Case-Study Analysis on Hygrothermal Performance of ETICS on Concrete Wall after Low-Budget Energy Renovation

Simo Ilomets **Targo Kalamees, PhD**

ABSTRACT

Hygrothermal performance of mineral wool and expanded polystyrene external thermal insulation composite system (ETICS/EIFS) was studied in field conditions and by computer simulations with the Delphin program. Temperature and relative humidity were measured in a additionally insulated large panel concrete element wall from September 2011 to January 2013 in the cold climate of Estonia. Measurements of indoor climate, air leakage, and thermal bridges through building fabric were conducted before and after the low-budget energy renovation pilot project of an apartment building.

Results showed that indoor climate and thermal comfort were not improved a lot in all aspects and the same was true for airtightness. Unacceptable thermal bridges remained at external wall/balcony, external wall/foundation wall junction, and also around the windows because they stayed in their original position. Built-in moisture of the whole wall dried out during the first heating season. Better agreement was found between measured and results if the convective moisture flow in addition to diffusion was taken into account in simulations. Average measured thermal transmittance during the winter was U_{wall} *0.17 W/(m*^{2}*·K) in the case of graphite enhanced EPS and 0.19 W/(m*^{2}*·K) with mineral wool. Long-term durability of ETICS in cold climate and under wind driven rain loads need further investigation.*

INTRODUCTION

It is estimated that there are 200 million dwellings and 25 billion m^2 of useful floor space in the EU27, Switzerland, and Norway (Dol and Haffner 2010; Economidou et al. 2011). In Europe, especially in Eastern Europe, a large number of buildings were constructed after the second World War. About 70% of the residential building stock is over 30 years old and about 35% are more than 50 years old (Balaras 2005). A general characteristic of dwellings in Eastern Europe constructed after the second World War and before the energy crisis in the 1970s is that buildings are generally poorly insulated compared to today's requirements for energy performance. Apartment buildings constructed in the late 1970s and 1980s typically have a much higher energy consumption. The energy-renovation measures of old apartment buildings are under discussion internationally (Hagentoft 2010; Silva et al. 2013; Nemry et al. 2010; Dall'O' et al. 2012; Uihlein and Eder 2010) as well as in Estonia (Kalamees et al. 2009).

In Estonia 65% of people live in apartment buildings. Nearly half of the apartment buildings constructed between 1961 and 1990 are composed of large panel prefabricated concrete elements. The condition of concrete façades is mainly satisfactory, except the low frost resistance and corrosion of reinforcement when the carbonation depth has reached close to reinforcement; steel connections of balconies and awnings have turned out to be problematic in some cases (Kalamees et al. 2009; Ilomets et al. 2011). In combination with the high indoor humidity load and thermal bridges, mould can grow at internal surfaces building envelope. Thermal transmittance of original external walls is 0.7–1.0 W/(m^2·K), being 3–5 times higher than considered reasonable today. Therefore, energy-renovation and better understanding of renovation solutions of apartment building is needed.

***Simo Ilomets** is a PhD student and chair of Building Physics & Energy Efficiency, Tallinn University of Technology, Tallinn, Estonia. **Targo Kalamees** is a professor and chair of Building Physics & Energy Efficiency, Tallinn University of Technology.*

The aim of the study was to explore hygrothermal performance of the existing concrete wall insulated with ETICS and to get data for calibrating a hygrothermal computer model for ETICS to permit applying the model to other climatic conditions and other structural dimensions. Other outcomes from energy-renovation pilot project are discussed briefly.

METHODS

An energy-renovation pilot project "Healthy and Cost-Saving Home" was started in spring 2010 in co-operation with two financing institutions together with a ministry, an energy company, a local municipality, and a university. The global purpose was to carry out an example renovation of a typical apartment building to demonstrate energy saving and improve indoor climate as well to motivate people to renovate their buildings. The renovation works lasted from summer to the end of 2011.

The case-study building is a five-story block of flats (Figure 1) constructed during 1966 with prefabricated large panel concrete elements. That type of construction was typical in Estonia during the period between 1961–90. Approximately half of apartment buildings in Estonia are composed of prefabricated concrete large panel elements.

Renovation Solution

Renovation solution was selected based on the energy and economical calculations:

- Improvement of building envelope:
    - External walls: +15 cm graphite enhanced expanded polystyrene (EPS) in the external thermal insulation composite system (ETICS): $U_{\text{external walls}} = 0.17$ W/(m^2·K);
    - Basement walls: +10 cm EPS covered with drained and ventilated cladding: $U_{\text{basementwall}} = 0.36$ W/(m^2·K);
    - Roof: +30 cm EPS above the roof $U_{\text{roof}} = 0.11$ W/(m^2·K);
    - Replacing of 33% of the old windows: $U_{\text{old window}} = 1.8$ W/(m^2·K), $U_{\text{new window}} = 1.0$ W/(m^2·K); because only 1/3 of the windows were replaced with new; all windows were left at their original position: inboard of the exterior concrete core of the external wall;
- Ventilation system: new exhaust ventilation with heat recovery (exhaust air [water to water] heat pump);
- Heating system: new hydronic radiator heating with thermostats.

Measurements

Measurements on the case-study building concentrated on the indoor climate, energy performance, and hygrothermal performance of the building envelope. During the study the following measurements were taken:

- The values of indoor temperature (t) and relative humidity (RH) conditions were measured with small data loggers at 1 h intervals over a 2 year period;
- Surface temperature of thermal bridges were measured by using infrared image camera "FLIR ThermaCam E320" (EN 13187) with minimum indoor and outdoor temperature difference at least 20 K. Tabulated surface emissivities from FLIR ThermaCam E320 user's manual was used;
- The air leakages of the building fabric of the apartment were measured with the standardized fan pressurization method (EN 13829), using "Minneapolis Blower Door Model 4" equipment; hygrothermal performance of east facing external wall (see Figure 1 and Figure 2), additionally insulated with ETICS, was studied using temperature and relative humidity sensors and heat flux plates.

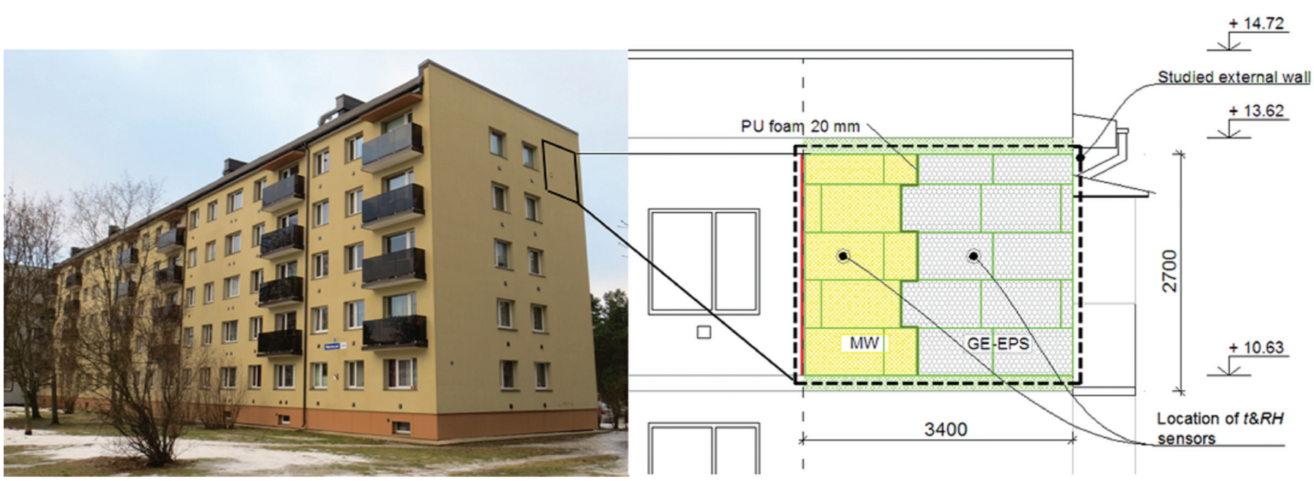


Figure 1 *View to the external wall with measurement areas of ETICS.*

Hygrothermal performance of face sealed, non-drainable external thermal insulation composite system (ETICS) (also called exterior insulation and finish systems, EIFS) with two different insulation materials was compared in two test-walls: mineral wool (MW) and graphite enhanced expanded polystyrene (EPS), see Figure 1 and Figure 2. All the other components (adhesive, base coat, reinforcement [glass fiber mesh], mineral finishing coat, paint coating) of two test-walls were the same. Test-walls were located exterior to the same room so that both test-walls experienced the same climatic conditions. Two walls were separated from each other with polyurethane (PU) foam insulation to minimize wall-direction moisture movement. The location of the test-walls at the upper corner of the wall was selected based on it having the highest driving rain intensity.

