Full paper no: 7

Air leakage and hygrothermal performance of an internally insulated log house

Üllar Alev, M.Sc [1]
Andres Uus, M.Sc [2,3]
Marko Teder, M.Sc [2]
Martti-Jaan Miljan, M.Sc [2]
Targo Kalamees, Professor [1]

[1] Tallinn University of Technology, Estonia
[2] Estonian University of Life Sciences, Estonia
[3] Hobbiton OÜ, Estonia

KEYWORDS: *air leakage, internal insulation, log house, test-house, corner notch*

SUMMARY:
In this study the air leakage of four different log corners and hygrothermal performance of three different interior insulation materials are studied in a log test house. Field measurements of the air leakages were analysed in a test house built with different types of log junctions: corner post, dovetail notch, Scandinavian saddle notch, and double notch with wind lock. One wall made of logs (average thickness of 270 mm) in a test house was internally insulated with three different materials: cellulose fibre, mineral wool and reed mat. The air leakage rate of the overall house was also measured using the standardized building pressurization technique. Hygrothermal performance of walls was measured with t&RH sensors and heat flow plates.

The mean air leakage rate of the overall house at the pressure difference of 50 Pa was q_{50}=2.8 $m^3/(h·m^2)$ and mean air change rate was n_{50}=5.0 h^{-1}. The air leakage rate lowered slowly over time. The lowest air leakage was through the Scandinavian saddle notch - 6.7 $m^3/(h·m)$.

Simulation models on the hygrothermal performance of the studied test walls were validated based on the measurement results. Temperature, relative humidity and heat flux showed good agreement between the measured and the calculated results.

1. Introduction

Log houses have a long history and they represent a variety of building techniques employed in Estonia and in other Nordic countries. Results of measurements of old log houses have shown that this building type is typical of the highest air leakage (Alev & Kalamees 2013). In a new log house, the quality of the envelope has to be higher than a century ago, because the requirements for comfort, function, and energy-efficiency of today's residents are different.

Uncontrolled air movement through a building envelope leads to problems related to the hygrothermal performance, health, energy consumption, performance of the ventilation systems, thermal comfort, noise and fire resistance. Air leakage through the building envelope depends on the results of the air-pressure differences across the envelope, the distribution of air leakage places and the airtightness of the building envelope.

Many studies have analyzed the possibilities to use the internal thermal insulation for improving the thermal resistance of external walls, including those focused on stone walls (Stopp et al. 2001; Häupl et al. 2004; Toman et al. 2009) and only few have studied the internal insulation of log walls (Ojanen 2007; Alev et al. 2012; Arumägi & Kalamees 2012; Arumägi et al. 2011). Ojanen (2007) studied the internal insulation only numerically and assumed that the log wall was completely airtight, but vertical air channels between the log and the insulation layer were suggested to reduce the moisture level. Arumägi & Kalamees (2012) and Alev et al. (2012) studied old walls with high leakage rate and found that the log wall is not completely airtight and to validate the simulation model the air change through the log wall had to be added. Other differences between mentioned studies include the type and usage of the house, used insulation materials, moisture excess etc. Therefore the measurements of new log wall were needed.

This study had two main objectives:

- to study the air leakages of different corners and the whole building of a new log house;
- to validate the simulation model of three different internal insulation constructions (materials).

2. Methods

2.1 Tested house

The field measurements were carried out in a small test house (one room with a net area of 18 m^2) specially designed and built for current study (FIG 1). The house was made of square logs with an average thickness of 200 mm (except the back wall with half round logs and an average thickness of 270 mm, insulated from the internal side). Every corner had a different type of log junction (FIG 2).

FIG 1. View of the test house from the back (left) and internally insulated wall (right).

