.2	4	2	Heat recovery
9	168.1	7.0	588.4	4	2	Heat recovery
10	210.6	9.1	638.9	3	3	Mechanical
11	134.2	7.5	503.2	3	2	Mechanical
12	233.5	7.1	828.9	4	2	Mechanical
13	340.2	8.9	757.1	4	4	Mechanical
14	168.0	5.9	991.5	3	1	Mechanical
15	209.4	7.1	743.4	4	2	Mechanical
16	163.7	6.2	511.6	4	2	Mechanical
17	210.5	7.0	736.8	4	2	Heat recovery
18	210.6	9.1	638.9	3	3	Heat recovery
19	182.2	7.3	665.0	4	2	Mechanical
20	140.2	6.2	438.3	4	2	Natural
21	107.3	4.0	432.4	4	1	Mechanical
22	115.7	6.8	393.5	4	2	Mechanical
23	167.1	7.5	626.6	4	2	Natural
24	173.7	7.6	658.3	4	2	Natural
25	203.7	9.2	627.5	4	3	Mechanical
26	107.5	5.8	623.5	4	1	Mechanical
27	289.4	8.7	838.2	4	3	Mechanical

Building energy performance assessment methods

The main energy performance requirements for new buildings in relation to the EPBD (article 5) are described in the Building Technical Regulation STR 2.01.09:2005. According to the methodology presented in the afore-mentioned Regulation, total annual energy consumption of the building Q_{sum} was calculated for the heating season, per square meter of building floor area (Eq. (1)):

$$Q_{sum} = \frac{Q_{env} + Q_{vent} + Q_{d1} + Q_{\inf} - Q_e - Q_i}{\eta_{h.s.}} + Q_E + Q_{h.w.}; \tag{1}$$

In this study, all parameters in Eq. (1), except Q_E, were calculated separately for individual houses of investigating except the value of annual electricity consumption Q_E. It is given by electricity suppliers of individual cities of Lithuania.

The efficiency coefficient of building heating system $\eta_{h.s.}$ was different for individual cases because it depends on the type of the heating control device and the type of heat source. The efficiency coefficient of a heating control device and the efficiency coefficient of heat source were given by Building Technical Regulation STR 2.01.09:2005 if home residents don't provide an official document with other value.

Building energy class is determined in part by the value of an energy indicator, denoted C_q, which is calculated as shown in Fig. 1.

In order to determine the value of qualifying indicator C_q, it is necessary to know the value of the regulatory annual energy consumption $Q_{N.sum}$ and the reference total energy consumption $Q_{R.sum}$.

These values are calculated according to the following Eqs. (2 and 3):

$$Q_{R.sum} = \frac{Q_{R.env} + Q_{R.vent} + Q_{d1} + Q_{R.\inf} - Q_e - Q_i}{\eta_{R.h.s.}} + Q_E + Q_{h.w.}; \tag{2}$$

$$Q_{N.sum} = \frac{Q_{N.env} + Q_{N.vent} + Q_{d1} + Q_{N.\inf} - Q_e - Q_i}{\eta_{N.h.s.}} + Q_E + Q_{h.w.}; \tag{3}$$

The reference annual energy consumption $Q_{R.sum}$ is calculated taking in to account reference heat loses through building envelope. Reference values of energy consumption are approved by regulation (STR 2.01.09:2005), which are statistically determined according to results of 50 buildings.

The regulatory annual energy consumption $Q_{N.sum}$ is calculated the same way as the reference annual energy consumption $Q_{R.sum}$, but instead reference values are defined in the regulation STR 2.01.09:2005.

When air tightness of the building is evaluated, it is very important to know the heat losses due to over norm infiltration and energy consumption for ventilation. Heat losses due to over norm infiltration of external air through windows and external doors Q_{inf} are taken into

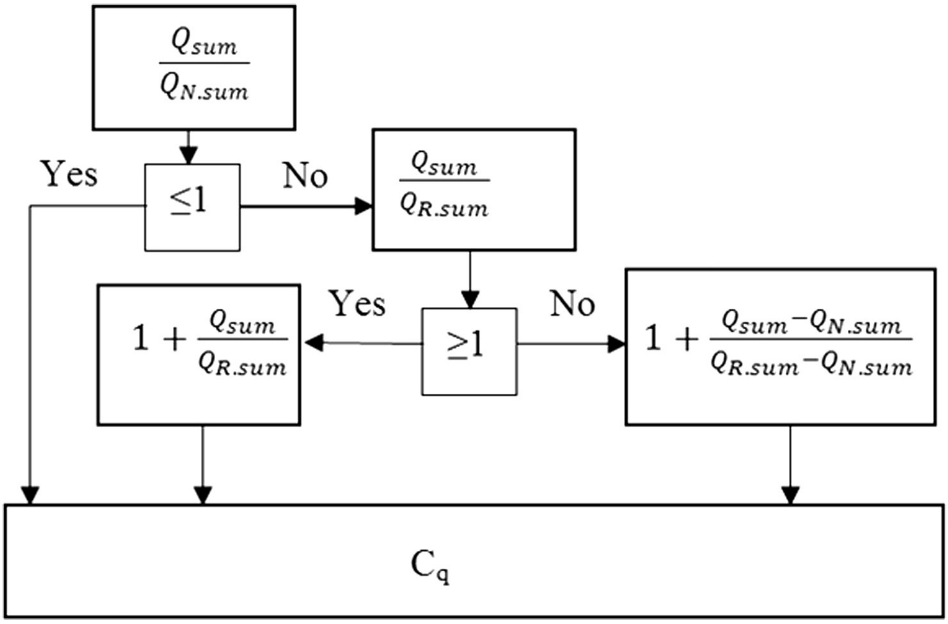

Fig. 1. A scheme for calculation of qualifying indicator *Cq*.

account during calculations of Q_{sum}. This is about 20% of the total building heat losses.

