Monitoring and Modelling of Energy Efficiency for Low Energy Testing Houses in Latvian Climate Conditions

Andris Jakovics, Stanislavs Gendelis, Janis Ratnieks and Saule Sakipova

***Abstract*—**Five experimental test buildings (stands) have been built in Riga, Latvia (see Figure 1). They are identical except external walls for which different, mainly regional, building materials have been used. However, projected heat transmittance (*U*-value) of the walls, floor and ceiling is the same for each test building. Initial moisture influences the relative humidity of indoor air, which can be higher at initial time period when buildings have just been built. As a result the *U*-values are also very different and cause different heating/cooling energy consumption. Measurements show that critical situation is observed for two test houses (aerated concrete constructions with insulation layer and ceramic block construction with insulation filling) where initial moisture is high and the drying process of external walls is slowly. Results show that the heat demand in cold period for this two test houses are significantly higher than another 3 test stands. Moreover, overheating risks for two "critical" test houses are significantly lower in summer. However, the situation is not normal in that case. Both summer and heating seasons have been analysed and differences between five test houses are discussed in details. Mathematical model to predict air flow velocity and temperature fields are developed and validated.

***Keywords*—**energy efficiency; low energy buildings; building materials; in-situ measurements; heating/cooling consumption.

I. Introduction

As the energy efficiency (EE) requirements in the context of building design and engineering performance become more rigorous, increasing attention must be paid to ensure the required indoor environment quality (IEQ). The task of a building's design and construction is to ensure that with the minimum energy expenditure yields as consistent IEQ at varying outdoor air conditions as possible. The choice of building's design affects the initial investment and exploitation costs as well as the long-term impact on human health, which is determined by the selected design characteristics (e.g., thermal inertia, hygroscopic qualities, etc.) and their impact on the ability to achieve the desired EE and IEQ performance. This article presents the implementation phase and first year's results of the test buildings monitoring project.

The choice of building material for the five different walls of experimental constructions was determined by the target to find the best possible application of materials produced from the local resources, and high-quality insulation materials. The expected outdoor and indoor air parameters and energy consumption monitoring data will provide an opportunity to analyse the buildings in which five different construction materials have been used. Similar studies were performed on a variety of building design solutions and material effect on energy consumption and indoor climate also in other countries, e.g. in Finland, Estonia, Spain [1, 2, 3].

Fig. 1. Experimental test buildings.

II. Description of the Testing Ground

In the framework of the project 5 test stands are built with different exterior materials, identical in terms of design, geographic location and engineering solutions. More detailed information about project is summarized in [4].

The building design provides solutions for reduction or elimination of thermal bridges. For all types of exterior wall constructions the *U*-value equals 0.16 W/(m^{2}K), calculated according to the standard EN ISO 6946. Constant air exchange rate of 0.4…0.5 h^{-1} is provided by the air-air heat pump, which is used also for heating and cooling.

The experimental constructions are localized in the urban environment, under natural conditions in Riga, Latvia, characterized by cold, maritime climate (duration of the average heating period of 203 days, the average outdoor air temperature during the heating period is 0.0°C, the coldest five-day average temperature -20.7°C, the average annual air temperature 6.2°C, the daily average relative humidity is 79%

Andris Jakovics is an associate professor at University of Latvia and the head of Laboratory for mathematical modelling of technological and environmental processes at Faculty of Physics and Mathematics, University of Latvia (8 Zellu Str., Riga LV-1002, Latvia; phone: +37129155711; e-mail: andris.jakovics@lu.lv; www.modlab.lv).

Stanislavs Gendelis is a senior researcher, Janis Ratnieks is a scientific assistant and Saule Sakipova is a visiting researcher at Faculty of Physics and Mathematics, University of Latvia.

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[5]). The selected location is the University's Botanical garden territory, all five stands are placed on equal relation to the sun and the surrounding shading objects (such as trees).

The experimental constructions are designed in order to minimize differences in output data of energy consumption and indoor climate measurement data analysis and interpretation. Each experimental stand imitates a free-standing building with an interior room (9 m^2 floor area, ceiling height of 3 m) with a window on the south façade and a front door on the north façade – see Fig. 2. Each building is placed on pillars and has no contact with the ground. To prevent the thermal bridges, window and door installations have been taken out to the insulation layer.

