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Air tightness and air leakages of new lightweight single-family detached houses in Estonia

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Abstract

A field measurement study of the air tightness and the air leakages of 32 detached houses was conducted during 2003–05 in Estonia. The buildings were classified according to the number of storeys, building technology, and the ventilation systems. Using the standardized BlowerDoor pressurization technique, the air leakage rate of each house was determined. To determine typical air leakage places and their distribution, an infrared image camera and a smoke detector were used.

The mean air leakage rate at the pressure difference of 50 Pa in the entire database was 4.2 $m^3/(h\,m^2)$. The mean air change rate at the pressure difference of 50 Pa from the entire database was 4.9 1/h. It was found that the number of storeys and the quality of workmanship and supervision play a significant role in the condition of air tightness.

The typical air leakage places in the studied houses were: the junction of the ceiling/floor with the external wall, the junction of the separating walls with the external wall, penetrations of the electrical and plumbing installations through the air barrier systems, penetrations of the chimney and ventilation ducts through the air barrier systems, leakage around and through electrical sockets and switches, and leakage around and through windows and doors.

According to the questionnaire conducted, fluctuating room temperature, cold floors and draught from electric sockets were related to the houses with air leakage rate $>3\,m^3/(h\,m^2)$ at 50 Pa.

Keywords: Air tightness; Fan pressurization test; Infrared thermography; Air infiltration

1. Introduction

While the hygrothermal performance of today's lightweight timber-frame envelope assemblies is becoming more complex, air tightness is becoming an important property of the building envelope. Air tightness of the building helps to avoid uncontrolled airflows through the building envelope, which can lead to problems related to the hygrothermal performance, health, energy consumption, performance of the ventilation systems, thermal comfort, noise, and fire resistance.

Moisture convection through the building envelope may cause severe moisture loads imposed on the structure. Air leakage and indoor air exfiltration may cause moisture accumulation or condensation, leading to the microbial growth on materials, change of the properties of the material or even to structural deterioration. Air exfiltration is a problem especially in the cold climate areas where the moisture content of the indoor air is much higher than that of the outdoor air. Hagentoft and Harderup [1] have shown that the air leakage carrying moist air into the construction leads to unacceptably high values even for moderate indoor moisture supplies. The simulation results of Janssens and Hens [2] have shown that even when a roof design complies with condensation control standards, a lightweight system remains sensitive to condensation problems because of air leakage through the discontinuities, joints and perforations, common to most existing construction methods.

Air convection through a building envelope could introduce outdoor or crawl space airborne pollutants into the indoor air. Field measurements [3,4] have shown evidence of fungal spores being transported indoors from

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a crawl space. Air leakage in house–garage interfaces may result in the transport of the contaminants generated in garages into adjacent living spaces [5]. Although radon can enter buildings by several mechanisms, the dominant radon entry mechanism is by air leakage through the basement floor [6]. It is shown that indoor air biocontamination originating from the envelope of a precast concrete panel building in a subartic climate is rare. However, the small-sized actinomycete spores, which have various adverse health effects, may infiltrate from the wall structures and cause indoor air contamination [7].

Air leakage results in an increased air change rate and energy use. According to the simulations by Jokisalo and Kurnitski [8], air tightness has a significant effect on the heat energy consumption of the detached house in the cold climate areas. By changing air change rate at 50 Pa, n_{50}, between 1, 3, 5 and 10 1/h, heating energy consumption increased from 4% to 21%. Infiltration may be responsible for about 13% of the heating loads and 3% of the cooling loads for US office buildings [9]. Due to the higher levels of insulation in more recent buildings, the infiltration is responsible for about 25% of the heating loads and 3% of the cooling loads. According to Binamu [10], up to 53% of the ventilation heating energy in buildings is lost due to uncontrolled air changes. Air leakages influence heat losses also through their effect on the function of the thermal resistance of insulation materials.

Air leakage is an important factor on the performance of the ventilation systems. The negative influence of leaky envelopes occurs mainly on the uncontrolled air intake and in pressure conditions. Therefore, ventilation standards also set the requirements for air tightness. For example, the National Building Code of Finland Part C3 [11] provides that to guarantee a proper function of ventilation devices, air tightness of a building envelope is recommended to be near the value $n_{50} = 1\,1/\text{h}$. The Belgian ventilation standard NBN D50-001 [12] set the air tightness criteria for dwellings with a mechanical ventilation $n_{50} < 3\,1/\text{h}$ and in the case of the balanced mechanical ventilation with a heat recovery: $n_{50} < 1\,1/\text{h}$.

The degree of air tightness influences the fire safety mainly due to the movement of smoke from a fire in the early stages of growth [13].

Air tightness has an impact also on the thermal comfort. The prevalence of complaints related to fluctuating room temperature and cold floor is significantly higher houses with air change rate at 50 Pa $n_{50} > 6\,1/\text{h}$ compared to lower leakage rates [14]. Due to draught problems, air tightness may increase the indoor temperature and therefore also energy consumption.