Regulatory heat losses, established by Ministry of Environment of Lithuania (STR 2.01.09:2005, Hygiene standards HN 42:2004), $Q_{N.inf}$ are set with provision that there should be no higher infiltration of external air than what is needed for the ventilation of building. Regulatory heat losses $Q_{N.inf}$ were considered to be insignificant in the energy performance calculation. From Eq. (1), it can be stated that the main criterion determining the value of heat losses because of extra regulatory infiltration of external air was the ratio between windows (roof windows, skylights, or other transparent envelops), external doors, and the heated floor area in buildings. Heat losses due to over norm infiltration of external air became higher if more glassed and open able parts were present in the building. These calculations took into consideration air permeability characteristic of windows or other glassed areas, i.e., air leakage value of open able parts. It is assumed that the buildings are air tight and that the air change per hour is not higher than values presented in the regulation. So $Q_{N.inf} = 0$. However, if total areas and air leakage values of the windows, skylights, and other transparent envelops, as well as external doors, are evaluated according to the manufacturer's declaration of product air permeability class, it might be that $Q_{N.inf} > 0$. Heat losses because of extra regulatory infiltration of external air through the windows and external doors Q_{inf} were calculated according to Eq. (4):

$$Q_{inf.} = 1.77 \cdot \left(\frac{K_R \cdot (A_{wd.sum} + A_{d.sum})}{A_p} + v_1 - v_o \right) \cdot (\theta_{i.w.} - 0.6); \tag{4}$$

Eq. (4) shows that Q_{inf} value depends on air leakage value K_R, difference, total areas $A_{wd.sum}$, $A_{d.sum}$ of windows, doors, roof windows, skylights, or other transparent partitions and entrance doors, building heated floor area A_p, amount of external air for ventilation of 1 m² of building v_0, amount of external air infiltration through the entrance door due to opening v_1, and average internal temperature during the heating season (for residential detached houses it was taken as 20°C). For calculations K_R air leakage value for residential detached houses was taken as 10.15, and v_0 as 0.7 $m^3/(h \cdot m^2)$.

Q_{vent} energy consumption for ventilation was calculated according to Eq. (5):

$$Q_{vent.} = 1.77 \cdot \frac{A_{n.v}}{A_p} \cdot v_0 \cdot (\theta_{i.w.} - 0.6) + 1.77 \cdot \frac{A_r}{A_p} \cdot v_0 \cdot (\theta_{i.w.} - 0.6) \times (1 - \eta_r) + 8.76 \cdot \frac{A_r}{A_p^2} \cdot \Phi_r + 8.76 \cdot \frac{A_m}{A_p^2} \cdot \Phi_m; \tag{5}$$

Eq. (5) shows that the value of Q_{vent} depends on the type of ventilation system, on the building heated floor area where certain ventilation system is installed and on average internal temperature during the heating season (for residential detached houses, it was taken as 20 °C).

Regulatory $Q_{N.vent}$ and reference $Q_{R.vent}$ was calculated according to Eq. (6):

$$Q_{N.vent} = Q_{R.vent} = 1.77 \cdot v_0 \cdot (\theta_{i.w.} - 0.6); \tag{6}$$

Measurement methods

Measurements of air tightness of buildings were performed in all tested buildings. Air leakage value was determined according to standard procedure described in EN 13829:2002 "Thermal performance of buildings – Determination of air permeability of buildings – Fan pressurization method." Prior to testingintentional vents, attic hatches, letterbox, and extract fans were closed but not sealed; ventilation channels were sealed.

Measurements were performed with "Infiltec Blower Door Model 4" equipment with an automated performance testing system (flow range at 50 Pa 25–7800 m^3/h, accuracy $\pm$3%). Measurements were made at pressure difference steps of 10 Pa from 0 to 60 Pa. The fan was secured to the house front door using the Blower Door soft panel frame. Pressure and flow rate were controlled using a laptop, connected to a DM-2A Automatic Micro-manometer, which controlled the fan. To compare different buildings, the air flow rate at the pressure difference 50 Pa was divided by the internal volume of the buildings to arrive at the air change rate at 50 Pa, ACH50 value.

If low air tightness was detected, leakages of the building were identified using an infrared camera model ThermaCAM B640 "(accuracy 2% or 2 °C). All the thermography tests were made later during the

Table 3
Calculated total annual energy consumption for investigated buildings, values of qualifying indicator C_q, determined energy performance classes and results of measured average air change rates per hour at 50 Pa pressure.