Simulations

The temperature and humidity measurement results from test-walls were compared with a hygrothermal simulation model Delphin 5.7.4 (Nicolai 2008):

- to validate the simulation model for future simulations with different initial and climatic conditions as well as with different dimensions of the building envelope;
- to understand better the performance of the external thermal insulation composite system.

Modified material properties were used from the Delphin's database. Table 1 shows the properties of materials used as compared to measured and simulated results when the best correlation was obtained. The dependency of hygrother-

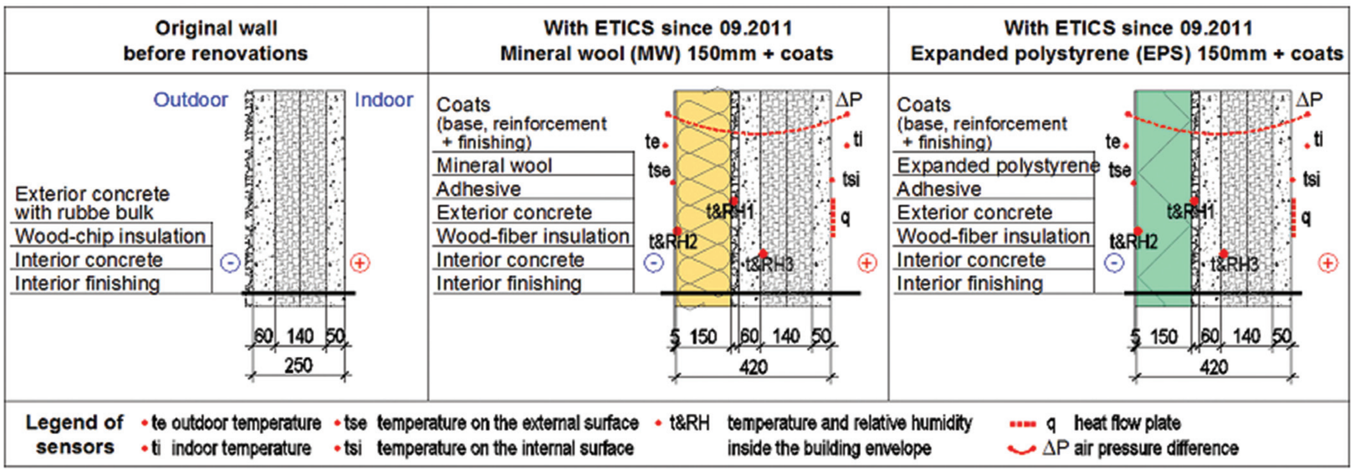


Figure 2 *Test-wall schematics and measurement points (red dots).*

Table 1. Main Hygrothermal Properties of Materials Used in the Simulation

	Concrete	Wood-Cement Chip Board	Adhesive Mortar	EPS	MW	Exterior Coating
Bulk density ρ, kg/m^3	2320	500	700	35	75	1270
Porosity *f*, m^3/m^3	0.14	0.93	0.73	0.94	0.92	0.50
Specific heat capacity *c*, J/(kg·K)	850	1470	945	1500	840	960
Thermal conductivity* λ, W/(m·K)	1.5	0.12	0.19	0.035	0.038	1.0
Water vapour diffusion resistance factor* μ, —	19	3.8	15	15	2	10
Liquid water conductivity* *k*, kg/(m·s·Pa)	$44 \cdot 10^{-12}$	$16 \cdot 10^{-9}$	$3.2 \cdot 10^{-9}$	0	0	$0.27 \cdot 10^{-6}$
Air permeability Kg, s	$1 \cdot 10^{-6}$	$7 \cdot 10^{-3}$	$1 \cdot 10^{-5}$	$1 \cdot 10^{-6}$	$1 \cdot 10^{-2}$	$1 \cdot 10^{-6}$
Built-in moisture *w*, kg/m^3 / rh, %	48 / 65	27 / 60	200 / 100	0.6 / 60	3.1 / 60	300

*Dry material

mal properties on the environmental conditions was taken into account: water vapour permeability, liquid water conductivity, thermal conductivity dependent on water content of a material (example of concrete is shown in Figure 3 [left]). Cross-section of simulated wall is presented in Figure 3 (right).

Thermal bridges before and after the renovation were evaluated by using a thermal camera and two-dimensional heat-transfer simulation software THERM 6.3 according to standard EN ISO 10211. Thermal bridges were assessed using the temperature factor (EVS-EN ISO 13788). The limit value for temperature factor in a dwelling with high or unknown humidity loads is considered to be ≥0.8 (Kalamees 2006).

RESULTS

Technical Condition of External Walls

External walls of the analysed building were composed of large-panel prefabricated concrete elements. Fourteen centimeters of wood-cement chip board (thermal conductivity λ ~0.12 W/[m·K]) was used for insulation between two layers of concrete and external surface is covered with rubble bulk. The main problems related to external walls are thermal bridges, corrosion of reinforcement, frost resistance, and large thermal transmittance. The layer between insulation and external concrete core is not ventilated but slightly drained (small tubes installed into the intersection of movement joints). The external core can become wet due to vapour condensation and wind-driven rain. This means that frost damages of concrete and corrosion of reinforcement can occur. Structures and technical condition of a building are shown in Figure 4–6.

Indoor Climate Conditions

Temperature and relative humidity were measured in four apartments before and after the renovation. There was significant difference ($P < 0.001$) in temperature measurement results, see Figure 7 left. A new adjusted heating system has even temperatures during a whole heating season after the renovation while there was a clear overheating before. There was no significant ($P = 0.3$) difference in RH before and after the renovation. Moisture excess (the difference between vapour content of the indoor and outdoor air), $\Delta\nu$, g/m^3 was calculated from indoor and outdoor climate, Figure 7 (right). Somewhat surprisingly, moisture excess was not lower but even higher (significant difference [$P < 0.001$]) after the renovation, especially during very cold days with outdoor air temperature lower than –10°C. Still, the level of moisture excess being up to ~3 g/m^3 on average and up to ~4 g/m^3 at 90% level are lower than in these types of buildings in general.

Thermal Bridges

Thermographic measurements before the renovation (see Figure 8) show very low surface temperatures (temperature factors f_{Rsi} ~0.6–0.7) that cannot be accepted in the cold climate of Estonia. In addition to lower average value of the temperature factor, the range of measurement results is wider before the renovation. After renovation and installation of additional thermal insulation, all thermal bridges were decreased. Thermal bridges that ended up being lower than the limit value of 0.8 after the renovation were at the external wall/window, external wall/balcony, and external wall/foundation wall junction.

Because before the renovation already 2/3 of windows were replaced, it was decided to change only remaining 1/3 windows. Therefore all windows were left at their original position (see Figure 9 left). That solution is comfortable from the point of view of inhabitant living conditions during the renovation (less work inside the apartment), but it is unreasonable in terms of energy efficiency, hygrothermal performance, and esthetics since serious thermal bridges remain at the junction of window/external wall.