In Estonia lightweight timber-frame envelopes are well-used for single-family detached houses. According to the Estonian standard EVS 837-1:2003 [15] the thermal conductance of the building envelope cannot exceed the following values: walls $U \leqslant 0.28\,\text{W/(m}^2\,{}^\circ\text{K)}$, roofs and floors, that are connected with the outdoor air $U \leqslant 0.22\,\text{W/(m}^2\,{}^\circ\text{K)}$, the slab on the ground $U \leqslant 0.36\,\text{W/(m}^2\,{}^\circ\text{K)}$, and the windows $U \leqslant 2.1\,\text{W/(m}^2\,{}^\circ\text{K)}$. The average air leakage rate at a pressure difference of ± 50 Pa should not exceed $3\,\text{m}^3/(\text{h}\,\text{m}^2)$ for residential and $6\,\text{m}^3/(\text{h}\,\text{m}^2)$ for non-residential buildings. These criterions have been applied from 1995, set in the Estonian building norm [16]. However, regarded as a guideline, it has been widely used by civil engineers and customers of the building, at the same time reflecting the principle of good engineering practice. In many cases we run into houses, where the thermal conductance of the building envelopes is low, but the envelope is not air tight. Therefore during last years, besides the low thermal conductance and avoiding thermal bridges in building envelope, attention is also being given to the air tightness of the building envelope. Jõgioja and Jõgioja [17] have measured air tightness of Estonian detached houses during 1999–2000. The mean air leakage at the pressure difference of 50 Pa was $n_{50} = 9.6\,1/\text{h}$ (the minimum being 4.9 1/h and maximum 32 1/h). As there was also reclamation cases measured in this study, the result can be worse than the average and does not show the actual picture of the air tightness of new Estonian detached houses. In this study a field measurements of the air tightness and the air leakages of randomly selected new Estonian lightweight (timber-frame and perforated light-steel-frame) detached houses are presented and analysed.

2. Methods

2.1. Studied houses

Air tightness measurements and air leakage analysis were carried out in 32 occupied lightweight single-family detached houses during the years 2003–05. Most of the houses were relatively new, built on average 2–3 years prior to the measurements. The average floor area of the studied houses was $138\,\text{m}^2$; the average volume was $352\,\text{m}^3$. The houses were randomly selected mainly from Tallinn area from the databases of the manufacturing and construction companies. The selection should represent newly built Estonian lightweight detached houses on average.

In most of the studied houses, the vapour barrier that controlled water vapour diffusion through the envelope was designed to function also as an air barrier. In the main inner surface of the walls, gypsum boards were used. The most common insulation material was mineral wool. The sheathing on the external side of the envelope was the mineral-wool board, gypsum board or the wooden fibreboard. The first floor was mainly (90%) composed of a slab on the ground, but there were houses also with a wooden floor and crawl space. None of the houses had a cellar.

The studied houses were constructed on site or built from insulated prefabricated wall elements or modular sections. Most of the wall elements were made from timber stud, but in three houses wall elements were made with perforated light-steel-frame stud. Manufactured houses were built mainly by professional building companies.

Houses that were constructed on site were built by house owners or by professional building companies.

2.2. Measurement methods

The air tightness of each building was measured with the standardized [18] fan pressurization method, using "Minneapolis Blower Door Model 4" equipment with an automated performance testing system (flow range at 50 Pa 25–7.800 m^3/h, accuracy $\pm 3\%$). Depending on the purpose, air tightness measurements were done under three different conditions. To determine the air tightness of the building envelope, depressurizing and pressurizing tests were conducted. All the exterior openings: windows and doors were closed; ventilation ducts and chimneys were sealed. Measurements were made at 10 Pa pressure difference step from 0 to 60 Pa.To estimate the natural infiltration rate in houses with natural ventilation and in houses with mechanical exhaust ventilation without a working fan, a third series of tests were conducted. These tests were made with normally opened passive fresh air inlets, opened window airings, and sealed ventilation exhaust ducts under negative indoor pressure conditions. To compare different buildings, the air flow rate at the pressure difference 50 Pa was divided by the external envelope area (resulting air leakage rate at 50 Pa) or by the internal volume of the building (result air change rate at 50 Pa, n_{50} value).

To determine typical air leakage places and their distribution, an infrared image camera Agema 450 (accuracy 2% or 2 °C, measurement range −20–500 °C) and a smoke detector were used. All the thermography tests were made later during the winter period. The difference between the indoor and the outdoor air temperature was at least 20 °C. Thermography investigations were done 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 had cooled the inner surface (~30 min) of the envelope, the surface temperatures were measured with the infrared image camera from the inside of the building.

Additionally, an interview questionnaire was completed for each house, where the building characteristics, the used building materials, the type of HVAC systems and its use, occupants' habits, typical perceptions, complaints and symptoms related to the indoor climate were included, whereas the occupant acted as a contact person of the study.