House	Q_{sum}, kWh/m^2·year	Value of qualifying indicator C_q	Energy performance class	ACH50, air change per hour
1	87.45	0.38	A	0.41
2	126.35	0.38	A	0.69
3	90.56	0.37	A	0.74
4	130.50	0.38	A	0.55
5	89.60	0.40	A	0.64
6	100.15	0.38	A	0.58
7	119.16	0.38	A	0.61
8	95.36	0.38	A	0.52
9	87.36	0.37	A	0.65
10	204.24	0.84	B	5.01
11	129.72	0.98	B	9.25
12	152.00	0.85	B	3.50
13	151.13	0.97	B	7.21
14	192.00	0.97	B	5.54
15	201.81	0.99	B	5.86
16	216.06	0.97	B	2.19
17	222.08	0.70	B	11.30
18	152.07	0.65	B	8.15
19	236.02	1.14	C	5.50
20	307.30	1.06	C	3.41
21	207.88	1.23	C	10.85
22	246.87	1.06	C	8.60
23	292.66	1.41	C	7.50
24	273.76	1.02	C	5.83
25	246.42	1.03	C	4.55
26	231.83	1.31	C	5.00
27	255.41	1.29	C	2.99

Table 4
Calculated energy consumption.

House	Class	Energy consumption Q kWh/(m^2·year)								
		Q_{env}	Q_{vent}	Q_{d1}	Q_{inf}	Q_e	Q_i	Q_E	Q_{hw}	η_{hs}
1	A	49.58	10.04	0.67	10.68	13.02	6.34	14.0	12.5	0.85
2	A	80.70	10.21	0.41	24.06	19.12	6.34	14.0	12.5	0.90
3	A	59.80	10.10	0.36	20.89	30.66	6.34	14.0	12.5	0.85
4	A	104.98	9.91	0.45	11.25	16.72	6.34	14.0	12.5	1.00
5	A	47.30	10.04	0.59	26.34	14.60	6.34	14.0	12.5	1.00
6	A	70.52	9.99	0.48	15.74	20.54	6.34	14.0	12.5	0.95
7	A	87.05	10.01	0.36	18.61	17.32	6.34	14.0	12.5	1.00
8	A	51.92	10.20	0.39	24.00	11.23	6.34	14.0	12.5	1.00
9	A	38.36	10.19	0.56	26.00	14.30	6.34	14.0	12.5	0.90
10	B	138.44	24.60	0.67	42.16	33.99	6.34	14.0	10.53	0.73
11	B	72.61	21.78	1.59	16.48	17.03	9.50	21.0	21.05	0.98
12	B	100.96	34.54	0.67	10.68	14.32	6.34	14.0	12.5	1.00
13	B	103.33	29.47	0.70	13.79	21.22	6.34	14.0	12.5	0.96
14	B	126.59	32.21	0.59	33.04	25.75	6.34	14.0	12.5	0.97
15	B	128.76	36.30	0.56	32.16	17.68	6.34	14.0	12.5	0.99
16	B	151.56	39.82	0.41	24.06	19.12	6.34	14.0	12.5	1.00
17	B	137.25	16.37	0.37	63.90	39.05	6.34	14.0	12.5	0.88
18	B	100.96	12.31	0.67	10.68	14.32	6.34	14.0	12.5	0.83
19	B	162.03	37.26	0.41	34.06	21.03	6.34	14.0	12.5	0.99
20	C	159.04	24.04	0.62	36.78	29.75	6.34	14.0	12.5	0.66
21	C	129.39	33.79	0.64	19.74	19.01	6.34	14.0	12.5	0.87
22	C	162.33	35.58	0.38	25.40	25.50	6.34	14.0	12.5	0.87
23	C	217.62	24.04	0.54	40.84	31.51	6.34	14.0	12.5	0.92
24	C	170.91	24.04	0.62	41.27	24.53	6.34	14.0	12.5	0.83
25	C	143.43	33.26	0.27	32.60	28.78	6.34	14.0	33.33	0.88
26	C	129.71	43.86	0.61	47.69	35.95	6.34	14.0	12.5	0.87
27	C	182.58	43.15	0.41	24.06	24.64	6.34	14.0	12.5	0.96

winter period. The difference between the indoor and the outdoor air temperature was at least 20 °C. Thermography investigations were done to determine the main air leakage places, the 50 Pa negative pressure under the envelope was set with the fan pressurization equipment. After the infiltration airflow, the surface temperatures were measured with the infrared camera from the inside of the building.

Results

Evaluation of building energy performance

The results of Q_{sum}, values of qualifying indicator C_q and determined energy performance classes are presented in Table 3.

The average value of energy consumption of investigated houses is provided in Fig. 2, which shows that the increase in the value of average energy consumption reduced energy performance class.

All calculated energy consumption values are presented in Table 4.

The results of calculated energy consumption in Table 4 showed that heat losses due to over norm air infiltration and ventilation systems were 30% of total calculated energy consumption for all tested buildings (A, B, and C energy performance class).

These calculations underestimated the over norm infiltration due to insufficient tightness between separate construction elements (windows, walls, roof, etc). Building energy performance calculation methodology is based on the assumption that air tightness of the buildings complies with national requirements and that construction and mounting quality is assured.

