RESULTS OF LONG-TERM ENERGY EFFICIENCY MONITORING OF TEST BUILDINGS UNDER REAL CLIMATIC CONDITIONS

Dr. Stanislavs Gendelis
Assoc. Prof. Dr. Andris Jakovičs
Jānis Ratnieks
Faculty of physics and mathematics, University of Latvia, Latvia

ABSTRACT
The calculated energy efficiency and specified physical properties of building materials may change significantly during the initial years of a building’s operation under real climatic conditions. Five small test buildings with different wall assemblies were built in Rīga, Latvia to compare different building construction characteristics under Latvian climate conditions. The heating energy consumption, thermal transmittance, air relative humidity and other important energy efficiency and environmental parameters have been monitored since late 2012 when the test buildings were constructed. Changes in characteristics have been observed and widely analysed. The monitoring results show significant differences in the initial moisture content of building materials and in U-value, and therefore, heating energy consumption and comfort conditions in the buildings. The differences between calculated and measured values are remarkable, even after two heating seasons. Parallel to the research on energy efficiency during heating seasons, an overheating risk analysis for the buildings during summer was also performed, showing the role of thermal mass on thermal comfort. An analysis of measurements made under real climatic conditions allows consideration for the difference in calculated and actual properties, for an estimation of the buildings’ real energy efficiency.

Keywords: test buildings, energy efficiency, real climatic conditions, U-value, overheating.

INTRODUCTION
Small experimental buildings with internal dimensions of 3×3×3 m (Fig. 1) have been built in Rīga (Latvia) to perform long-term monitoring of various energy efficiency and comfort related parameters. The test buildings are localized in an urban environment, in a warm-summer humid continental climate. The average heating period in Rīga is 203 days and the average temperature for this period is 0.0 °C [1]; while the summer season is short, overheating issues are still present.

The buildings have identical floor and ceiling constructions (U=0.16 W/m²K), and the same doors and windows (U=0.8 W/m²K). Only the walls have been built with different materials, to reach the same calculated U-value of 0.16 W/m²K. The main layers of material for the walls in the different buildings are (see Fig. 2):

- aerated concrete blocks (375 mm) with stone wool outside layer (AER).
- perforated ceramic blocks (440 mm) with stone wool insulation outside (CER).
- perforated ceramic blocks (510 mm) with insulation in air enclosures (EXP).
- laminated beams (200 mm) with a stone wool insulation layer and wood panelling inside (LOG).
- modular plywood panels with stone wool filling (200 m) and fibrolite plates (70 mm) inside (PLY).

All the test buildings are equipped with identical air–air heat pumps, used for the heating/cooling and electric convection heaters; two buildings are additionally equipped with different air–water heat pumps. Three ventilation modes are provided using installed air–air heat pump systems with outdoor air intake.

The measurement data from more than a hundred sensors is taken every minute from the weather station and each building, with the help of a distributed multi-sensor real-time monitoring system with remote data access [2]. The placement of main temperature/humidity sensors is shown in Fig. 1.

After more than 4 years of real-time monitoring, much of the collected data is widely used for comprehensive research in different fields, including heat transfer and numerical modelling [3], thermal comfort estimation [4], humidity monitoring and mould growth risk analysis [5], evaluation of heat pump efficiency [6] and many others. Similar studies are also being performed in other countries with different climatic zones, e.g. the United Kingdom [7], Finland [8], Spain [9] and Italy [10], and include a wide spectrum of investigated problems – building materials, structures, installed systems and innovative technologies.

Figure 1: Overview of the test buildings (left) and location of the main temperature and air humidity sensors (right) marked as dots, and the heat flux sensor (Q-WALL).

Figure 2: Placement of temperature/humidity sensors in different wall envelopes.
**RESULTS: TEMPERATURE**

Monthly average temperatures during the monitoring period have fluctuated in the range that is typical for Riga – from -5°C in winter to 20°C in summer (Fig. 3). The average temperature in each building does not differ more than 0.9 °C (excluding some separate experiments), therefore the maximum error for research in heating energy is estimated at less than 5%.

For summer periods without forced cooling, average monthly temperature differences in the buildings increase by up to 2°C, mainly due to different thermal inertia for buildings with different weights (Table 1). A small thermal inertia is the main reason for an increase in indoor temperature (known also as overheating) in lightweight buildings without cooling and ventilation, and in the case of intensive solar radiation. The maximum difference for indoor temperatures between lightweight and heavy constructions reaches 6°C (Fig. 4). The effect of thermal mass is also observed after cold nights when the temperature in the lightweight buildings decreases faster and heating is needed. Switching between cooling, heating and/or ventilation systems is needed more often for lightweight buildings to provide thermal comfort, meaning additional energy consumption and lower energy efficiency.

![Figure 3: Monthly average temperatures.](image)

![Figure 4: The difference in indoor temperatures without cooling and ventilation during hot summer days (overheating).](image)
### Table 1: Weights of wall constructions.

<table>
<thead>
<tr>
<th>Material</th>
<th>AER</th>
<th>CER</th>
<th>EXP</th>
<th>LOG</th>
<th>PLY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main material</td>
<td>aerated concrete</td>
<td>ceramic blocks</td>
<td>ceramic blocks</td>
<td>laminated beams</td>
<td>stone wool</td>
</tr>
<tr>
<td>Weight (kg/m²)</td>
<td>165</td>
<td>363</td>
<td>426</td>
<td>152</td>
<td>79</td>
</tr>
</tbody>
</table>

![Figure 5](image.png)

**Figure 5:** The difference in indoor temperatures without heating and ventilation after cold nights.

### RESULTS: HUMIDITY

Humidity is an important aspect regarding construction characteristics, energy efficiency and occupant comfort [11]. High relative humidity of indoor air induces mould growth on surfaces with low temperatures (e.g. room corners), corrosion and moisture related deterioration. Increased moisture content in building structures significantly affects thermal conductivity, leading to higher energy consumption for heating. From a human comfort point of view, the relative humidity needs to be in the range of 25–60%.

