Commissioning of thermal performance of prefabricated timber frame insulation elements for nZEB renovation

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Abstract. The current study contains a commissioning of thermal performance of highly insulated building envelope, located in cold and humid Estonian climate. The focus is on the renovation of old apartment building to nearly-zero energy building with prefabricated timber frame insulation elements with designed thermal transmittances $U=0.10-0.12$ W/(m²·K). Air tightness, heat flux and temperatures were measured after renovation. Results of commissioning are showing some deviations from designed values, possibly caused by internal convection, improper tightening of joints of elements and poor quality of sealing of layers which must be kept airtight. The results have shown that analysis of designed solutions before, during and after renovation is worthwhile. Thorough inspection and strict rules of quality control on work site are essential for high-quality, sustainable outcomes of renovation with timber frame insulation elements and to guarantee designed thermal performance.

1 Introduction

To decrease energy use, EU member states shall establish a long-term renovation strategy to decarbonised building stock by 2050 [1]. This requires increasing requirements on energy performance of new and existing buildings. Future nearly-zero energy buildings (nZEB) should be more highly insulated than buildings developed some years ago [2]. Comparison of measured real energy use and energy use predicted by calculations have shown that the energy performance gap is larger for more energy efficient buildings [3]. This could be partly caused by user behaviour [4,5].

Increasing energy performance has been the driving force for renovation of old apartment buildings because energy related measures help to increase cost-effectiveness and the upkeep of buildings [6,7]. An innovative way of renovation is the application of prefabricated renovation elements which has the potential to reduce costs and renovation time, to lower disturbance for occupants and enhance quality and performance in terms of energy efficiency and indoor climate [8–10].

As the total energy use decreases, all deviations make a large relative difference for buildings with higher energy efficiency. Therefore, quality control and commissioning

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procedures become more and more important when designing, constructing new, and renovating existing energy efficient buildings.

2 Methods

2.1 Commissioning of heat loss

Space heating is one of the largest single energy consumption components in Estonian old apartment buildings [11]. The space heating depends strongly on specific heat loss H , W/K (1), transmission and infiltration losses through the building envelope [12]. Therefore, the main components of heat loss (thermal transmittance, thermal bridges and air leakages) of building envelope were studied in commissioning of heat loss.

$$H = \sum_i U_i \cdot A_i + \sum_j \Psi_j \cdot l_{j+} \cdot \sum_p \chi_p \cdot n_p + \dot{V} \cdot \rho_a \cdot c_a \quad (1)$$

where $\sum_i U_i \cdot A_i$ is the sum of heat loss, caused by thermal conductivity, $\sum_j \Psi_j \cdot l_{j+} \cdot \sum_p \chi_p \cdot n_p$ is the sum of heat loss due to thermal bridges and $\dot{V} \cdot \rho_a \cdot c_a$ is the infiltration heat loss.

2.2 The case study building

A 5-story apartment building with total area 4318 m², constructed in 1986 (see Fig. 1, left) was renovated by using prefabricated timber frame insulation elements [13]. Because of serious thermal bridges in these type of buildings [14], mould growth was present on interior surfaces, especially in the corners of exterior walls and roof before renovation and the thermal transmittance of the external envelope was $U=0.9-1.1$ W/(m²·K). The energy need for heating and domestic hot water was close to 300 kWh/(m²·a). The building had insufficient ventilation, it was subject to overheating during winter and provided unsatisfactory thermal comfort.

Fig. 1. Overview of the building in 2015 before (left), in summer 2017 during (middle), and in autumn 2017 after (right) the nZEB renovation with prefabricated timber frame insulation elements.

The building was renovated to fulfil nZEB requirements (see Fig. 1, middle and right) in 2017 by using prefabricated timber frame insulation elements filled with light mineral wool. A designed value for roof was set to $U=0.10$ W/(m²·K), for additionally insulated wall $U=0.11$ W/(m²·K) and for balcony wall $U=0.12$ W/(m²·K). See designed wall and roof types in Fig. 2.

Designed roof elements (see Fig. 2, right) were installed on a specially built wooden frame because the original roof had an inward slope and parapet. Therefore, under the formed sloped roof, in a 0.6-1.2 m high attic space between the old and new roof, technical appliances were placed (e.g. heat exchangers, duct dispensers, automatics etc.).

Fig. 2. Prefabricated timber frame insulation elements on the wall (left) and on the roof (right).

2.3 Measurements

Measurements at the case study building were completed, and hourly logged data was collected, before and after nZEB construction phase. See Fig. 2 for location of temperature (T) and relative humidity (RH) sensors and heat flux plates (q).

Thermal transmittance of walls and roof was measured with heat flux plate by using Hukseflux HFP01 (Ø8 cm) and HFP03 (Ø17 cm) sensors (measurement range ±2000 W/m², accuracy +5...-15%).

Air and surface temperatures were measured with HOBO temperature/relative humidity/2 external channel (TMC6-HD) data loggers (U12-013, measurement range -20...+70°C, accuracy ±0.35°C). Temperature factor f_{Rsi} was calculated, based on hourly measured surface temperatures (t_{si} , t_{se}) of insulated envelope. A designed limit of temperature factor was set to $f_{Rsi}>0.8$ according to preceding research [15].