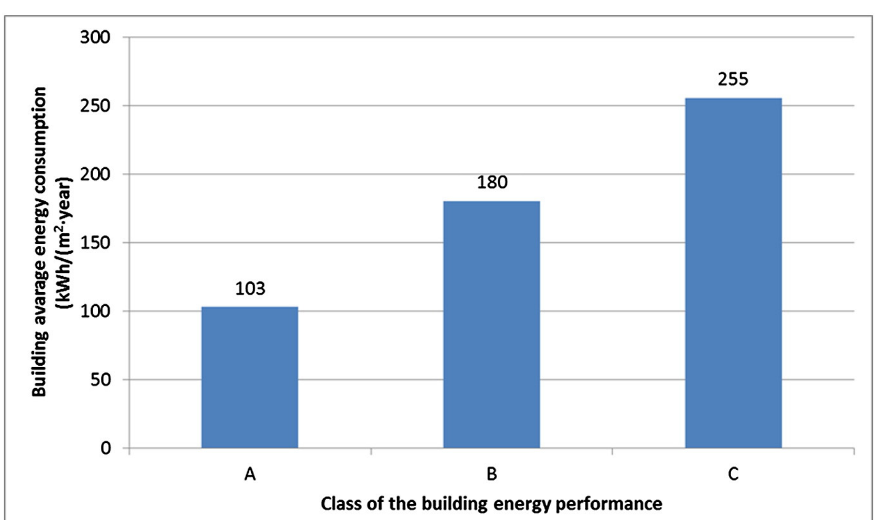

Fig. 2. Building average energy consumption.

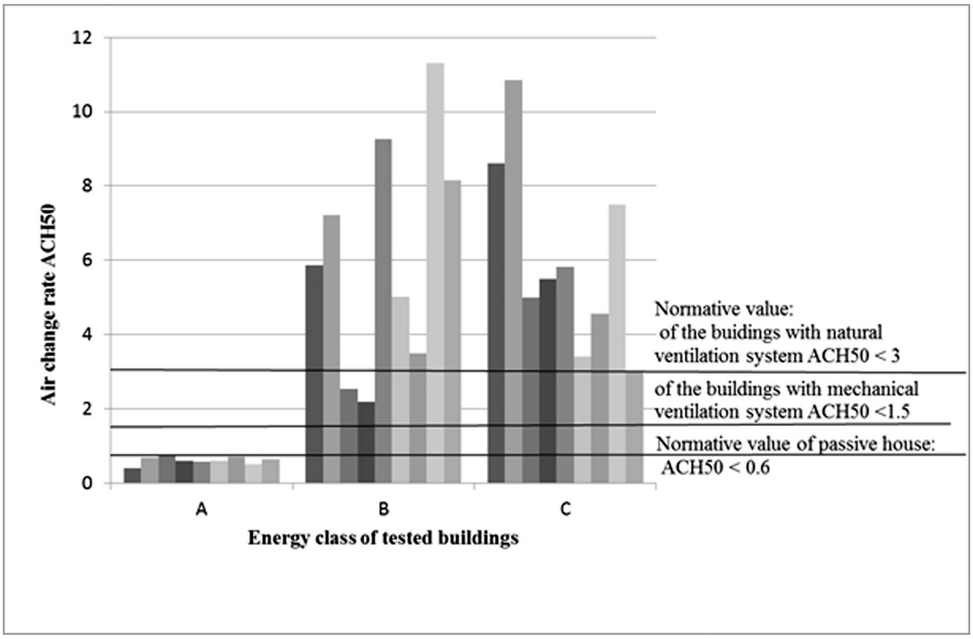

Fig. 3. Air change rate ACH50 of the tested buildings.

Value of the energy consumption for ventilation depended on ventilation type: natural, mechanical, or mechanical with heat recovery. Energy consumption was highest for mechanical ventilation with no heat recovery system, as compared to other systems.

Therefore, the next step of this research was to determine air tightness level in new Lithuanian buildings and to verify the assumption regarding reliability of the building energy performance calculation methodology mentioned earlier.

Air tightness

Air tightness of the buildings was measured after calculating Q_{sum} and C_q for each building. The results are presented in Fig. 3.

The results of air tightness of the buildings obtained indicated that the average ACH50 value with air pressure of 50 Pa was 4.73 air changes per hour; the minimum rate was 0.41 air changes per hour, and the maximum was 11.3 air changes per hour. The minimum values corresponded to building of A energy performance class and maximum to buildings of B energy performance class.

In fact, the results presented in Fig. 3 indicate that air tightness measurement results of low-energy buildings did not differ from the requirements presented in regulation STR 2.01.09:2005. The average rate of air changes per hour ACH50 = 0.6. However, air change rate ACH50 values in buildings with B and C energy performance classes were higher than regulatory ones. In none of the investigated B and C class buildings, the average rate of air change was lower than 1.5 air changes per hour, although buildings were equipped with mechanical ventilation system devices. Two buildings with energy performance class B had air change rates lower than 3 air changes per hour, and one building with class C reached the limit value of ACH50 = 3 air changes per hour.

Table 5
Statistical data of air change rate ACH50 of the tested buildings.

Energy performance class of the building	Mean value of ACH50 (air change per hour)	Std. Deviation	90 % Confidence interval
A	0.6	0.10	0.55–0.67
B	6.1	3.13	4.17–8.05
C	6.0	2.54	4.45–7.60

Mean values, standard deviation, and confidence interval of 90% of air change rate ACH50 are presented in Table 5.