If windows remain at their original position, linear thermal transmittance of external wall/window increases, see Figure 9. For that reason, this junction remains a domi-

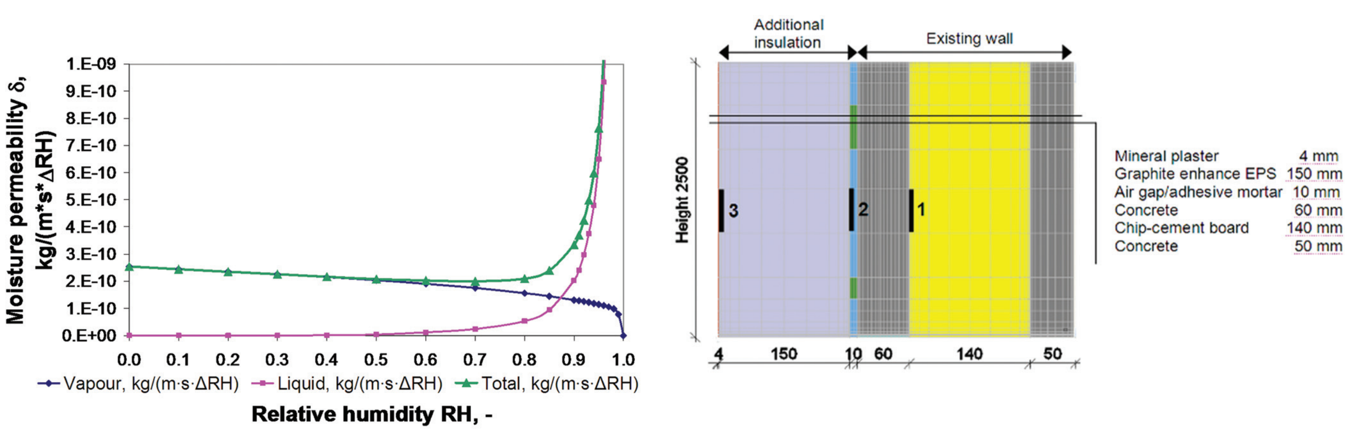


Figure 3 *Moisture permeability of concrete as liquid and vapour at different RHs (left). Example of wall section in simulation tool Delphin with measurement points of temperature and RH 1, 2, 3 (right).*

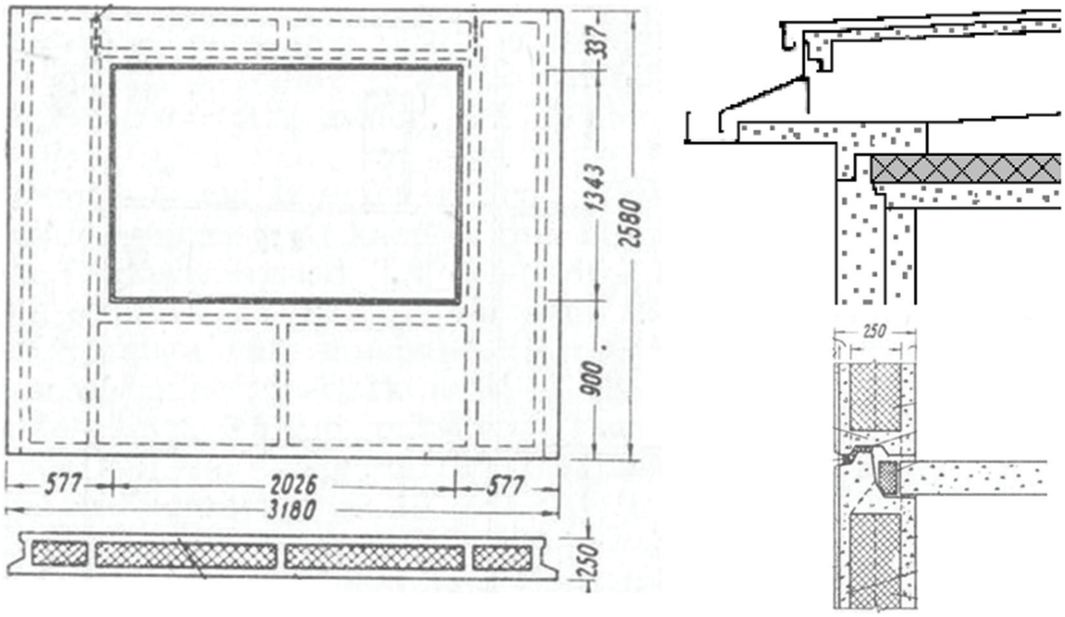


Figure 4 *Original design drawing of a large panel prefabricated concrete element (left). External wall/roof junction (right top) and external wall/inserted ceiling (right bottom).*

Figure 5 *Reinforcement steel between layers of concrete has started to corrode (left and middle). In principle, this steel should be cast into expanded clay concrete, but in reality it is often not so. Cross-section of a concrete wall element (right).*

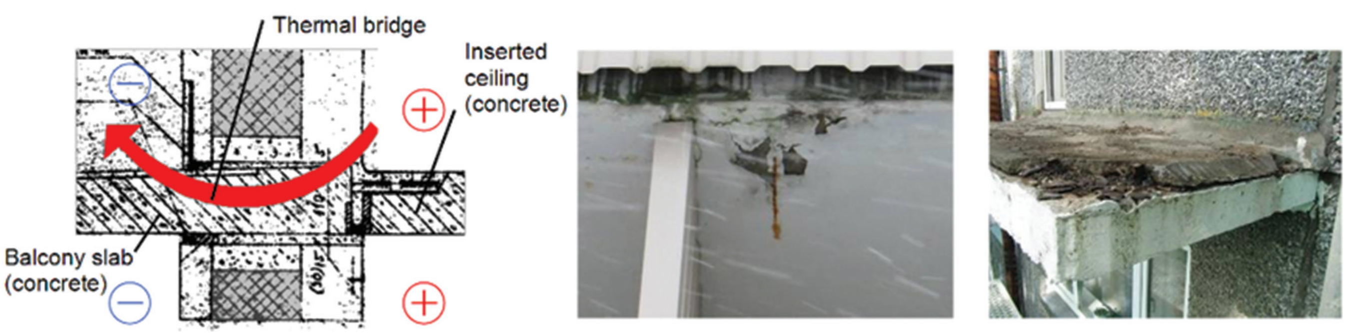


Figure 6 *Original drawing of an external wall/console balcony junction with a thermal bridge (left) and a picture of a degrading balcony (middle and right).*

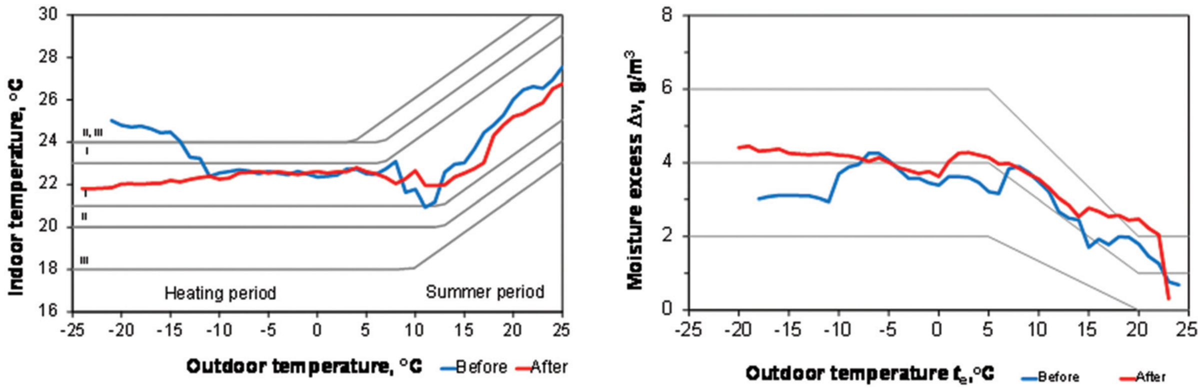


Figure 7 *Measurement results of indoor air temperature (left) and moisture excess (right) depending on the outdoor air's temperature before and after the renovation.*