3. Results

3.1. Air tightness

Building air tightness is expressed either by the average air leakage rate at a pressure difference of ± 50 Pa ($m^3/(h\,m^2)$) or by the air change per hour at 50 Pa (1/h) (n_{50} value). The Effective Leakage Area (cm^2) is defined as the area of a special nozzle-shaped hole that would have the same flow rate as the building does at a pressure difference of 4 Pa. Effective Leakage Area is normalized by dividing it by the floor area (m^2). The entire database allowed for the determination of variables that have a major effect on the air tightness of the envelopes. The houses were divided into subdivisions according to different variables of comparison. The average values of air tightness and their standard deviations in different subdivisions are shown in Table 1.

Table 1
Results of air tightness measurements

	Number of houses	Air leakage at 50 Pa ($m^3/(h\,m^2)$)		Air change rate at 50 Pa, n_{50} (1/h)		Effective Leakage Area at 4 Pa (cm^2/m^2)	
		Average	St. dev.	Average	St. dev.	Average	St. dev.
All measured data	32	4.2	3.3	4.9	3.5	326	273
One-storey house	9	1.9***	0.8	2.3***	0.7	105***	59
Two-storey house	23	5.1***	3.5	5.9***	3.5	413***	271
House built under professional supervision	23	3.0*	1.8	3.5**	2.1	218**	194
House built without professional supervision	9	7.2*	4.5	8.4**	3.7	602**	243
Constructed on site	17	5.3*	4.0	6.0*	3.9	427*	307
House with pre-fabricated wall or room elements	15	2.9*	1.8	3.5*	2.1	211*	166
Natural ventilation	4	10.1*,*	5.2	11.0**,**	2.4	689**,**	185
Mechanical exhaust ventilation	16	3.5*	2.0	4.4**	2.9	273**	238
Balanced ventilation with heat recovery	12	3.1*	2.0	3.5**	2.1	277**	254

*Significant, $P<0.05$; **Highly significant, $P<0.01$.;***Extremely significant, $P<0.001$.

In the measured houses, the mean air leakage at the pressure difference of 50 Pa in the entire database was $4.2\,m^3/(h\,m^2)$, the minimum being $0.9\,m^3/(h \cdot m^2)$ and the maximum $17.9\,m^3/(h\,m^2)$. The mean air change rate at the pressure difference of 50 Pa from all the databases was 4.9 1/h, the minimum being 0.7 1/h and the maximum 13.6 1/h.

The influence of different comparison variables is described as follows:

Number of storeys. Most of the single-family timber-framed detached houses in Estonia have one or two storeys. The air tightness of the studied houses was significantly ($P<0.0002$) worse in two-storey houses. The main reason for that was probably the junction of the ceiling/floor and the external wall that was also confirmed by the thermography investigations (Figs. 5, 6). Two two-storey houses that were built on site and showed almost lowest air-leakage rate show that low air-leakage can be archived also in two-storey houses. In these houses a special solution was used to keep air barrier unbroken in the junction of the floor and the external wall.

Workmanship quality and supervision. It is not rare in Estonia for a house owner to build a detached house on his own, with the help of some friends or a couple of workers. In that case, only professional supervision is necessary. However, unfortunately it is common to save here. Those houses can be divided into two groups: those that are built by professional builders or under professional supervision and those based on one's own effort with no professional supervision. It was found that the air tightness of the latter is significantly ($P<0.02$) worse.

Building technology. Houses in two building technology groups were studied. The first group included houses constructed on the building site. The other group was those built with pre-fabricated wall or room elements that were made in factory conditions and mounted on the building site. A significant difference ($P<0.02$) between the prefabricated houses and those that were constructed on the building site was observed. Houses that were constructed on site were leakier than other types. Nevertheless, taking into account cross dependence effect of different variables we see that workmanship quality and supervision as well as number of storeys of the house had stronger effect than building technology (prefabricated house or houses constructed on the building site). In subdivision of houses that were constructed on site, were more air tight ($P<0.02$) houses that were built by professional builders or under professional supervision compared to those built based on one's own effort with no professional supervision. One-storey houses were more air tight than two-storey houses in subdivisions of prefabricated houses ($P<0.005$) and in subdivisions houses that were constructed on the building site ($P<0.03$). Comparing all two-storey houses, there were more air tight ($P<0.03$) houses, that were built by professional builders or under professional supervision compared to those that were built based on one's own effort with no professional supervision. Other components

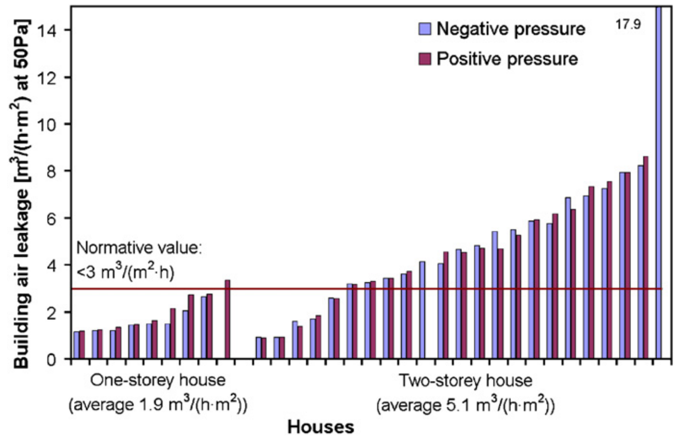

Fig. 1. Distribution of the results of air tightness measurements in houses on the subdivisions based on building storey.