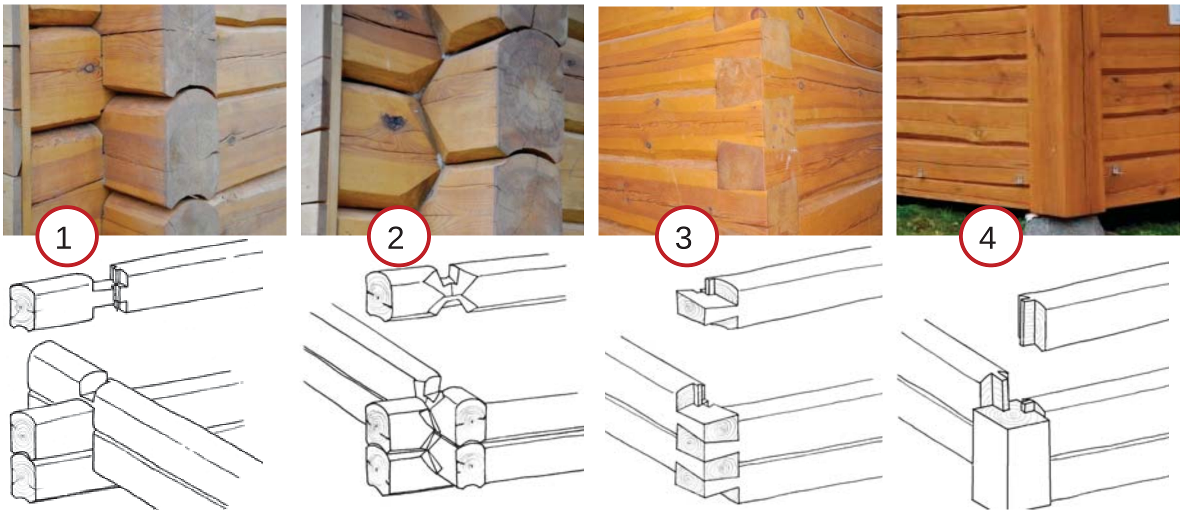

FIG 2. Different corner notches of the log wall: double notch with wind lock (1), Scandinavian saddle notch (also known as Norwegian notch) (2), dovetail notch (3) and corner post (4).

The types of corner notches were selected based on popularity among log house construction companies in Estonia. In the corner notches, a special self-expanding sealing tape for log houses (Classic Log Home Tape LHC 20-20-06) was used.

One wall was insulated internally with three different materials (FIG 1, left): mineral wool, cellulose fibre (both covered with vapour retarder and gypsum board) and reed mat with clay plaster. The internally insulated wall faced west and it was shaded with wooden boards (not present in FIG 1 (left), between the boards and the log wall there was a ventilated air gap of 250 mm) to protect the wall and sensors from direct sunlight. The indoor climate conditions created in the house were based on the results of a study in Estonian wooden apartment buildings (Kalamees, Arumägi, et al. 2011). The room was heated with an air-air heat pump with the heating setpoint of 21°C. The room was also humidified, the target of the automatic humidification system was to hold the moisture excess of 5.5g/m^3 in the winter period and 2.5g/m^3 in the summer period constant.

2.2 Measurement methods

The air tightness of the entire test building was measured with the standardized (EVS-EN13829 2001) fan pressurization method, using ‘‘Minneapolis Blower Door Model 4’’ equipment with an automated performance testing system.

A special timber framed structure with the width of 1414 mm made of 20x80 mm planks was set inside the pre-milled 50mm deep gaps in the log walls at each corner of the test house. The timber frame, ceiling and floor were sealed with a 0.15mm thick PVC-membrane with an opening of ø110mm to measure air leakage of every corner separately using an anemometer. A special self-expanding sealing tape was used to ensure the air tightness between the log wall and timber frame. In the calculations the air leakage of the plain wall was subtracted from the total air leakage rate of the corner based on the wall area and the air leakage rate of the plain wall.

To determine the air tightness of the building envelope, depressurizing and pressurizing tests were conducted. Measurements were made at 10 Pa pressure difference step from 0 to 60 Pa. An exponential trend line was calculated according to the measurement points and an exact 50 Pa reading was taken from the trend line. Measurements of every corner were repeated for 11 times during one year. The pressure difference was generated with “Minneapolis Blower Door Model 4” equipment, the air flow was measured with an anemometer (Ahlborn FVA 915 MA1; measurement range 0.2…20 m/s ±0.5%) and the pressure difference was measured with a pressure sensor (FD8612DPS; measurement range was 1 mbar (100 Pa) ±1%), both were continuously recorded with a data logger (Almemo® 2890-9) over a period of 30 s with a 1 s interval.