The air tightness of low-energy buildings (A class) was high and sampling data were highly concentrated compared with the data of buildings of other classes. Monitoring data of buildings with B and C energy performance classes were widely dispersed and partly overlapping. The results did not indicate any significant difference between the obtained average values.

Summing up, from the obtained results, it can be stated that air tightness of low-energy Lithuanian buildings was assured and met regulatory requirements. However, new buildings in Lithuania, with B and C energy performance classes, were not air tight enough and did not meet regulation STR 2.01.09:2005 requirements. Therefore, it is possible that energy consumption of buildings with B and C classes would be higher if calculated according to methodology presented in STR 2.01.09:2005.

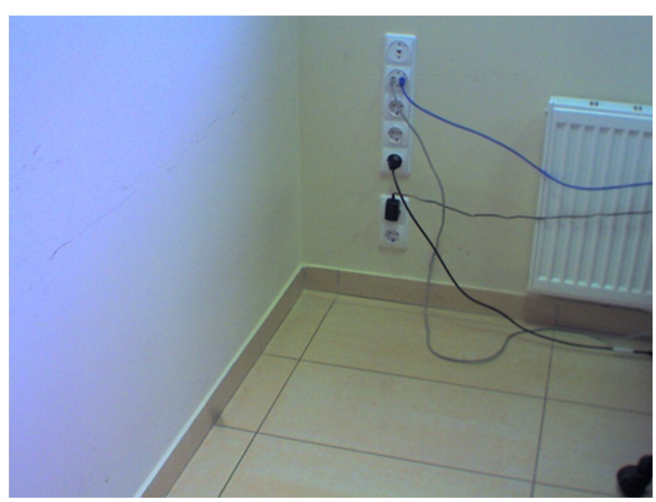

Fig. 4. Typical air leakage places in the studied houses. Junction of the ceiling and floor with the external wall and penetrations of electrical and plumbing installations through the air barrier systems.

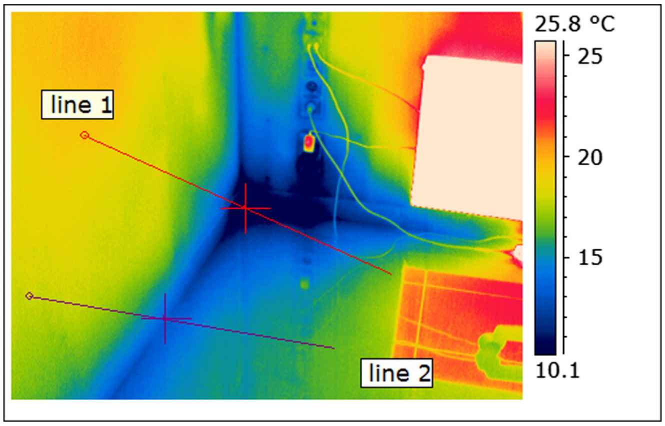

Fig. 5. Thermographic photo of junction of the wall and floor leakage places.

Thermographic survey

A thermographic survey was performed in order to determine causes of low air tightness of buildings, which revealed defects associated with poor quality of mounting work. The most common defects are cracks in the construction joins as can be seen in Figs. 4 and 7 and this is reflected in the thermographic photos in Figs. 5 and 8. The distribution of buildings' surface temperature is presented in Figs. 6 and 9.

Line 1 drawn in Fig. 5 includes leakage places of junction of the wall and floor. The maximum temperature of wall surfaces $\theta_{si} = 19.7$ °C, and minimum wall and floor angle surface temperature $\theta_{si} = 5.5$ °C. The difference between surface temperatures was approximately 14 °C (Fig. 6). It is likely that condensation processes will take place in this leakage area, and conditions for mold growth will appear.

The indoor environment of this building will have negative influence on people: air movement will be felt during the cold season, because of the large temperature difference between the surface and air temperature; and flow of cold air will be felt, resulting in requirement of higher amount of energy to heat the building.

Mounting of windows, skylights, and other glass enclosures and external doors was another common case of poor-quality work. Skylight mounting defects are presented in Fig. 8. The heat was lost through the skylight's sash and cracks around the construction frame. Thermographic analyses presented in Fig. 9 indicate that the maximum temperature of ceiling surface was $\theta_{si} = 20.5$ °C and minimum temperature at skylights frame was $\theta_{si} = 10.7$ °C.

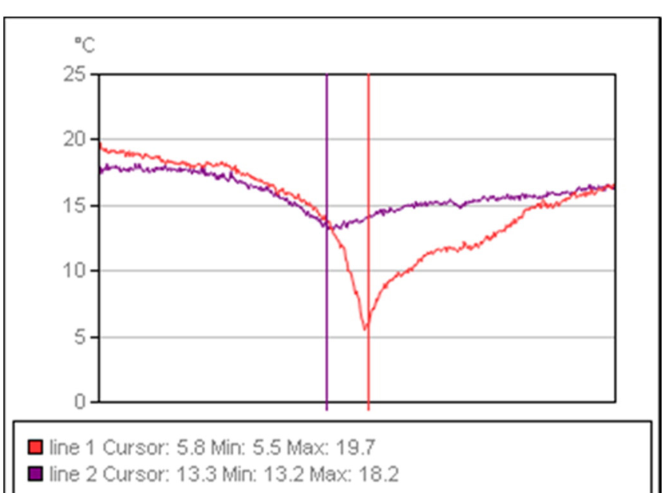

Fig. 6. Thermographic analyses of junction of the wall and floor leakage places.