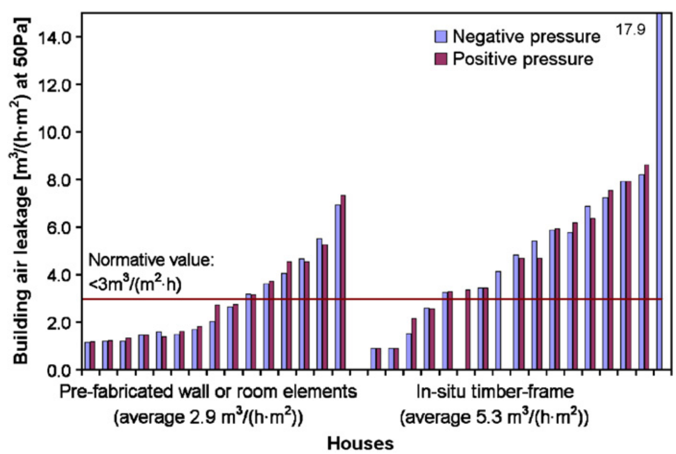

Fig. 2. Distribution of the results of air tightness measurements in houses on the subdivisions based on building technology.

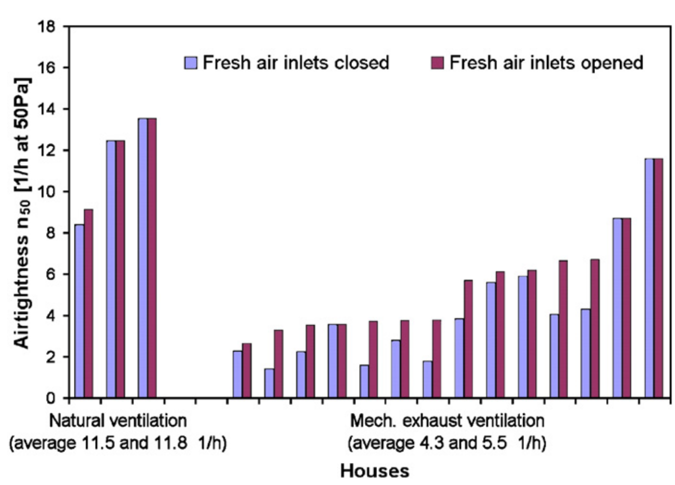

Fig. 3. The result of the air leakage measurements with sealed fresh air inlets (light column) and opened fresh air inlets (dark column) under 50 Pa negative pressure conditions.

that improved air tightness were shifting air barrier 30–50 mm inside to building envelope and avoiding electrical sockets and switches in external walls (they located in separating walls).

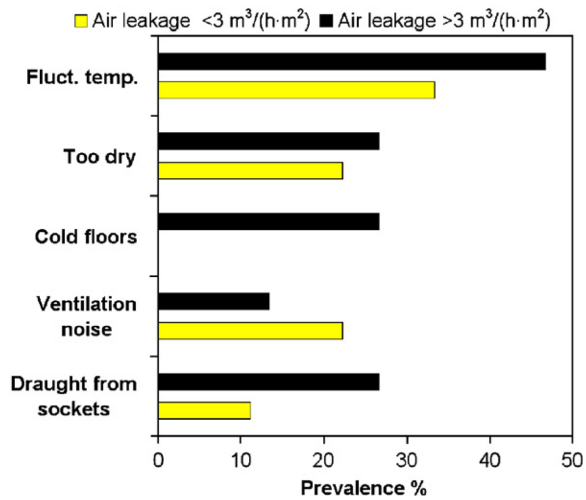

Fig. 4. Main complaints related to indoor climate during winter in houses with different air tightness.

Ventilation systems. The air tightness of the building envelope was significantly worse in houses with natural ventilation than in those with mechanical exhaust ventilation ($P<0.05$) or in houses with balanced ventilation with heat recovery ($P<0.05$).

The distribution of the results obtained from air tightness measurements in houses on the subdivisions according to the storey and building technology is shown in Figs. 1 and 2.

To estimate the influence of air inlets on the overall air leakage rate, the test series were conducted with normally opened passive fresh air inlets, and window airings and sealed ventilation exhaust ducts under negative indoor pressure conditions. Fig. 3 shows the air leakage difference between the opened and the closed air inlets. If we compare these two measurements series, we can see that, in houses with air inlets, average air change rate was 55% higher in case of opened air inlets. It is possible to estimate natural infiltration under normal pressure conditions with different empirical [19–21] or semi-empirical models [22–24]. From measurements the estimated natural infiltration rate stayed on a lower level to guarantee the air change rate 0.5 1/h in the most of cases.