The values of the temperature, the RH both inside and outside the wall and the heat flux were measured over a one-year period at one-hour intervals. The following sensors were used: temperature sensors (TMC6-HD; measurement range: -40 °…+100 °C, accuracy: ±0.25 °) with HOBO U12-013 data loggers; temperature and RH sensors (Rotronic HygroClip SC05 ∅5mm×51mm, measurement range: -40 °…+100 °C and 0…100%, accuracy: ±0.3 °C and ±1.5%); and heat flux plates (Hukseflux HFP-01-05, measurement range ±2000 W/m^2, accuracy: ±5%). Measurement results were saved with a Grant Squirrel SQ2020 data logger. Together with airtightness measurements the moisture level in the logs at different heights was measured with Gann Hydromette HT 85 (with puncture probe M40, accuracy ±2%) to observe the drying out process of the logs.

2.3 Simulations

The measurement results were compared with a complex hygrothermal simulation model, WUFI 5.1 Pro. The comparison was made to validate the simulation model for future simulations with different initial and climatic conditions as well as with different dimensions of the building envelope layers.

3. Results

3.1 Air tightness of the corners and the envelope

The airtightness of the entire house was measured for seven times during a one-year period. The average air leakage rate of all measurements of the entire envelope at the pressure difference of 50 Pa was q_{50}=2.8 m^3/(h·m^2) (FIG 3 left) and the mean air change rate was n_{50}=5.0 h^{-1}. The air leakage rate lowered slowly over time until the two last measurements in spring; these measurements show more than 1 m^3/(h·m^2) higher value than before. The air-tightness of the log house is influenced by several factors: volume changes of the logs due to water vapour (de-)sorption processes, the efficiency of insulation and sealing in notches and grooves (joints of logs), accuracy of notches and grooves, tightening of walls caused by the weight of the roof, and the overall building quality. The change of airtightness in time can be explained in several ways. The reduction of air leakages was probably caused by the weight of the roof that tightened the joints between the logs (grooves and notches). By the time of the last two measurements, the weight of the roof was significantly decreased, because the thick layer of snow had melted. Another reason for increased air leakages during spring was the drying process of the logs caused by intensive solar radiation (FIG 3 left). The drying process is more intensive near the ends of the logs and therefore the shrinkage of the logs near the corners is higher and the cracks (grooves) will widen. The wider cracks near the corners increased the air leakage both of the whole house and also in every corner (FIG 3 right).

The air leakages of the corners were measured for 11 times during the study. The average air leakage rate of all measurements in every corner was 10 m^3/(h·m). The air leakage of the corners were (FIG 3 right):

- Scandinavian saddle notch 6.7 m^3/(h·m);
- dovetail notch 6.8 m^3/(h·m);
- corner post 10.4 m^3/(h·m);
- double notch with wind lock 17.3 m^3/(h·m).

When comparing the change of the air leakage rate in time, all the corners except the Scandinavian saddle notch started to improve after the second measurement. In the case of the Scandinavian saddle notch, it can be explained as the combination of drying of the logs (shrinkage of volume), effectiveness of sealing and tightening of the wall due to weight. During winter the snow layer added extra weight to the roof and to the wall, thus the tightening process of the corners was the greatest.

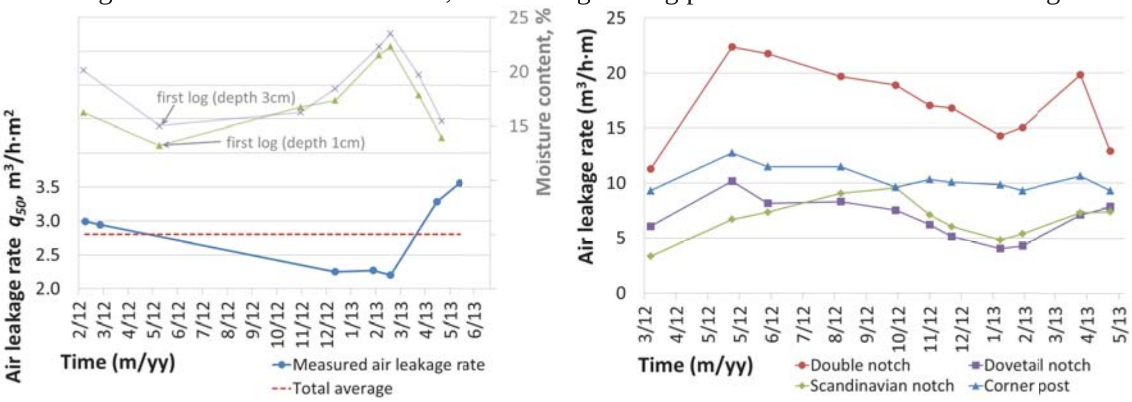

FIG 3. Air leakage rate of the total house (left) and the corners (right).