Fig. 7. Typical air leakage places in the studied houses around and through the windows or skylights.

Thermal bridges (values were considerably higher than regulatory ones (STR 2.05.01:2005)) were formed as surface temperature at window frames was 50% decreased. Investigations indicated that if influence of thermal bridges on heat losses through the windows is not taken into consideration, then it is possible that the actual heat losses could be twice as high as the calculated values. In most critical cases, not only water vapor condensation, but also frost (at negative temperatures) or mold (when condensation is not evaporating for a long time) may occur in places of thermal bridges (Ramanauskas et al., 2005).

Typical air leakage places in the studied houses were junction of the ceiling and floor with the external wall, junction of the separating walls with the external wall and roof, penetrations of electrical and plumbing installations through the air barrier systems, leakage around and through the windows and doors (Kauppinen and Siikanen, 2011).

Discussion

The energy performance certification of Lithuania existed since 2007. According to the requirements of European Parliament and Council Directive 2010/31/EC, energy consumption of buildings should be substantially reduced, and no later than 31st of December of 2020, all new buildings should be nearly zero-energy buildings (A class in Lithuania), i.e., buildings that generate nearly the same amount of renewable energy on site as the actual energy consumption. Now

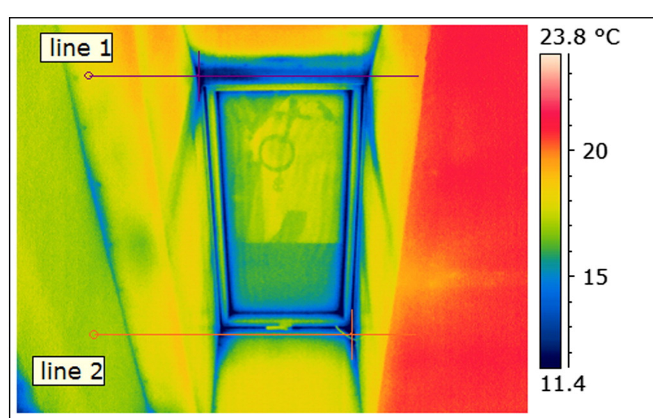

Fig. 8. Thermographic photo of skylight mounting leakage places.

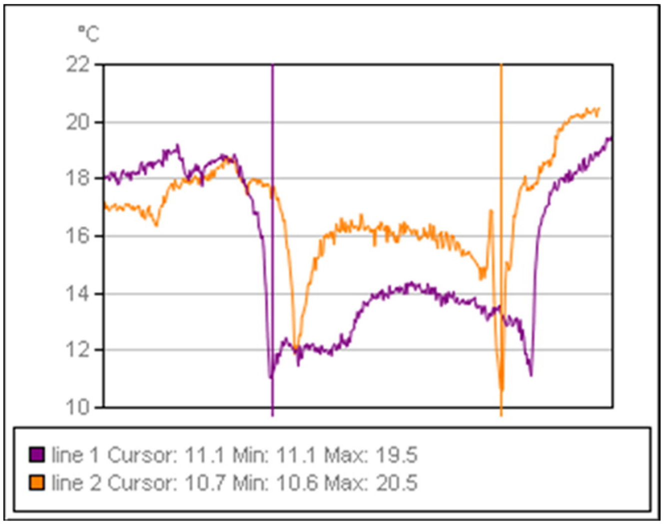

Fig. 9. Thermographic analyses of skylight mounting leakage places.

there is a transitional period in Lithuania when the allowing tightening of requirements. New buildings of A energy performance class had to be built since 2013. If the new building does not correspond A class construction not get work completion statement and the building does not get permission to use. Also, this certificate is needed for selling of buildings. The residents cannot sell the house if they don't know energy performance class of house. Therefore, the class of energy performance of building is importance in Lithuania.

Results of the investigation and calculations showed that only A class buildings pass the air tightness (air change rate ACH50) requirements presented in the regulations. Besides certain requirements presented in regulations for A class buildings, air tightness test should be performed during the certification procedure. However, variation of air change rate ACH50 results of B and C energy performance class buildings was very high (Table 4), as there is no requirement in the regulations to control this value for B and C class.

B and C class buildings could be renovated or reconstructed. It could have the very good insulating of envelopes, modern ventilation, heating, or cooling systems. This kind of buildings could be A, B, C, or D class according to the methodology of calculation at this moment, but energy performance evaluation is not accurate, because there is no checked air tightness. When building air tightness is not evaluated, calculation of energy performance becomes meaningless as the results do not represent the real energy consumption for heating. For example, energy performance class of one of the investigated building (no. 17 in Table 3) was B, which indicates that this building is attributed to energy performance building groups. The total annual energy consumption of this house was 222.08 kWh/m^2·year. However, after the air tightness test it was revealed that air change rate ACH50 was approximately 4 times higher (11.30 air changes per hour) than the requirements laid down in the technical standards for detached houses without ventilation devices and it was approximately 7.5 times higher for detached houses with ventilation devices. This indicates that the construction quality of the building was poor and a large part of the heat was lost through the cracks and leakage areas of the building.