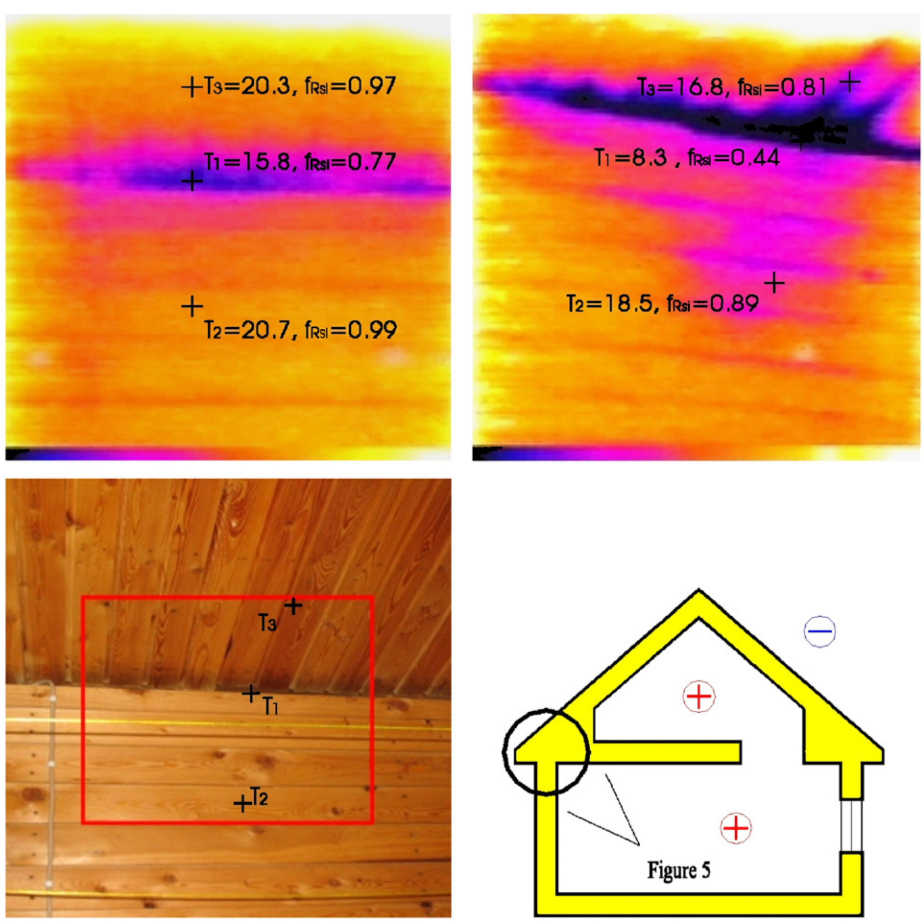

Fig. 5. An example of air leakage on the junction of the ceiling and the external wall on no additional pressure difference (upper left) and under −50 Pa pressure conditions (upper right). Lower Figures show the picture (left) and the section from the junction.

Occupants' opinions concerning indoor climate and thermal comfort collected from the questionnaires and the results of air tightness measurements were compared. According to the questionnaire, fluctuating room temperature, cold floors and draught from electric sockets were related to houses with an air leakage $>3\,m^3/(h\,m^2)$ at 50 Pa, Fig. 4.

3.2. Typical air leakage places

To determine typical places of air leakage and their distribution, the infrared image camera and smoke detector were used. Figs. 5 and 6 show the examples of air leakage places on the junction of the ceiling and the external wall. From measured internal surface temperature ($T_{s,in}$, °C), indoor temperature (T_{in}, °C) and outdoor temperature (T_{out}, °C) the temperature factor at the internal surface ($f_{R_{si}}$, –) was calculated according to Eq. (1):

$$f_{R_{si}} = \frac{T_{s,in} - T_{out}}{T_{in} - T_{out}}. \quad (1)$$

Typical air leakage places in the studied houses were:

- junction of the ceiling/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;
- penetrations of the chimney and ventilation ducts through the air barrier systems;
- leakage around and through electrical sockets and switches;
- leakage around and through windows and doors.

4. Discussion

Depending on the material and design, a number of alternatives are available to ensure the air tightness of building envelope. The air barrier can be placed on either the outer or the inner side of the insulation. Also, the insulation itself may be the air barrier, e.g. urethane insulation on a timber frame envelope assembly. In most of the studied houses, the vapour barrier that controls vapour diffusion functioned also as an air barrier. That is also a common building practice in Estonia. To select the air barrier material in addition to the air permeability, other material properties, mainly water vapour permeability, should be taken into account. The hygrothermal performance of the timber-frame envelopes is appreciably improved using the vapour permeable sheathing that has