The basic materials used for the ventilated facade exterior wall construction are (see Figure 3):

1) perforated ceramic blocks (440 mm) with flexible stone wool insulation outside (type CER);
2) aerated concrete blocks (375 mm) with flexible stone wool layer outside (type AER);
3) modular plywood panels with flexible stone wool filling (200 mm) and fibrolite (70 mm) inside (type PLY);
4) perforated ceramic blocks (500 mm) filled with insulating granules (type EXP);
5) laminated beams (200 mm) with flexible stone wool insulation layer and wood paneling inside (type LOG).

It is crucial for experiment to ensure same heating/cooling conditions as well as air exchange in the room. Also it is important to keep the operative costs low. Heat pumps have been tested widely nowadays, for example in [6, 7]. Water – water heat pumps and air – water heat pumps show slightly better results, but the construction costs are higher and same air exchange for each stand can't be ensured. This is why each building is equipped with an air-air heat pump (heating/cooling capacity 3.6/2.8 kW; outdoor air supply 24/32 m^3/h). Air conditioning equipment is installed above the door. Air leakage from the building exists through natural ventilation ducts fitted with a gravity louver, the channel which is located above a window.

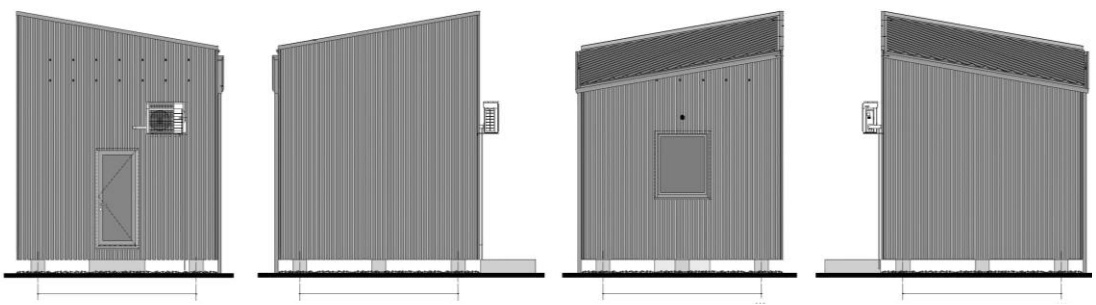

Fig. 2. The facades of one experimental building

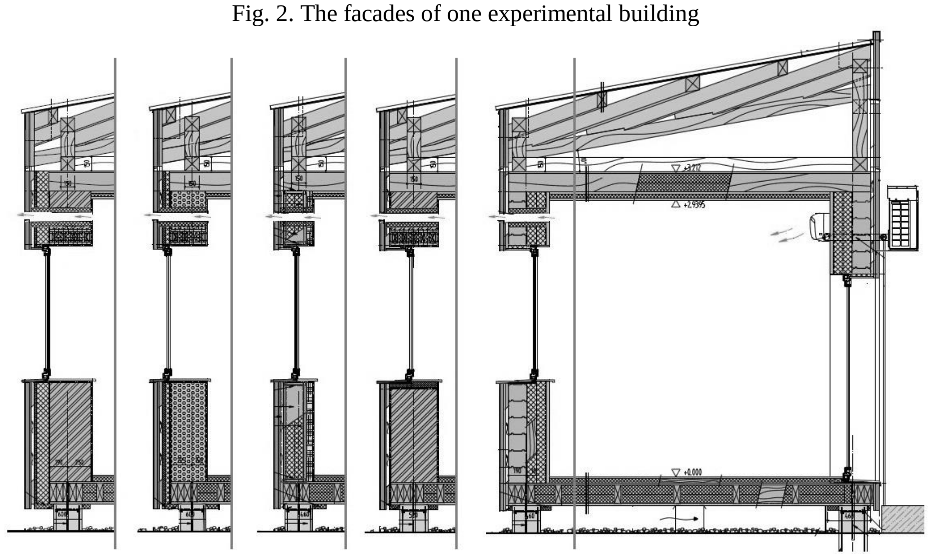

Fig. 3. Cross-section of different types of test buildings.