In order to fulfill the requirements of the European Energy Performance of Buildings Directive (EPBD) for the reduction of energy consumption, it's necessary to rely not only on theoretical calculations, but also to evaluate technical features of the buildings evaluated as well as the quality of the construction work. This is possible after performance of the air tightness test. Therefore, in order to increase the reliability the results of the evaluation of buildings' energy performance, its proposed to perform building energy certification according to the following scheme (Fig. 10).

Before the start of the evaluation of energy efficiency of the building, it is necessary to perform air tightness test as per EN 13829:2002 requirements. If the obtained results satisfy national Building Technical Regulation requirements, calculations of total annual energy consumption are made and value of qualifying indicator C_q is determined which identifies energy performance class of the building. If the average air change rate of the tested building corresponds to ACH50 < 0.6 air changes per hour, the building could be A, B, or C class. It will depend on the thermal properties of the external walls, use of electric power, energy used for the ventilation of the building during the heating season, etc. The air tightness of the building might correspond to ACH50 < 0.6 air change per hour; however, if there are high energy losses through the external envelops or high-energy consumption, the building might be in the range of B class. That is the reason why arrows are presented in Fig. 10, showing that this kind of building might be A or lower class (B or C). If buildings with ventilation equipment have ACH50 < 1.5 air changes per hour and if buildings with natural ventilation have ACH50 < 3 air changes per hour, such buildings can be B or C energy performance class. If the average air change rate values are higher than those presented in the national requirements, then newly constructed buildings cannot be certified. According to the Building Technical Regulation STR 2.01.09:2005, the energy performance class of new buildings (or buildings parts) must not be lower than C class. Buildings which are not air tight should be rectified in order to ensure air tightness.

According to the presented energy performance evaluation scheme, under which performed evaluation of energy performance of buildings

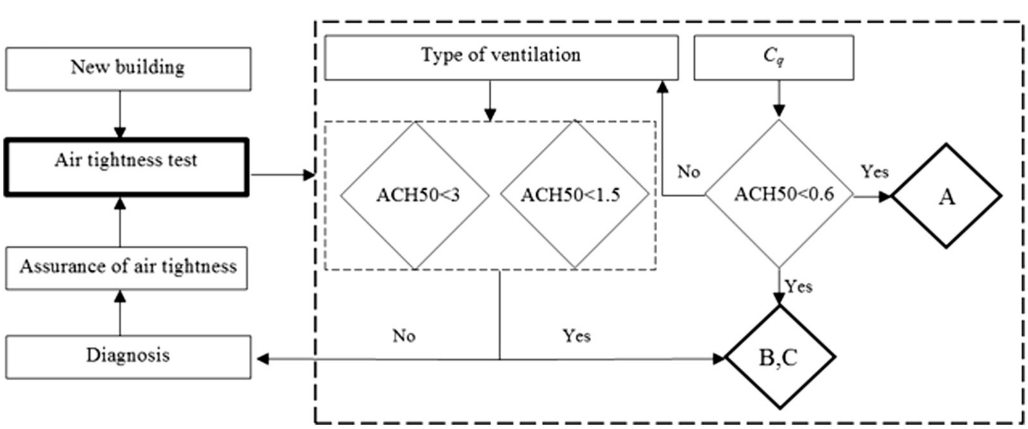

Fig. 10. Building energy certification scheme.

ensures high quality of construction work, building's durability, the reliability of calculations of heat losses.

Conclusions

Air tightness of low-energy buildings was sufficient and met requirements of STR 2.01.09:2005 regulation. The average value ACH50 = 0.6 air change per hour.

The results of this work showed that new Lithuanian buildings (2007–2011 construction year) of B and C energy performance class were not sufficiently air tight. The average air change rate, when air pressure of 50 Pa was present, was 2 times higher than the regulatory value (ACH50 = 3 air change per hour).

Typical air leakage places in the studied houses were junction of the ceiling and floor with the external wall, junction of the separating walls with the external wall and roof, penetrations of the electrical and plumbing installations through the air barrier systems, leakage around and through windows and doors.

Building's energy performance calculation methodology is reliable only after verifying that the build is air tight. Otherwise, the heating energy consumption in buildings can significantly differ from the calculated values.

The energy performance evaluation scheme presented in this paper ensures high quality of construction work, building's durability and reliability of calculations of heat losses.

It is recommended that a requirement to perform air tightness test for B and C energy efficiency class buildings before evaluating building's energy performance should be introduced in the building regulations.

References

Alberini A, Banifi S, Kapoor S, Ramseier C. Energy efficiency investments in the home: Swiss homeowners and expectations about future energy prices. Energy J 2013; 34(1):49–86.

d'Ambrosio Alfano FR, Dell'Isola M, Ficco G, Tassini F. Experimental analysis of air tightness in Mediterranean buildings using the fan pressurization method. Energy Build 2012;53:16–25.

Andaloro APF, Salomone R, Ioppolo G, Andaloro L. Energy certification of buildings: a comparative analysis of progress towards implementation in European countries. Energy Policy 2010;38:5840–66.

Chel A, Janssens A, De Paepe M. Thermal performance of a nearly zero energy passive house integrated with the air–air heat exchanger and the earth–water heat exchanger. Energy Build 2015;96:53–63.

Czako V. Evolution of Hungarian residential energy efficiency support programmes: road to and operation under the Green Investmen Scheme. Energy Effic 2012;5(2): 163–78.