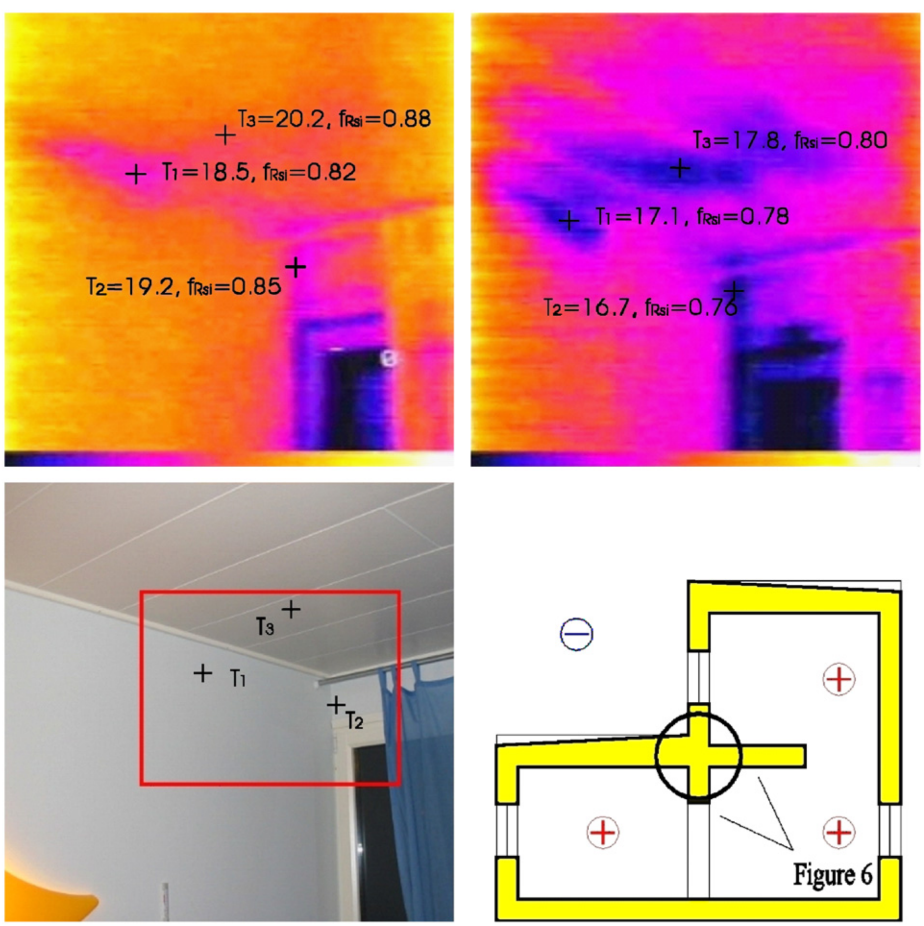

Fig. 6. An example of air leakage on the junction of the ceiling, roof and the external wall on no additional pressure difference (upper left) and under −50 Pa pressure conditions (upper right). Lower Figures show the picture (left) and the section from the junction.

Table 2
Comparison of air tightness of detached houses in different countries

Country, measurement time	Number of houses	Air change rate at 50 Pa, n_{50} (1/h)		Remarks
		Average	Min–max	
Belgium, 1995–98 [26]	51	7.8	1.8–25	
Canada, 1985–95 [27]	222	3.1	0.4–11	New conventional houses
	47	1.2	0.13–2.6	R2000 low-energy houses
Estonia, 1999–2000 [17],	19	9.6	4.9–32	
Estonia, 2003–05 (current study)	31	4.9	0.7–14	Built in 1993–2004
Finland, 1979–81 [28]	16	6.0	2.2–12	Common pre-fabricated timber-frame wall-element houses
	28	3.5	1.0–7.5	Special attention is paid for the air tightness
Finland, 1981–98 [29]	171	5.9	1.6–18	Mostly reclamations cases
Finland, 2002–04 [30]	100	3.9	0.5–8.9	Timber-frame envelope
Norway, 1980 [31]	61	4.7	2.0–8.0	
Norway, 1984 [32]	10	4.0	3.3–5.4	Built in 1980, low-energy houses.
Sweden, 1978 [33]	205	3.7	St. dev. 1.24	Built in 1982–89
Sweden [34]	44	1.02		Timber-frame envelope
United Kingdom, [35]	471	13.1	2–30	
USA, [36]	12,902	29.7	0.5–84	Built in 1850–1993

high thermal resistance. However, the choices of sheathing materials that are vapour permeable and have high thermal resistance and low air permeability, to guarantee adequate air tightness, are limited. In Estonian climatic conditions, a special vapour barrier is almost always necessary for detached houses. In these circumstances, it is preferred to have a vapour barrier that will function also as an air barrier. In fact, it sets much higher requirements for the installation works. If the joints are taped, the service life of the tape should equal that of the building envelopes. According to the field survey, the best results are acquired, where the joints of the air barrier are fixed between two solid material layers.