3.2 Hygrothermal performance and validation of the simulation model

The daily average outdoor microclimate near the test wall varied between -27 °C and +28 °C. The average outdoor temperature during summer (June…August) was +17.9 ^{o}C and during winter (December…February) was -4.5 ^{o}C and the RH was accordingly 72% and 89%.

Modified material properties were used from the WUFI database. Table 1 shows the properties of the materials used in comparison of the simulated measured and results when the best correlation was obtained. Although the wall was made as airtight as possible, the air change through the log wall was necessary to match the calculated results with the measured results. The air change rate of 0.3 h^{-1} was added during the cold period (November to the February). The RH level of kiln dried logs at the time of building was 21.6% at the depth of 3 cm.

Table 1. Main hygrothermal properties of the materials used in the simulation

	Wooden log	Mineral wool	Cellulose fiber	Reed mat	"Intello" membrane	Clay mortar	Gypsum board
Bulk density ρ, kg/m^3	390	60	60	136	425	1568	850
Porosity f, m^3/m^3	0.75	0.95	0.95	0.9	0.001	0.41	0.65
Specific heat capacity c, J/(kg·K)	1600	850	2000	2000	2300	488	850
Thermal conductivity λ, W/(m·K)	0.12	0.04	0.037	0.075	0.17	0.48	0.2
Vapour diffusion resistance factor μ, -	108	1.3	1.5	2.0	37500	20	8.3
Built-in moisture w, kg/m^3	65	4.5	4.5	6.0	0	100	2.0

Two methods may be used to compare the thermal performance of the test walls: to compare temperatures on the inner surface of the log, or to compare the measurement results of the heat flux plate. The simulation model and this experiment were validated in both ways. The figures below show the difference between the measured and the calculated temperatures (FIG 4), RH (FIG 5) and water vapour pressure (FIG 6) between the log wall and the insulation layer for three materials. Thin lines on both figures represent the measured values and thick lines the calculated values. There is a good correlation between the measured and the calculated results in addition to the temperature and the RH, also with the heat flux. Differences in the temperatures reflect the different thermal resistances of the insulation materials. Reed mat has higher thermal conductivity and therefore the temperatures between the insulation layer and the log wall were higher during the winter period.

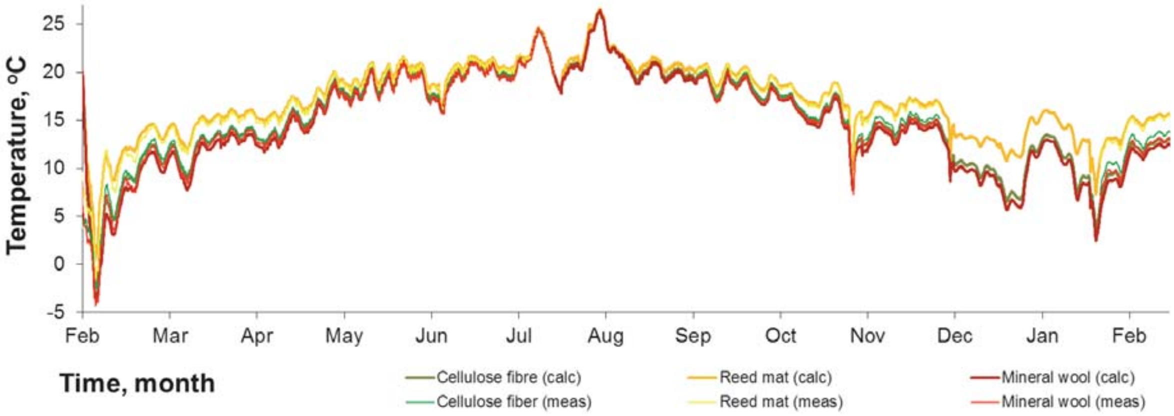

FIG 4. Measured and calculated temperatures on the inner surface of the log wall.

The log wall with an average thickness of 27 cm had a thermal transmittance of U=0.49 W/m^{2}K. After adding internal insulation, the thermal transmittance decreased to U=0.31 W/m^{2}K in the case of cellulose fibre, U=0.28 W/m^{2}K in the case of mineral wool, and U=0.36 W/m^{2}K in the case of reed mat.