Air leakage of timber frame building envelope joints was measured by using Minneapolis BlowerDoor fan pressurization equipment together with identification of air leakage and thermal bridge places with thermography by using FLIR E302 thermal camera (measurement range -20...+500°C, sensitivity 0.10°C, accuracy ±2°C and +2%). A designed limit of air leakage $q_{50}<2.0$ m³/(m²·h) was set according to local regulation [16].

3 Results

3.1 Thermal transmittance of external envelope and thermal bridges

The designed values and measurement results of thermal transmittance are shown in Fig. 3 (left). Calculated on base of measured surface temperatures and heat flux (see Fig. 2 for location of sensors) results of temperature factor were varying $0.85<f_{Rsi}<0.95$.

Light mineral wool layer (see Fig. 2 left, pos.2; Fig. 3, right) was intended to fill the obliquities and unevenness between old wall and insulation element. Though the insulation was installed properly in factory under production surveillance, within inspection on-site, at some locations, airgaps between wool layer and the old wall surface were reported. This

may contribute to air leakages and internal convection. The reported places were resealed properly and/or closed with polyurethane (PUR) foam.

Fig. 3. Designed and measured values of thermal transmittance (left). Schematic of possible heat and air leakages in the envelope structures (middle). Photo about not sufficiently installed light insulation layer between insulation element and the old wall (right).

3.2 Air leakage of external envelope

First measurement of air leakage (result: $q_{50}>3.0 \text{ m}^3/(\text{m}^2\cdot\text{h})$) was done right after the construction works and some leaking spots were found (around pipes through the roof and ceilings, surrounding of the windows, see Fig. 4). After the additional examination of the building with under-pressure conditions and thermography, the leaking places were detected and subsequently carefully resealed. As a result, air leakage was obtained under the designed limit value (result: $q_{50}<1.8 \text{ m}^3/(\text{m}^2\cdot\text{h})$).

Fig. 4. Faults of airtightness of envelope around windows, reported within inspection.

4 Discussion

Described hereinbefore, the measured results and calculated values are showing quite a good correspondence with our expectations formed at the preliminary analysis and design phase.

Temperature factor (f_{Rsi}) values, calculated on base of measurements after installation of prefabricated elements, are showing that the external envelope does not have remarkable

thermal bridges. Thermography measurements before and after depression (-50 Pa during ~30 minutes) indicated some minor air leaking places, especially around the windows and penetrations of air barrier. Therefore, we may conclude that conducted monitoring of energy performance and quality commission are unavoidable steps in nZEB and deep energy renovations.

Variations of designed and measured thermal transmittances (U) are noticeable in some cases, see Fig. 3 (left). Lower, than designed, values may be explained with the variability of properties of materials, particularly with thermal conductivity (e.g. $\lambda_{90/90}$). A possible reason, for measured values being higher than designed, may be uncertain convection in the conjunction area between the existing wall and installed elements (local warm air leakages from interior side and/or cold air from exterior side). A probable cause for that deviation could be also the variation of the hourly measured heat flux, which may be explained by some internal convection and sun radiation. Described in Fig. 3 (middle and right) gaps may be the reason, why measurements with heat flux plates gave results with such a big difference (see Fig. 3, left).

The place for measurement was problematic to find because available space on external walls was limited: windows and heating radiators occupied large area of walls. Where is the best spot then to get the most reliable measuring results? Is it in the ventilation gap or inside the envelope structure, where constraining factors are minimised? Since heating device can significantly affect the estimation of the thermal resistance [17], the methods are applied to the prefabricated element rather than to the retrofitted envelope: internal surface temperature and heat flux are measured at the insulation/cavity interface. Other authors [18] have stated that there are some variances, caused by several aspects. Also, [19] have pointed out the influence of internal convection in the highly insulated timber frame walls. Hence, it is quite difficult to conduct such kind of measurements after the construction processes, as the mentioned places are covered with finishing layers. Therefore, the need for future investigations to find reliable, better ways of implementation of measurements is necessary.

Measurements of the airtightness of the envelope (q_{50}) showed the importance of the quality of sealing of all joints and leakages of the envelope, particularly around pipelines and ducts, penetrating the external walls or roof structures, on contact surfaces with untreated concrete, as well as on areas around windows. Air tightness and ageing of PUR foam, used widely for these purposes, are not validated and reported firmly. Authors [20] have studied the control methods and stated importance of proper sealing of joists in similar climate conditions.

5 Conclusions

As presented results have shown, there may be a big difference of thermal performance and risk of failure when designed solutions are not followed properly in the construction process or in the use period without complementary control measurements. It is very important to consider the possible building technology mistakes or cracks and open joints in existing structures which allows uncontrolled heat and moisture flow towards to outer layers where it may cause problems because of moisture excess. Particularly because of the unknown state of existing structures and primarily because of its moisture content, this is a firm suggestion to conduct hygrothermal measurements of existing structures before the final design decisions and construction works.

As the commissioning of thermal performance of prefabricated timber frame insulation elements showed some variance in designed values, differences may also occur in the designed and actual energy performance values.

A careful analysis and selection of materials allows to design efficient timber frame insulation elements and provide low thermal transmittance of nZEB, but inspection, careful and high-quality installation technology on-site are even more important.

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