The natural infiltration rate that was roughly estimated from air tightness measurements with opened fresh air inlets was too low. The natural air change rate in houses with mechanical ventilation is not sufficient without a working ventilation fan. In mechanically ventilated buildings, an air tight envelope is desirable, especially when the buildings are equipped with a heat recovery ventilation system. In the case of the naturally ventilated houses with an air tight envelope, the type and number of air in- and outlets should be carefully selected and designed. The area of the outdoor air inlets depends on the type of dwelling, number of storey, location of the apartment in the building and the required area is somewhere between 2 and 7 $cm^2/(m^2$ floor area) [25].

The air tightness of the building envelope was tested, mainly to guarantee of cleanliness with closed and sealed fireplaces. In common use, substantial leakage through open fireplaces and woodstoves may occur. This may influence the estimation of the natural infiltration rate.

To compare the results with other studies, it is necessary to know how the characteristic values, n_{50} or air leakage per building envelope area, are calculated. While the volume and area are to be calculated according to national regulations, the result may be slightly different. In this study, the internal volume of buildings was calculated from the net area of the room and the net ceiling height. It means that internal walls were not taken into account on the volume calculation. The volume of furniture was not subtracted from the building volume. While the area under a built-in oven or chimney was not included in the total net floor area, these volumes were not taken into account. For the building envelope area, also the concrete slab on the ground was taken into account.

The air tightness of detached houses has been investigated also in earlier studies. Table 2 shows the comparison of current study with some other studies from different countries.

5. Conclusions

The mean air leakage at the pressure difference of 50 Pa in the entire database was 4.2 $m^3/(h\,m^2)$ (the minimum being 0.9 $m^3/(h\,m^2)$ and maximum 17.9 $m^3/(h\,m^2)$) that is somewhat higher than standard value 3 $m^3/(h\,m^2)$. The mean air change rate at the pressure difference of 50 Pa in all the databases was 4.9 1/h (the minimum being 0.7 1/h and maximum 13.6 1/h). According to the results, significant factors affecting the air tightness were first of all the quality of workmanship and supervision as well the number of storeys of the house.

The typical air leakage places in the studied houses were: the junction of the ceiling/floor with the external wall, the junction of the separating walls with the external wall, penetrations of the electrical and plumbing installations through the air barrier systems, penetrations of the chimney and ventilation ducts through the air barrier systems, leakage around and through electrical sockets and switches, and leakage around and through windows and doors.

According to the questionnaires, fluctuating room temperature, cold floors and draught from electric sockets were associated with houses with air leakage $>3\,m^3/(h\,m^2)$ at 50 Pa.

While the building standard sets a limit for the air tightness of the building envelope, the results showed that this requirement was fulfilled only in 41% of cases. Therefore in future, more attention shall be paid for the realization of air tightness of building envelope. Together with rising of air tightness of building envelope more attention should be paid to the performance of ventilation.