The RH level of different materials was different due to different construction methods. Insulation with cellulose fibre was most critical, because it was installed by a wet spray method. While the cellulose was covered with water vapour barrier, the drying out of moisture was also slow (about six months). The reed mat itself was dry, but the added plaster layer added a significant amount of water into the insulation layer, therefore the RH was high during the first month. The drying process was faster than in the cellulose fibre part, because the water vapour resistance of the clay layer is much lower than the resistance of the PE-membrane used for water vapour barrier on the cellulose fibre and on the mineral wool part. The mineral wool part had no additional moisture during installation and therefore the RH level was low at the beginning of the measurements. The RH level increased because of the moisture dried out from the logs. The RH in the reed mat in summer was about 10% lower than in the mineral wool and cellulose fibre because the moisture can dry out to the room side easily. In the mineral wool and cellulose fibre part the moisture mainly dried out to the external side due to air convection through the log wall, which is much more intensive during the cold period (beginning from November).

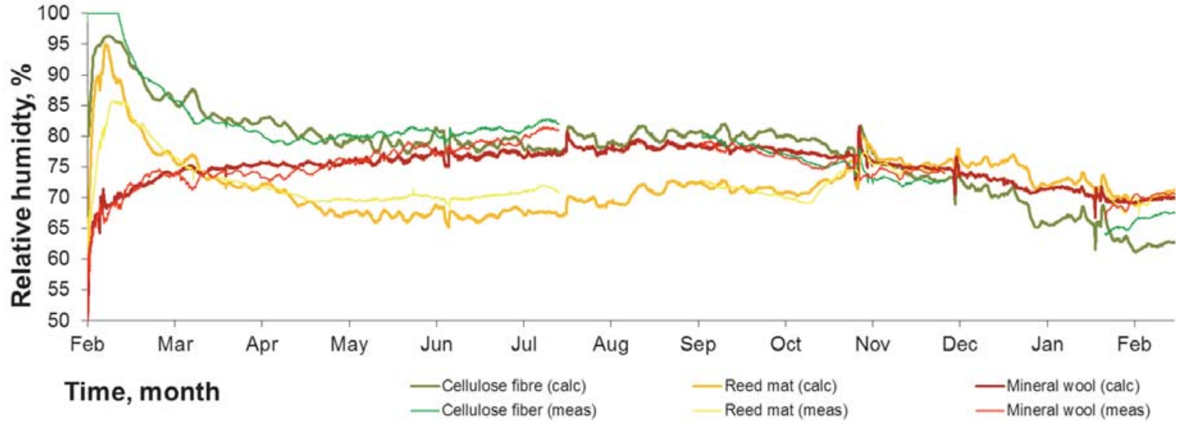

FIG 5. Measured and calculated RH on the inner surface of the log wall.

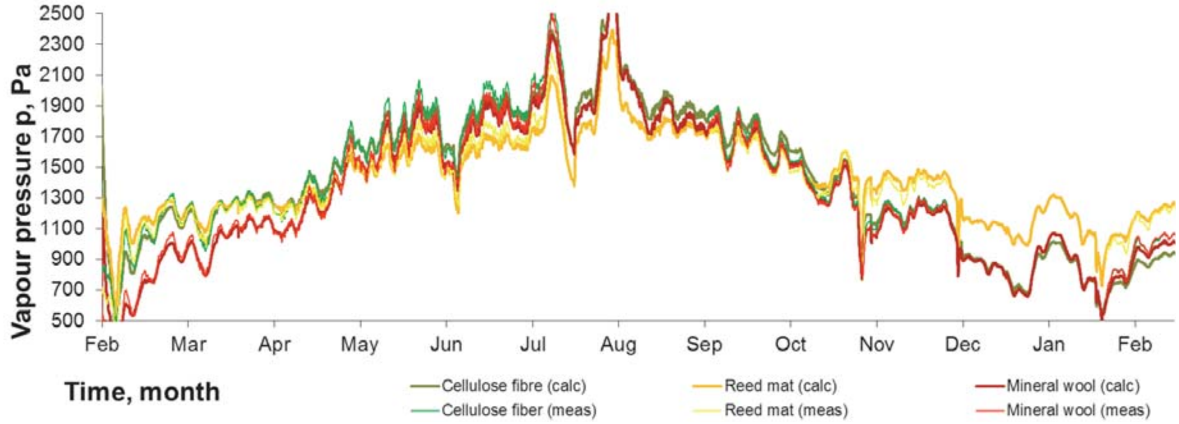

FIG 6. Water vapour pressure on the inner surface of the log wall.