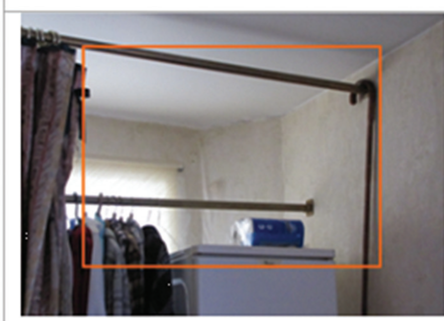
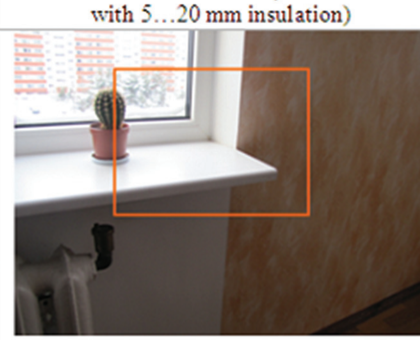
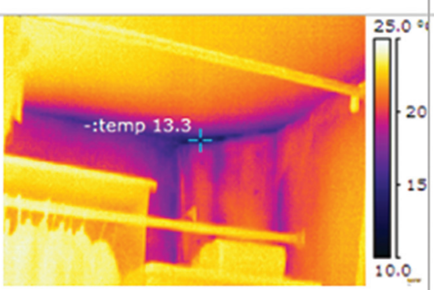
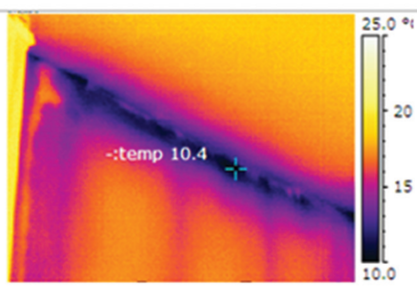
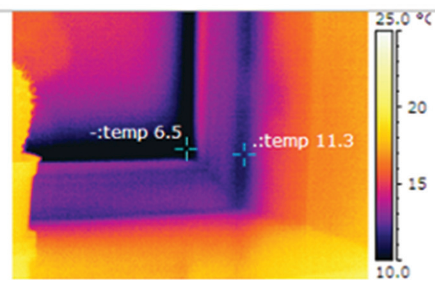
Corner of external walls	External walls/ inserted ceiling	External walls/ windows (jamb insulated with 5…20 mm insulation)
		
		
Before $\overline{f_{Rsi}}$ 0.77; σ 0.09	Before $\overline{f_{Rsi}}$ 0.66; σ 0.12)	Before $\overline{f_{Rsi}}$ 0.74; σ 0.08
After $\overline{f_{Rsi}}$ 0.93; σ 0.03	After $\overline{f_{Rsi}}$ 0.87; σ 0.08)	After $\overline{f_{Rsi}}$ 0.78; σ 0.09

Figure 8 *Measured range of temperature factor* f_{Rsi}, *of thermal bridges with average and standard deviation* σ . *Pictures were taken before the renovation.*

nant thermal bridge in terms of heat loss. Results are very sensitive about the thickness of insulation on a window's jamb (cheek) (window return).

It is not possible to install a sufficient layer of insulation (>30 mm) to the window jambs because of the shape of the concrete element that windows are attached to, see Figure 10. To avoid serious thermal bridges around the windows, all the windows should be placed to the external side of the existing concrete element that moves them more in-line with the additional exterior insulation.

Hygrothermal Performance of External Walls

Temperature and RH were measured in both test-walls: MW and EPS external thermal insulation composite systems

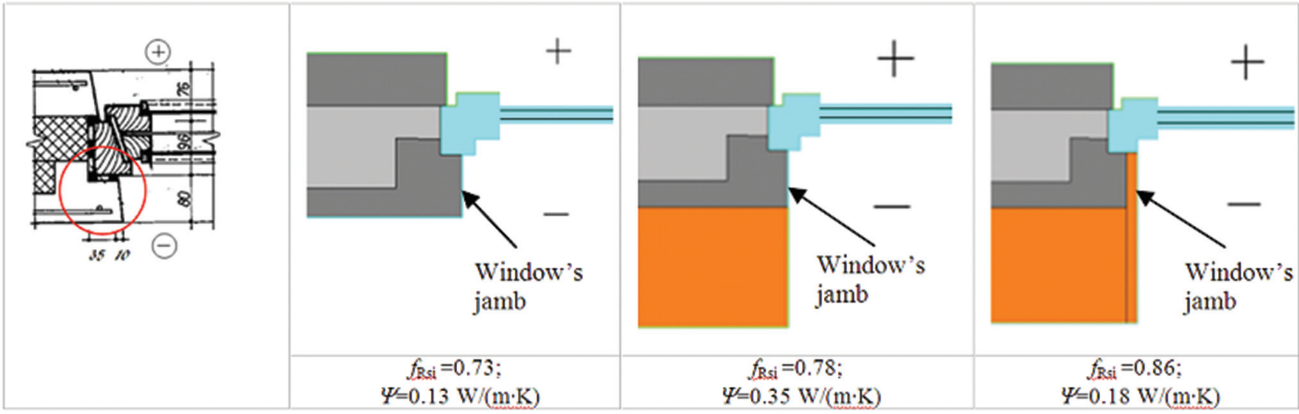


Figure 9 *Calculation results of temperature factor* f_{Rsi} *and linear thermal transmittance* ψ *of the external wall/window junction. Inside area of original drawing (left) the red circle shows the proportion of the jamb of a window covered.*

Figure 10 *Picture of an old window (left) and of new windows placed at their original position. Most of the jamb is covered and only a thin layer of insulation (5…20 mm) can be attached to the jamb.*

(ETICS). Measurements lasted for one and a half heating periods from September 2011 until December 2012. Hygrothermal performance of both walls was also simulated by Delphin 5.7.4.

In general, agreement of temperature, vapour pressure, and RH between the measurements and calculations was good, except RH between mineral wool insulation and plaster (measuring point 3, see Figure 14) where the measured value was higher. Results presented in Figure 12–Figure 14 of the cold period fit also with steady-state distributions of temperature, vapour pressure, and RH. After first calculations, there was also a mismatch about the drying out period. According to the measurements, moisture in the wall (existing moisture in the external core and additional moisture from adhesive mortar) dried out during within 3–4 months, mainly by diffusion and with minor convection. We ended up with acceptable agreement after adding small air gaps between measurement points 1 and 2 with air pressure difference at outdoor climate conditions in cross-section 2, see Figure 3 right. The effect of moisture movement without convection can be seen in Figure 11. If in fact moisture in measuring points 1 and 2 dried out during half of heating season it was much slower by diffusion only according to calculations. There is also some difference in the beginning of the second winter.

Calculated and measured temperatures of both walls match quite well. In the case of MW, calculated temperatures at measurement point 1 and 2 are up to 1°C lower than measured (Figure 12) and up to 1°C higher than measured in the case of EPS (Figure 15). Measured temperatures of two test-walls are similar, maximum 0.5°C higher in the case of EPS.

Also, vapour content/vapour pressures were calculated from the measured temperature and RH in both test-walls and calculated with software. Results for MW are shown in Figure 13 and for EPS Figure 16, respectively. Vapour pressure starts to increase right after the beginning of the heating season in the second half of October 2011 but then starts to decrease. Measurement point nr 2 is not graphically presented. It behaves as point nr 1 but its level is somewhat lower.

Results of measured and calculated RH are presented in Figure 14 for MW and in Figure 17 for EPS. As it

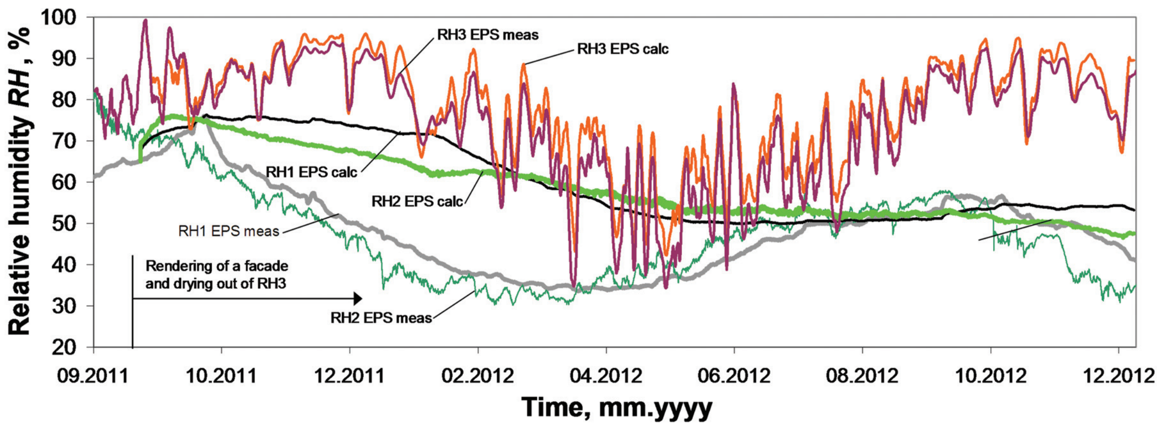


Figure 11 *Comparison of measured (meas) RH and calculated (calc) RH moisture movement only by diffusion of ETICS with graphite enhanced EPS.*