EN 13829:2002. Thermal performance of buildings – determination of air permeability of buildings – fan pressurization method. Brussels: European Committee for Standartisation; 2002.

ETAG 004. Guideline for European Technical Approval of External Thermal Insulation Composite Systems With Rendering. Brussels: European Organisation for Technical Approvals; 2008 [June 2008, 144 p. + app. 29 p. [cited 28 Mart 2015]. Available from Internet: http://www.ue.itb.pl/files/ue/etag/etag_004.pdf].

European Commission. Towads a European strategy for the security of energy supply. Green Paper; 2000. [2000].

Directive 2010/31/EC of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast), Brussels, [cited 26 June 2012].

Maldonado E, Wouters P, Papaglastra M. Implementing the Energy Performance of Building Directive (EPBD). Featuring Country reports 2010. European Union; 2011. p. 342. [ISBN 978-92-9202-090-3].

Feist W, Schnieders J, Dorer V, Haas A. Re-inventing air heating: convenient and comfortable within the frame of the Passive House Concept. Energy Build 2005;37:1186–203.

Gonzalez ABR, Diaz JJV, Caamano AJ, Wilby MR. Towards a universal energy efficiency index for buildings. Energy Build 2011;43:980–7.

Groh S. The role of energy in development processes – The energy poverty penalty: Case study of Arequipa (Peru), 18; 2014. p. 83–99.

Gualberti G, Martins LF, Bazilian M. An econometric analysis of the effectiveness of development finance for the energy sector. Energy Sustain Dev 2014;18:16–27.

HN 42:2004 Microclimate of residential and public houses, Vilnius Ministry of Environment of Republic of Lithuania.

Jaraminienė E. Research on air infiltration in buildings according to the uncertainty analysis. Doctoral thesis Vilnius: Technika; 2008. p. 146.

Kalamees T. Air tightness and air leakages of new lightweight single-family detached houses in Estonia. Build Environ 2007;42:2369–77.

Kalamees T, Kurnitski J, Jokisalo J, Eskola L, Jokiranta K, Vinba J. Measured and simulated air pressure conditions in Finnish residential buildings. Build Serv Eng Res Technol 2010;31(2):177–90.

Kauppinen T, Siikanen S. Improvement of energy efficiency – the use of thermography and airtighness test in verification of thermal performance of school. Thermosense: thermal infrared applications XXXIII, Proceedings of SPIE-The International Society for Optical Engineering. 8013; 2011.

Kovanen KA, Laamanen J, Kauppinen T, Duanmu L. Air tightness of New Residential Buildings in Finland. 6th International Symposium on Heating, Ventilating and Air Conditioning. Proceedings. Vols I–III; 2009. p. 207–13.

Malmqvist T, Glaumann M, Scarpellini S, Zabalza I, Aranda A, Liera E, et al. Life cycle assessment in buildings: the ENSLIC simplified method and guidelines. Energy 2011;36:1900–7.

Matrosov YA, Chao M, Majersik C. Increasing thermal performance and energy efficiency of buildings in Russia: problems and solutions, *ASHRAE*. 2007. Available from Internet http://www.cenef.ru/file/St-267e.pdf.

Pan W. Relationships between air-tightness and its influencing factors of post-2006 vew-build dwellings in the UK. Build Environ 2010;45:2387–99.

Ramanauskas J, Bliūdžius R, Stankevičius V. Thermal properties of windows. Monograph. Kaunas: Technologija; 2005. p. 135.

Šadauskienė J, Banionis K, Paukštys V. Air permeability tests of masonry structures. J Sustain Archit Civ Eng 2014;9(4):74–82.

Šadauskienė J, Banionis K, Paukštys V, Šeduikytė L, Ramanauskas J. Diagnostics and problems analysis of buildings air tightness. J Sustain Archit Civ Eng 2013;3(4):52–8.

Sfakianaki A, Pavlou K, Santamouris M. Air tightness measurements of residential houses in Athens, Greece. Build Environ 2008;43:398–405.

Sinnott D, Dyer M. Air-tightness field data for dwellings in Ireland. Energy Build 2012;51: 269–75.

Smeds J, Wall M. Enhanced energy conservation in houses through high performance design. Energy Build 2007;39:273–8.

Stankovic B, Kostic A, Popovic J. Analysis and comparison of lighting design criteria in green building certification systems—guidelines for application in Serbian building practice. Energy Sustain Dev 2014;19:56–65.

STR 2.05.01:2005 Thermal Technology of Building Elements, Vilnius: Ministry of Environment of Republic of Lithuania.

STR 2.01.09:2005 Energy Performance of Buildings. Certification of Energy Performance, Vilnius: Ministry of Environment of Republic of Lithuania.

Tronchin L, Fabbri KA. Round robin test for buildings energy performance in Italy. Energy Build 2010;42:1862–77.

Venckus N, Bliūdžius R, Endriukaitytė A, Parasonis J. Research of low energy house design and construction opportunities in Lithuania. Technol Econ Dev Econ 2010;16(3): 541–54.

Wouters P, Carrie FR. Implementation of energy performance regulations: opportunities and challenges related to building air tightness, EPBD Building Platform. 2008. Available from Internet http://www.buildup.eu/sites/default/files/P072_ASIEPI_WP5_IP1_p3067.pdf.