Monthly average relative air humidity outside and in each building from the beginning of the experiment is shown in Fig. 6. It can be seen, that during the winter period the outdoor relative humidity level is close to saturation, despite the absolute humidity being much lower than during the summer. This is the main reason why relative humidity inside the buildings can get down to 25%. These conditions do not meet the requirements of human comfort; however, it must be noted that there are no moisture sources inside the test buildings and humidity will be higher in an occupied building.

Unlike controlled temperatures during heating seasons, differences in relative air humidity between the buildings are much higher, especially at the beginning of the experiments. Due to high initial moisture content [12], relative air humidity in the AER building, which is mainly built from aerated concrete, remains higher than the others at least for the first two heating seasons (Fig. 6). Measurements from the sensors placed between the construction layers or in the materials (see Fig. 2) also show the high initial moisture content of the aerated concrete building (AER), producing a relative humidity
value of 100% that begins to decrease only after a year and a half (black line on Fig. 7) – it causes observed intensive mould growth in this building.

On the other hand, relative air humidity in the building made from dry laminated beams (LOG) did not even reach 60% during the first season. As can be clearly seen from the graphs in Fig. 6, the relative air humidity after the first two years becomes very similar, meaning that equilibrium moisture content conditions have been reached. Looking at the data from the humidity sensors in the building structures (Fig. 7), it can be seen, that PLY readings significantly differ from other sensors and are very close to outdoor humidity (Fig. 6) – the reason for this is that the location of this sensor is close to the outside plywood layer.

![Figure 6: Monthly average air relative humidity.](image1)

![Figure 7: Relative humidity inside wall construction (see Fig.2).](image2)

**RESULTS: U-VALUES**

The measurements of thermal transmittance or U-value (W/m²K) are taken for the different building constructions in all test buildings, just after they are constructed and are repeated at a later date. During the first two heating seasons, measurements were carried out using a portable measuring system (for walls, floors, ceilings, windows and
doors). Later, long-term monitoring of heat-flux density was provided by stationary heat-flux sensors placed on the walls only. Results of the measured U-values during four heating seasons are visually summarised in Fig. 8. The variation in determined U-values is mainly caused by the different humidity conditions of the building structures. Comparing experimental results with the calculated ones (U=0.16 W/m²K) it can be seen, that measured values for the walls in the LOG and PLY buildings, as well as for the floors and ceilings in all buildings, are very close to the theoretical ones. The measured U-value for the LOG wall was initially lower than calculated: this can be explained by low moisture content in timber constructions just after manufacturing, which increases during exploitation under real climatic conditions.

High U-values obtained for aerated concrete and ceramic block buildings (AER, CER, EXP) can be explained by a significant influence of the moisture content on the thermal conductivity of such materials. Calculations of thermal transmittance values are based on the manufacturers’ specified thermal properties, which are usually obtained in laboratory conditions and can significantly differ from the properties under real climatic conditions. In addition, a high U-value for the EXP building is also determined by mistakes during the manufacturing of the ceramic blocks, resulting in the highest volume of ceramics.

![Figure 8: Experimentally measured U-values.](image)

**RESULTS: HEATING ENERGY CONSUMPTION**

The heating energy consumption is strongly linked with the above-mentioned thermal transmittance properties, ventilation regime (the same for all buildings) and indoor temperature, which may differ slightly. To compare the seasonal results, consumption for each building should be normalized to the same temperature difference and to the lowest energy consumer for the period. The results of such calculations in heating energy consumption for all buildings for the last two heating seasons are shown in Fig. 9, where two types of heating – electric heaters for the 2015/16 season (circles) and air–air heat pumps for the 2016/2017 heating season (diamonds) are combined. As shown,
the maximum difference obtained between the best performing LOG building and the EXP building is about 35%, which can be easily explained by the difference in thermal transmittance of the walls (Fig. 8).

Variations in ratios for different types of heating (electric and heat pump) is explained by the changed structure of airflow in the rooms. This causes a different distribution in heat loss by transmittance, which is different for each building, and ventilation, which is the same for each building. Thus, in the case of air–air heat pump operation, the warm airflow may be directed to the window and exhaust ventilation opening.

![Figure 9: Normalized energy consumption for electric (circles) and air–air heat pump (diamonds) heating systems in the test buildings.](image)

**CONCLUSION**

Long-term measurements of test buildings’ characteristics under real climatic conditions show that initial conditions have an important impact on the material properties and total energy efficiency for at least two years. The initially high moisture content is the main source of a building construction’s inability to achieve the calculated energy consumption, and is the key factor for possible mould growth, corrosion and other damage.

Use of building constructions with higher thermal mass allows for an improvement in thermal comfort during the summer, preventing overheating and at the same time reducing, or even excluding the cooling energy required during rapid changes in indoor temperature, caused by direct solar radiation. This effect is also useful to reduce the heating needed in autumn or spring with short-term temperature drop-off.

The real thermal transmittance for building constructions may differ significantly from the calculated U-value, which is generally based on properties measured in laboratory conditions. This affects the energy efficiency for the whole building, which may also change during the year if there are annual humidity fluctuations (like in the Latvian climate).
ACKNOWLEDGEMENTS

This research was conducted with the financial support of the European Regional Development Fund, project “Development, optimization and sustainability evaluation of smart solutions for nearly zero energy buildings in real climate conditions”. (1.1.1.1/16/A/192).

REFERENCES