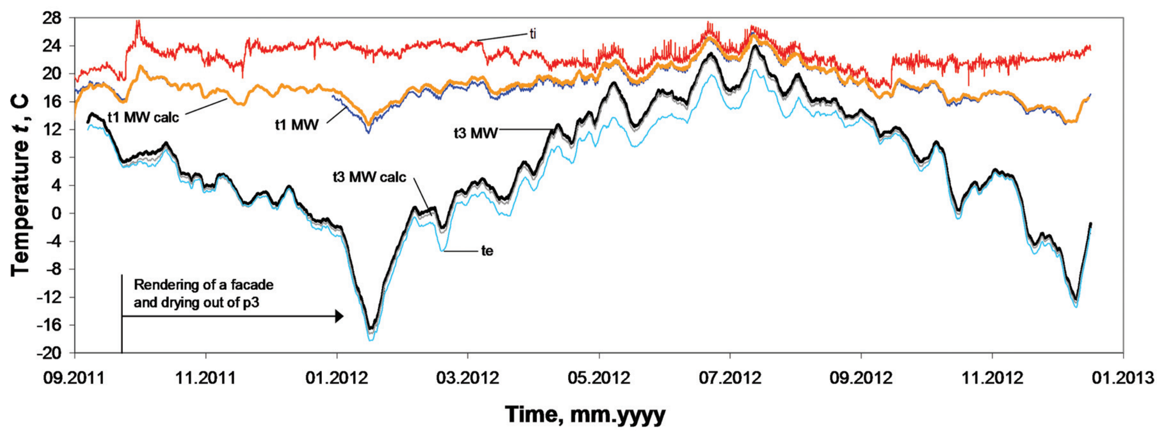


Figure 12 *Measured and calculated temperature (t) in the wall additionally insulated with MW. Location of measurement points see in Figure 2.*

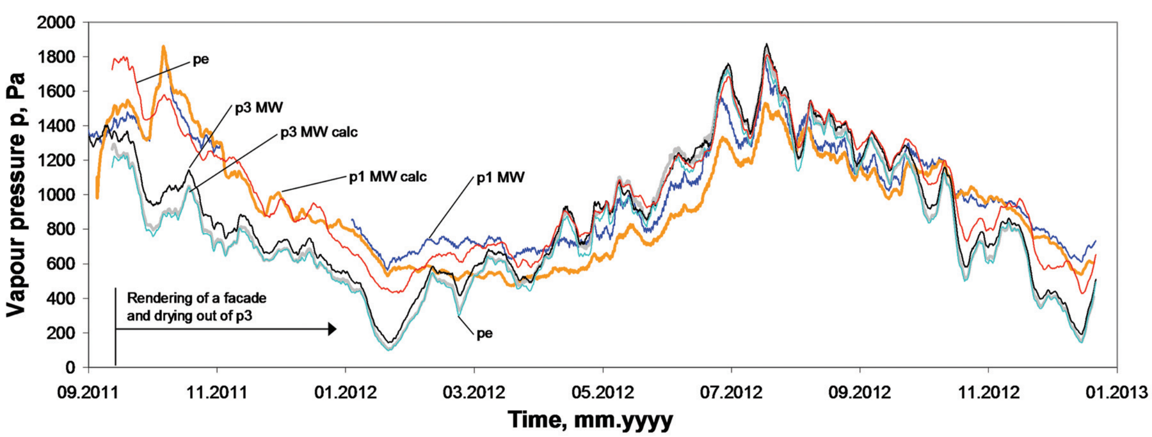


Figure 13 *Measured and calculated vapour pressure (p) in the wall additionally insulated with MW.*

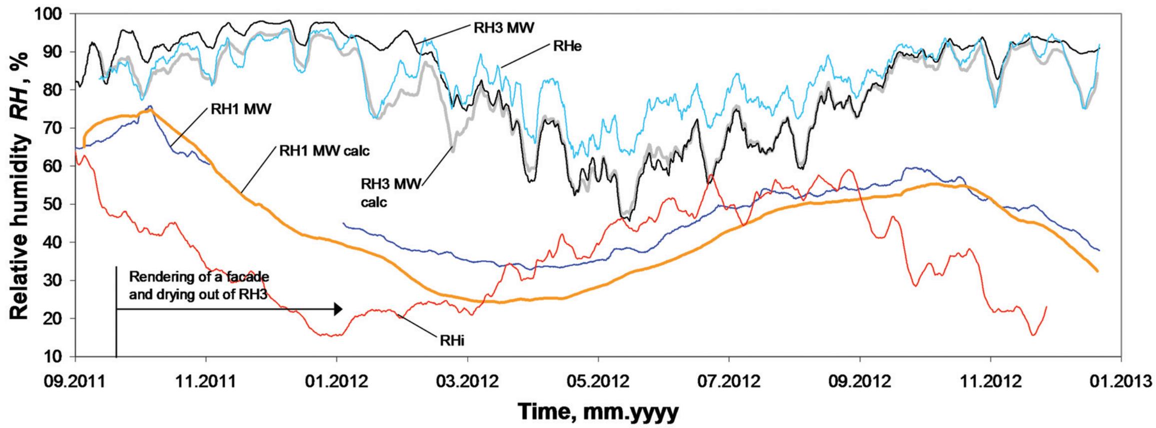


Figure 14 *Measured and calculated RH in the wall additionally insulated with MW.*

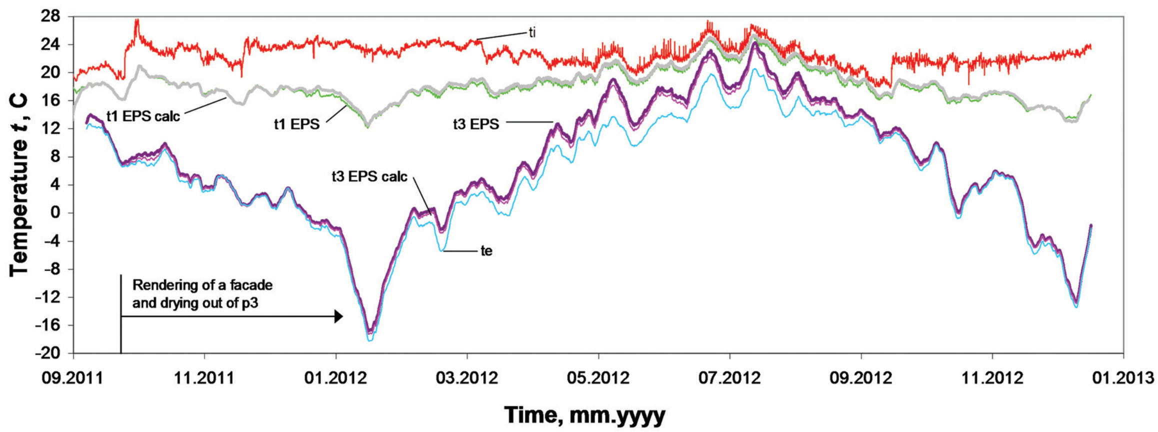


Figure 15 *Measured and calculated temperature in the wall additionally insulated with expanded polystyrene (EPS). Location of measurement points see in Figure 2.*