The required moisture excess was guaranteed over the first half year without the use of air humidifier, caused by the drying out of the logs and the absence of ventilation. The vertical temperature gradient was small due to air movement in the room caused by the air-air heat pump.

4. Discussion

Comparison of airtightness measurements of this specially built house (2.8 $m^3/(h \cdot m^2)$) and previous measurements in the log houses in Estonia reveals substantial improvements using the new sealing method and the quality of work: the average airtightness of 12 log dwellings was 9.2 $m^3/(h \cdot m^2)$ (Kalamees 2008); the average of 35 measurements in wooden apartment buildings (made of logs) 10

$m^3/(h \cdot m^2)$ (Kalamees, Arumägi, et al. 2011) and the average airtightness of 24 old rural log houses was 15 $m^3/(h \cdot m^2)$ (Kalamees, Alev, et al. 2011).

When sealing different corners, especially the double notch with the wind lock, the placement and the choice of seal has an important role. A wide seal (15 cm) expanded less than a narrow one (2 cm). Also, the logs should be as dry as possible before erecting the house to prevent the cracks caused by the shrinking of the logs.

In this study the process and influence of the drying out of the logs on the internal insulation layer is visible (FIG 5). On the one hand, it is reasonable to let the logs dry out more easily as in reed mat part. On the other hand, the moisture level in reed mat raised to the same level as other insulation materials during the winter period when the humidifier produces extra moisture to the room to hold the moisture excess of 5.5g/m^3. In the cellulose fibre part the RH stayed above the critical level for mould growth (80%) more than half a year. The mould growth index (calculated according to Hukka & Viitanen (1999)) on the surface of the log behind the cellulose fibre insulation layer had the highest value of 1.3 during April, which means that there could be some growth detected by microscopy. After removal of insulation there was no mould growth detected visually and it was not viewed with a microscope.

5. Conclusions

The average air leakage rate of all measurements of the entire envelope at the pressure difference of 50 Pa was q_{50}=2.8 $m^3/(h \cdot m^2)$. The average air leakage rate of all measurements in every corner was 10 $m^3/(h \cdot m)$. The lowest air leakage was through the Scandinavian saddle notch - 6.7 $m^3/(h \cdot m)$, almost the same was through the dovetail notch - 6.8 $m^3/(h \cdot m)$), the corner post had much higher leakage rate of 10.4 $m^3/(h \cdot m)$ and the double notch with the wind lock was the leakiest - with 17.3 $m^3/(h \cdot m)$.

The internal insulation parts were constructed differently from the hygrothermal point of view. The mineral wool part was constructed as a dry wall, cellulose fibre was installed using a wet method and the reed mat was covered with clay plaster that added also moisture to the reed mat. Cellulose fibre and mineral wool were covered with water vapour barrier, which prevented these wall parts to dry to the room side. The reed mat with clay plaster dried out within less than a month. The RH in the cellulose fibre part was over 80% for over 6 months and the RH level in the mineral wool part had increased to the same level as in the cellulose fibre part after 6 months and both started to dry out to the external side during the winter period. During the warm period the RH was about 10% lower than in other parts, during the cold period the RH level increased at the same rate as in other parts.

The simulation models of three internally insulated log walls were validated using long-term field measurements. The WUFI was selected for the hygrothermal performance simulations. A good correlation between the calculated results and the measured values was achieved after the modification of the material properties and adding a factor as the air change rate in the material layers inside the wall. The thermal transmittance decreased by 27..43% in different internally insulated wall parts as compared to an uninsulated wall. Drying and wetting are determined more accurately if the convective air flow is included in the hygrothermal simulation model. The drying out moisture from fresh, but a kiln-dried log with an average RH level of 21.6% caused significant moisture excess to the room and increased the RH in the internal insulation layer. The validated model will be used in our further studies to focus on the performance of the internally insulated log wall in cold climates.

6. Acknowledgements

The research has been conducted as part of the projects IUT1-15 “Nearly-zero energy solutions and their implementation on deep renovation of buildings” financed by Estonian Research Council.