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References

[1] Hagentoft CE, Harderup E. Moisture conditions in a north-facing wall with cellulos loose-fill insulation: construction with and without a vapor retarder and air leakage. ASHRAE Transactions 1995;101(1):639–46.
[2] Janssens A, Hens H. Interstitial condensation due to air leakage: a sensitivity analysis. Journal of Thermal Envelope and Building Science 2003;27(1):15–29.
[3] Airaksinen M, Pasanen P, Kurnitski J, Seppänen O. Microbial contamination of indoor due leakages from crawl space. Indoor Air 2004;14(1):55–64.
[4] Mattson J, Carlson OE, Engh IB. Negative influence on IAQ by air movement from mould contaminated constructions into buildings. In: Proceedings of indoor air 2002, vol. 1. Monterey, California, USA, 2002. p. 764–9.
[5] Emmerich SJ, Gorfain JE, Howard-Reed C. Air and pollutant transport from attached garages to residential living spaces—literature review and field tests. The International Journal of Ventilation 2003;2(3):265–76.
[6] Nazaroff WW, Doyle SM. Radon entry into houses having a crawl space. Health Physics 1985;48(3):265–81.
[7] Pessi AM, Suonketo J, Pentti M, Kurkilahti M, Peltola M, Lehtimäki AR. Microbial growth inside insulated external walls as an indoor air biocontamination source. Applied and Environmental Microbiology 2002;68(2):963–7.
[8] Jokisalu J, Kurnitski J. Simulation of energy consumption in typical Finnish detached house. Helsinki University of Technology, HVAC-laboratory, Report B74; 2002.
[9] Emmerich SJ, Persily AK. Energy impacts of infiltration and ventilation in US office buildings using multi-zone airflow simulation. In: Proceedings of ASHRAE IAQ and energy 98 conference. New Orleans, LA, USA, 1998. p. 191–203.
[10] Binamu A. Integrating building design properties "air tightness" and ventilation heat recovery for minimum heating energy consumption in cold climates. Dissertation. Tampere University of Technology, 2002.
[11] C3. Thermal insulation in a building. National building code of Finland, 2002.
[12] NBN D50-001. Ventilatie voorzieningen in woongebouwen. Brussels: Belgian Institute for Standardisation; 1991 (in Dutch).
[13] Marchant EW. Fire safety systems—interaction and integration. Facilities 2000;18(10/11/12):444–55.
[14] Kurnitski J, Eskola J, Palonen J, Seppänen O. Ventilation in 102 Finnish single-family houses. In: Proceedings of the eighth REHVA world congress clima. Lausanne, Switzerland, 2005.
[15] EVS 837-1:2003. Piirdetarindid. Osa 1: Üldnõuded [Enclosing structures. Part 1: General requirements]. Estonian Centre for Standardisation; 2004 (in Estonian).
[16] EPN 11.1. Piirdetarindid. Osa 1: Üldnõuded [Enclosing structures. Part 1: General requirements]. ET-Information Centre; 1995 (in Estonian).
[17] Jõgioja E, Jõgioja M. Air tightness of detached houses. In: Proceedings of the Baltic symposium on indoor air quality and building physics. Tallinn, Estonia, 11–12 August, 2000. A satellite conference of Healthy Buildings 2000. Espoo, Finland, 6–10 August, 2000.
[18] EVS-EN 13829:2001. Thermal performance of buildings—determination of air permeability of buildings—fan pressurization method. Estonian Centre for Standardisation; 2001.
[19] Kronvall J. Testing of houses for air-leakage using a pressure method. ASHRAE Transactions 1978;84(1):72–9.
[20] Dubrul C. Inhabitant behaviour with respect to ventilation—a summary report of IEA Annex VIII. Air Infiltration and Ventilation Centre, Technical note 23, 1988.
[21] Persily AK, Linteris GT. A comparison of measured and predicted infiltration rates. ASHRAE Transactions 1983;89(2B):183–200.
[22] Sherman MH, Grimsrud DT. Infiltration–pressurisation correlation: simplified physical modelling. ASHRAE Transaction 1980;86(2):778–807.
[23] prEN ISO 13789:2005. Thermal performance of buildings—transmission and ventilation heat transfer coefficients—calculation method. European Committee for Standardization, 2005.
[24] Warren PR, Webb BC. The relationship between tracer gas and pressurisation techniques in dwllings. In: Proceedings of the first AIC conference, air infiltration instrumentation and measuring techniques. Windsor, England, 1980.
[25] Blomsterberg. The influence of outdoor air vents and airtightness on natural ventilation—calculations based on measurements. AIVC 17th conference, UK, Air Infiltration and Ventilation Centre, 1996, "optimum ventilation and air flow control in buildings", vol. 1, held 17–20 September 1996, Gothenburg, Sweden. p. 253–62.
[26] Bossaer A, Demeester J, Wouters P, Vandermarke B, Vangroenweghe W. Airtightness performance in new Belgian dwellings. Proceedings of AIVC 19th conference "ventilation technologies in urban areas", 28–30 December, Oslo, Norway, 1998. p. 77–84.
[27] Hamlin T. Airtightness and energy efficiency of new conventional and R-2000 housing in Canada. Ottawa: Canada Centre for Mineral and Energy Technology, Natural Resources Canada; 1997.
[28] Polvinen M, Kauppi A, Saarimaa J, Haalahti P, Laurikainen M. Rakennusten ulkovaipan ilmanpitävyys [Airtightness of the building envelope]. Technical Research Centre of Finland, VTT. Research Reports 215. Helsinki, 1983 (in finnish).
[29] Kauppinen T. Air tightness of buildings in Finland. Proceedings of SPIE Thermosense XXIII, 16–19 April 2001, pp. 4360–36.
[30] Korpi M, Vinha J, Kurnitski J. Air tightness of timber-farame houses with different structural solutions. Proceedings of IX international conference on performance of exterior envelopes of whole buildings, 5–10 December, Session XIB, (CD), Florida, USA, 2004, 6p.
[31] Brunsell JT, Uvslokk S. Boligers lufttetthet: resultater fra lufttetthetsmaalinger av nyere norske boliger [Airtightness of buildings: results from airtightness measurements in new Norwegian houses]. Norges Byggforskningsinstitutt report no. 31, 1980 (in Norwegian).
[32] Granum H, Haugen T. Ventilation and indoor air quality in new Norwegian dwellings. Proceedings of AIC seventh conference

"occupant interaction with ventilation systems", 29 September–02 October, Stratford-upon-Avon, UK, 1986. p. 10.1–10.10.
[33] Kronvall J. Air tightness measurements and measurement methods. Stockholm: Swedish Council for Building Research, D8, 1980.
[34] Nilsson I, Rosell L, Thorstensen E. Luftkvalitet och ventilation i täta småhus—en uppföljning av 44 Hjältevadshus byggda under åren 1982-89. [Air quality and ventilation in airtight houses—follow up of 44 houses during 1982–89]. Borås: SP Swedish National Testing and Research Institute (SP REPORT/RAPPORT), 1993. p. 18.
[35] Stephen RK. Airtightness in UK dwellings: BRE's test results and their significance. Report 359, Building Research Establishment, United Kingdom, 1998.
[36] Sherman MH, Dickerhoff DJ. Airtightness of US dwellings. ASHRAE Transaction 1998;104(2):1359–67.