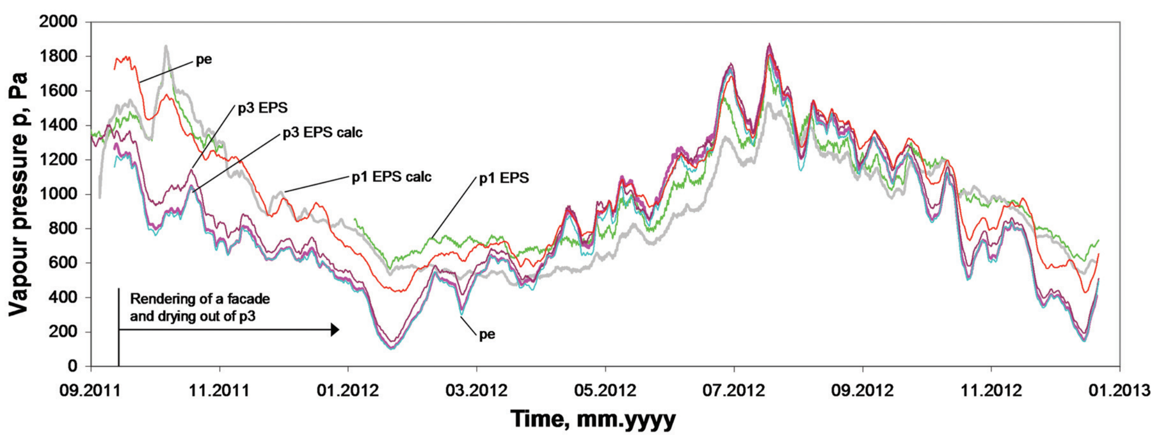


Figure 16 *Measured and calculated vapour pressure in the wall additionally insulated with EPS.*

appears, measured RH at point 3 with MW is somewhat higher than calculated during winter period. In spring measured RH at point 1 is somewhat higher than calculated with both insulation materials. Correlation in summer period is very good, especially in the case of MW. To the contrary, agreement with EPS is better at winter time. Results of measuring point 2 follow the results of point 1 but at 10%–15% lower level. That is a result of higher vapour pressure at point 1 compared to point 2 at almost same temperatures.

Results of thermal transmittance of walls are presented in Figure 18. It can be seen that the calculated thermal transmittance of MW is substantially higher than the rest of three lines. Fluctuation of measurement results appears probably because solar radiation affects temperature of the external surface of the wall. Average thermal transmittances of winter months are 0.17 W/(m^2·K) for EPS and 0.19 W/(m^2·K) for MW.

One of the important research questions was the drying out period of the external core of the original external wall. Analysis of time for drying out period at different initial moisture conditions (from 80% to 100% rh) is shown in Figure 19.

DISCUSSION

Indoor Climate and Thermal Comfort

Indoor climate measurements before and after the retrofit showed small improvement at air temperatures, where no overheating appears at very cold period because of better adjustment of a new heating system.

Natural passive stack ventilation was changed into mechanical exhaust ventilation with exhaust air heat pump. Recovered heat was used for domestic hot water and heating. The air change did not improve after the renovations. It can be seen from moisture excess (Figure 7 right). There are several reasons that are more or less related to each other. First, the

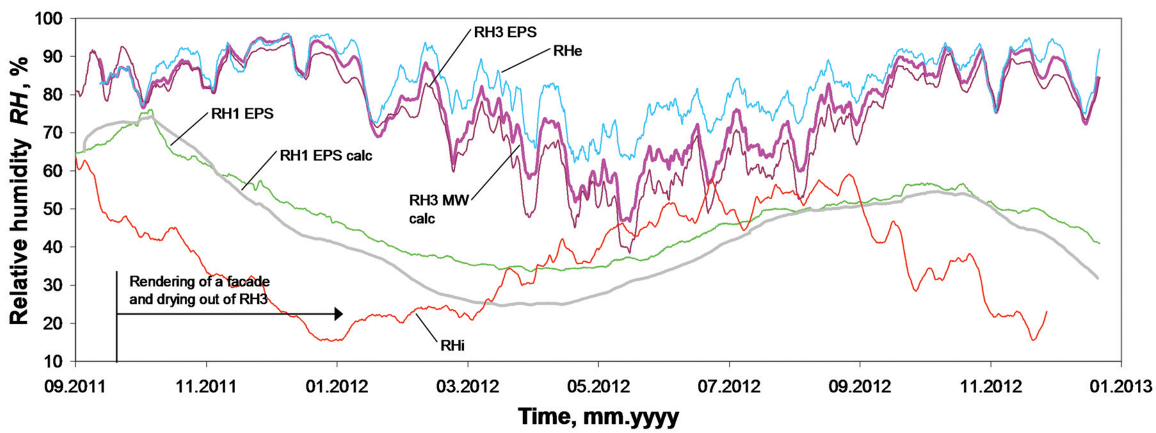


Figure 17 *Measured and calculated RH in the wall additionally insulated with EPS.*

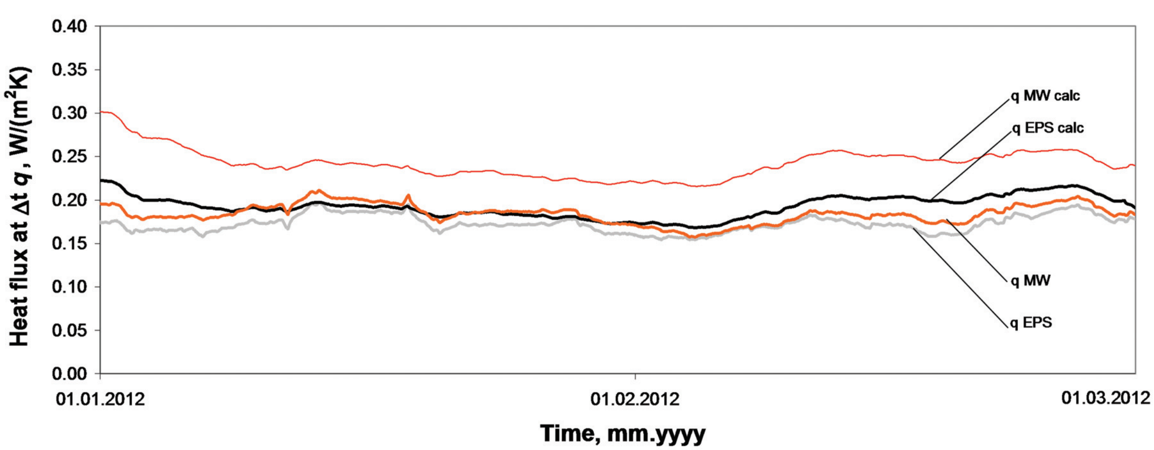


Figure 18 *Measured and calculated thermal transmittances in the wall additionally insulated with EPS and MW. Lines represent weekly average values.*

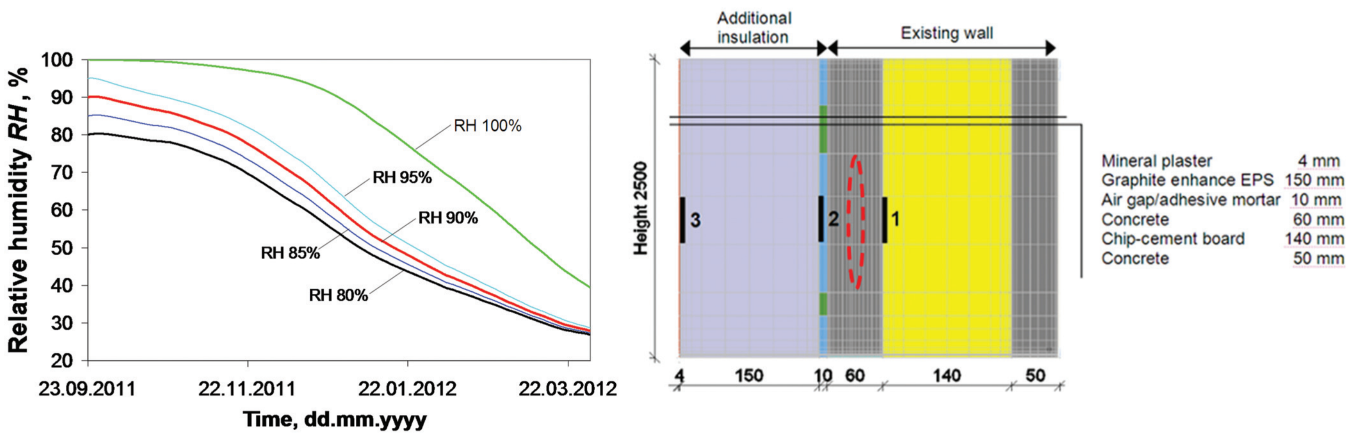


Figure 19 *Moisture drying out time from the external layer of concrete between measuring points 1 and 2 (right) with different initial moisture.*

exhaust fan was set to minimum speed soon after the installation due to energy saving, lower sound level, and better thermal comfort. Also, building fabric became more airtight with new windows and additional insulation that decreased infiltration. The indoor moisture excess 2–3 g/m^3 after the renovation indicates average indoor humidity load level. This means that moisture production/living density had been relatively low.

There was a problem with low floor temperatures on the first floor. The floor was not insulated from the bottom side (cellar's ceiling) because of lack of finance, low height of cellar, and impracticability of workmanship (pipes, lighting, cables, etc. are attached to the cellar's ceiling).

Thermal Bridges

During typical low-budget energy renovation, only old wooden windows are replaced and previously replaced windows remain in the same location. Since the thickness of additional insulation into walls is typically 150–200mm, windows become located 200–270 mm inside the surface of the façade instead of 50–70mm originally. This is a problem because of esthetics and architecture, reduced day lighting, energy efficiency, and mainly thermal bridges around the windows. Negative impact is greater in the case of small and narrow windows. Generally, some insulation is recommended to be placed at window's jamb, but in practice this is complicated and often only 5–20mm is achievable. If the temperature factor f_{Rsi} does not change much, then the linear thermal transmittance Ψ is very sensitive to the jamb's insulation. A remarkable impact of a window's position in the wall and sensitivity on the jamb's insulation has been also found by Hens and Carmeliet (2002). Heat loss through thermal bridges around the windows compared to the rest of a wall is often at a similar scale. In the future, moving of all the windows towards outside is advisable. Also, most of the windows installed about 10 years ago can be replaced again since selective covering was not yet common then and remarkable development of windows has taken place during last years.

Another thermal bridge that remained after the renovation is the external wall/balcony junction. It could be eliminated by insulating a balcony slab from the bottom and top. Technical condition of concrete balconies and awning is sometimes problematic and steel elements, including reinforcement mesh, is sometimes corroded. Since after additional insulation the original 1 m width of a balcony becomes only about 0.8 m, removal of all existing balconies should be considered. New, durable, and wider balconies containing minor thermal bridges would be a sustainable investment.

Hygrothermal Performance of ETICS on a Concrete Element

One of the main goal of this study was to analyse hygrothermal performance of an external wall insulated additionally with mineral wool and expanded polystyrene ETICS. Initial simulation results considering only diffusion showed remarkable mismatch during the first heating season. Although the adhesive mortar/air gap was sealed with PU foam at the basement wall and roof, there was probably some air leakage. Air leakage between the insulation and original wall (measurement point 2) is possible because of rubble bulk covered with particles of different sizes. This in contact with adhesive mortar did not assure totally airtight connection. The air pressure difference created by stack effect enabled some air movement along the wall. Calculations show that a narrow 0.5–1 mm opening below and above the wall is able to transport more moisture than by diffusion. Cracks with such a small width could originate from shrinkage of monolitization concrete connecting pre-fabricated elements or those could be in the elements produced from three layers. Considerable impact of air gaps in the ETICS has been also found by Olson and Taylor (2009) and Sedlbauer and Krus

(2002). In Sedlbauer and Krus (2002), a drying out time of up to 8 years is stated.

The impact of air convection between the additional thermal insulation and original wall is small enough not to appear in the results of thermal transmittance of the wall in practice, see Figure 18. Small impact of air convection to thermal transmittance is also found by Hens and Carmeliet (2002) where 2 mm air gap increased thermal transmittance 12% at ETICS on masonry. Higher calculated thermal transmittance might be caused by air leakage through MW insulation. Slightly higher thermal transmittance in case of MW can be explained with lower thermal conductivity of EPS, having declared value λ_D = 0.032 W/(m·K) compared to λ_D = 0.038 W/(m·K) in the case of MW. The addition of 150 mm of additional EPS/MW insulation contributes more than 2/3 to the total thermal resistance of the wall.

Measurements and calculations showed that moisture in the analysed wall dried out in half of the heating season (see Figure 11 and Figure 19), approximately 3–4 months. If dried only by diffusion, it would have taken about a year for most of the moisture and the rest of it would have dried out during the second year. Slow drying out by diffusion from ETICS on masonry is also declared by Hens and Carmeliet (2002). In the analyzed case with convection totally wet, an external layer would have dried out from most of the moisture also within 3–4 months but in that case, large moisture flux through the wall and possible condensation behind the plaster would be a threat. In that case there would probably be some drying out toward indoors as found in work made by Hens and Carmeliet (2002).

Different aspects of hygrothermal performance of ETICS have been studied for decades. There should be separate viewpoint between ETICS on concrete/masonry and wooden structures. Although it has been found to be a functioning solution in principle (Karagiozis and Kumaran 1997; Holm and Künzel 1999; Kvande 2008; Künzel, H.M. and Zirkelbach, D. 2008) it is very sensitive to driving-rain-caused water leakage from cracks in finishing layer (Bomberg et al. 1997; Krus et al. 2008). Already, 1% of driving rain leakage can be crucial (Künzel 1998). Performance of ETICS has also been studied by Balocco at al. (2008). Solid computational analyses are done by Vares et al. (2012) and Desjarlais (2001). Literature review is conducted by Cheple and Huelman (2000).

According to Zwayer (1995), performance of ETICS walls depends on the design and materials choice, connections between plaster and other materials in joints, workmanship, technology, and quality. In the cold climate of Finland, Pakkala (2011) has found poor frost resistance of ETICS to be a problem and testing methods and criteria according to ETAG 004 worked out in central Europe might not be proper.

Tested walls had also minor driving rain loads since it was sheltered by a neighboring higher building and because of other factors of the surrounding environment. Performance of ETICS walls under high driving rain loads and in the case of higher buildings must be handled as another field of research that was not the aim of this paper.

Also, durability and factors impacting it in addition to climate loads (content and type of plaster, vapour permeability, water uptake coefficient, adhesion, cracking, frost resistance, etc.) is a field of the future research. During maintenance of ETICS, one should also consider a possible layer of painting that might be added later.

General Success of Current Energy-Renovation Pilot Project

The main progress of the current energy renovation pilot project was its better design and workmanship quality. It must be noticed that since it was a pilot project, workmanship under strict supervision was probably somewhat better than usual. From now on, similar renovations can be started with existing know-how about success and problems. In addition to lower heating bills, renovation should lead also to better durability, longer service life of structures, and better indoor climate and aesthetics. These all have also a positive impact on the value of real estate. One should also move on towards the next more progressive steps by modernizing older housing stock.

Similar low-cost renovation described in this paper is wide-spread in Estonia and in neighboring countries today. Often renovation is conducted in many stages without a holistic approach. Main renovation solutions employed are typical: additional external insulation and changing of old wooden windows. Together with the change of membrane waterproofing, an additional thermal insulation is added to the roof. The renovation of balconies and awnings depends on damages.

Overall success of this example project can acquire satisfactory evaluation avowals. A novel solution in this pilot project was holistic approach and an air heat pump for heat recovery of the new mechanical ventilation. Attitudes of inhabitants to the renovation varied both before and after renovation. In the current pilot project, people were somewhat more tolerant since approximately half of the whole investment came from sponsors and subsidizers. Still, there were complaints about designed solutions, execution of workmanship, and some unfamiliar changes.

CONCLUSIONS

This case-study analysis studied measured and calculated hygrothermal performance of a mineral wool (MW) and graphite enhanced expanded polystyrene (EPS) external thermal insulation composite systems (ETICS/EIFS). Also, indoor climate, air leakage rate and thermal bridges were measured before and after the low-budget energy renovation of an existing concrete large panel elements apartment building.

Indoor climate measurements showed no major changes in moisture excess, mostly because mechanical ventilation airflows were decreased by the operator. Overheating that existed before was avoided after the renovation with a new adjusted heating system. Airtightness of the building fabric improved only in apartments where old leaky windows were replaced. Additional external insulation solves the serious problem of thermal bridges, except at external wall/window junction if windows remain at their original position and also at external wall/balcony and external wall/foundation wall junction. Therefore, windows should be attached to the external side of the existing façade.

Measured hygrothermal performance of both walls was good and correlation existed with the calculated temperature, vapour pressure, and RH distributions. Built-in moisture of the whole wall (measuring spots 1 and 2 on both sides of the external layer of concrete) dried out during the first heating season, achieving RH values below 50%. Moisture in thin plastering (measuring spot 3 between insulation and plaster) dried out within few days but stayed quite high, especially in the case of mineral wool, being over 90%. It means that the content and properties of the external finishing plaster must be carefully designed to achieve low enough vapour permeability and low water uptake. This becomes even more crucial at a greater vapour flow due to material with higher vapour permeability instead of concrete. Average measured thermal transmittance U during the winter was 0.17 W/($m^2 \cdot K$) in the case of graphite enhanced EPS and 0.19 W/(m^2K) for mineral wool. This is close to the expected value calculated from a producer's data and allows us to make positive conclusions about thermal performance. Hygric performance was also satisfactory and moisture dried out during the first heating season. Measurements and calculations showed that there had been some convection of moist air in the wall. A drying out process by diffusion only would have been much slower.

Short term hygrothermal performance of ETICS is normal when proper design and workmanship is performed, in particular, related to joints. Additional insulation lowers the RH inside the existing wall that stops the corrosion process and frost damages. Long term performance and durability of ETICS in cold climate and under driving rain loads needs to be further investigated with special attention to content and properties of render, frost resistance, cracking, staining, maintenance, and repainting.

ACKNOWLEDGMENTS

The research has been conducted as part of the IUT1−15 project "Nearly-zero energy solutions and their implementation on deep renovation of buildings."

REFERENCES

Balaras, C.A., Droutsa, K., Dascalaki, E., Kontoyiannidis, S. 2005. Deterioration of European apartment buildings. *Energy and Buildings*, 37 (5), pp. 515–527.

Balocco, C. / Grazzini, G. / Cavalera, A. Transient analysis of an external building cladding, *Energy and Buildings*, 40 (7), p.1273–1277, Jan 2008.

Bomberg, M. / Lstiburek, J. / Nabhan, F. Long-Term, Hygrothermal Performance of Exterior Insulation and Finish Systems (EIFS), *Journal of Building Physics*, 20 (3), p.227–248, Jan 1997.

Cheple, M. and Huelman, P. (2000). Literature Review of Exterior Insulation Finish Systems and Stucco Finishes, Report MNDC/RP B80-0130, University of Minnesota.

Desjarlais, A.O., Karagiozis, A.N., and Aoki-Kramer, M. (2001): Wall Moisture Problems in Seattle. Buildings VIII proceedings, ASHRAE, 8p.

Dol, K.; Haffner, M. 2010. Housing Statistics in the European Union 2010. OTB Research Institute for the Built Environment, Delft University of Technology.

Dall'O', G., Galante, A., Pasetti, G. A methodology for evaluating the potential energy savings of retrofitting residential building stocks. *Sustainable Cities and Society*. 4-1, October 2012, Pages 12–21.

Economidou, M., Atanasiu, B., Despret, C., Maio, J., Nolte, I., and Rapf, O. (2011). European buildings under the microscope: A country-by-country review of the energy performance of European buildings. Buildings Performance Institute. Europe 2011.

EN ISO 10211 *Thermal bridges in building construction - Heat flows and surface temperatures - Detailed calculations*. Part 1:2000 and Part 2:2001.

EN ISO 13788 *Hygrothermal performance of building components and building elements - Internal surface temperature to avoid critical surface humidity and interstitial condensation - Calculation methods*.

EN 13187 *Thermal performance of buildings - Qualitative detection of thermal irregularities in building envelopes - Infrared method*.

EN 13829 *Thermal performance of buildings - Determination of air permeability of buildings - Fan pressurization method*.

Hagentoft, C. E. 2010. Importance of a correct overall performance assessment – Probability assessment of performance and cost. Large scale national implementation plans for building airtightness assessment: a must for 2020. We should start now to be ready in 2020. June 14–15, 2010 Brussels, Belgium.

Hens, H. and J. Carmeliet, (2002), Performance prediction for masonry walls with EIFS using calculation procedures and laboratory testing, *Journal of Thermal Envelope and Building Science*, 25(03).

Holm, A. and Künzel, H.M, (1999), Combined effect of temperature and humidity of the deterioration process of insulation materials in ETICS, Building Physics in the Nordic Country, August, Gothenburg.

Ilomets, S.; Kalamees, T.; Agasild, T.; Õiger, K.; Raado, L. M. (2011). Durability of concrete and brick facades of apartment buildings built between 1960–90 in Estonia. In proceedings: XII DBMC International Conference on Durability of Building Materials and Components, Portugal, Porto, 2011, 1171–1178.

Holopainen, R., Tuomaala, P. (2011) Effect of energy renovation on thermal sensation and comfort during heating season. 9th Nordic Symposium on Building Physics - NSB 2011 p. 1069–1076.

Kalamees T; Õiger K; Kõiv T. A., et al. 2009. Technical condition and service life of Estonian apartment buildings, built with prefabricated concrete elements. Tallinn University of Technology (in Estonian).

Kalamees, T., 2006. Hygrothermal Criteria for Design and Simulation of Buildings. Doctoral theses, Tallinn University of Technology, Tallinn: TTU Press.

Karagiozis, A. and Kumaran, K. (1997). Drying Potential of EIFS Walls: Innovative Vapor Control Strategies. STP 1339, American Society for Testing and Materials (ASTM), West Conshohocken.

Krus, M., Hofbauer, W. and Lengsfeld, K. Microbial Growth on ETICS as a Result of the New Building Technology? Building Physics Symposium. Leuven, Belgium 2008-10-29 - 2008-10-31.

Kvande, B. Bergheim Einar Thue, Jan Vincent. Durability of external thermal insulation composite systems (ETICS) with rendering. Building Physics Symposium Leuven, Belgium 2008.

Künzel, H.M.: Drying of Masonry with Exterior Insulation. Proceedings of the Fifth International Masonry Conference. British Masonry Society, No. 8, Stoke-on-Trent 1998, pp 245–250.

Künzel, H.M.; Zirkelbach, D. Influence of rain water leakage on the hygrothermal performance of exterior insulation systems. In Rode, C.; Technical University of Denmark -DTU-, Lyngby: 8th Nordic Symposium on Building Physics in the Nordic Countries 2008. Proceedings. Vol.1: Copenhagen, June 16–18, 2008 Lyngby, 2008 (DTU Byg Report 189).

Nemry, F., Uihlein, A., Colodel, C.M., Wetzel, C., Braune, A., Wittstock, B., Hasan, I., Kreißig, J., Gallon, N., Niemeier, S., Frech, Y. Options to reduce the environmental impacts of residential buildings in the European Union-Potential and costs. Energy and Buildings Volume 42, Issue 7, July 2010, 976–984.

Nicolai, A. 2008. Modeling and Numerical Simulation of Salt Transport and Phase Transitions in Unsaturated Porous Building Materials, Dissertation, Syracuse University.

Olson P.E., E.K., Taylor, J.A. 2009. Retrofitting barrier exterior insulation and finish system: Methodology and performance assessment. ASTM Special Technical Publication 1493 STP, pp. 229–237

Sedlbauer, K. and Krus, M., (2002), Information and Technology Transfer from IBP: Mold Growth on ETICS (EIFS) as a Result of “Bad Workmanship”?, *Journal of Thermal Envelope and Building Science*, vol. 26, no. 2, pp. 117–121.

Silva, P.C.P., Almeida, M., Bragança, L., Mesquita, V. Development of prefabricated retrofit module towards nearly zero energy buildings. *Energy and Buildings*, Volume 56, January 2013, 115–125.

Uihlein, A., Eder, P. Policy options towards an energy efficient residential building stock in the EU-27. 2010. *Energy and Buildings* 42 (6), pp. 791–798

Vares Sirje, Pulakka Sakari, Toratti Tomi, Fulop Ludovic, Hradil Petr, Vesikari Erkki, et al. 2012. Sustainable refurbishment of exterior walls and building facades. Final report, Part B – General refurbishment concepts. VTT TECHNOLOGY 33. ISBN 978-951-38-7849-8, ISSN 2242-122X. VTT. Espoo Finland. 244 p. + App. 30 p.