III. Measurement Data Acquisition System

All the test stands are equipped with the same set of sensors. 40 different sensors include:

1) temperature and humidity (T/H) sensors,
2) air velocity flow sensors,
3) solar radiation sensor,
4) energy meter,
5) differential pressure sensor,
6) heat flow sensor,
7) atmospheric pressure sensor.

The locations of main air T/H sensors are shown in Fig. 4 as black dots. The data logger is collecting all sensor data including data from the electric energy meter. To collect meteorological data a weather station is installed on the top of a test stand with the separate data logger. Details of the developed measuring system can be found in publication [8].

The webserver and the FTP server are installed in each data logger providing remote access to the stored data for each sensor and to the software's parameters. All measurements are performed every minute and saved to the logger memory. The measurement data file from loggers is sent to the main FTP server once a day, where the data is collected and post-processed for detailed analysis. Measurements can be displayed directly using Web access to the logger memory, and using data from the user FTP server.

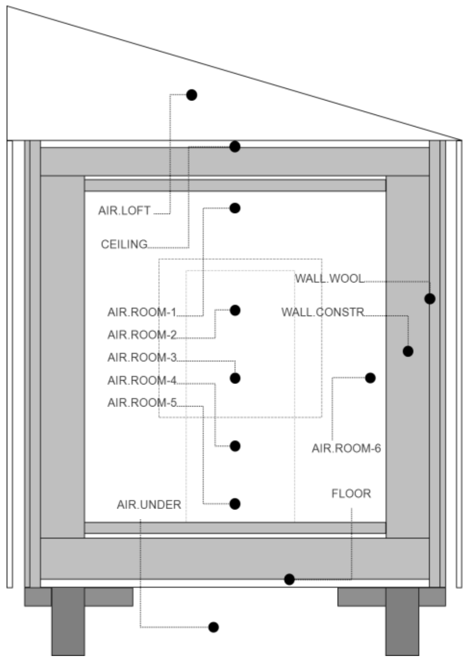

Fig. 4. The location of T/H sensors in a test building.

IV. Air exchange rate measurements

The main aim of the project is to determine and analyse energy consumption for all test buildings, therefore it is very important to evaluate all the heal losses. One of them is convection heat losses through ventilation opening and construction joints, which can be characterized by the air exchange rate in the room. Tracer gas method [9,10] and special measuring system *Lumasense* [11] including multipoint sampler/doser *Innova 1303* and photoacoustic gas monitor *Innova 1412* are used for this purpose (Fig. 5).

Experimental studies of actual air change were made in all the test buildings after airtight sealing and with ventilation system running in standard mode. Measurements were carried out at least for 24 hours for every building. Obtained results (Table 1) show that the actual air exchange rate with switched on ventilation system in all test buildings is within the range of 0.43…0.50 h^{-1}. An additional measurement was carried out with switched off ventilation system and sealed ventilation opening; this study shows that air change in this case is very close to zero (see [12]). The general finding of this experiment is test buildings are very air-tight and the actual air exchange rates *n* with switched on ventilation system are very close, which means that more than 90% of actual air exchange is a result of mechanical ventilation system operation.

Fig. 5. System used for tracer gas air exchange measurements.

Table 1. Air exchange rate *n* (h^{-1}) for test building under actual operating conditions.

Test building	Air exchange rate n (h^{-1})
LOG (log house / internal insulation)	0.45±0.03
EXP (polystyrene filled ceramic blocks)	0.48±0.02
AER (aerated concrete / external insulation)	0.50±0.03
CER (ceramic blocks / external insulation)	0.43±0.04
PLY (plywood boards / mineral wool filling)	0.44±0.01

V. U-value measurements

The measurements of heat transmittance or *U*-value (W/m^2K) are made for constructions in all different test buildings just after test buildings are built and after one year of operation. Measurements are carried out using long-term monitoring of heat flux density and temperature difference (Fig. 6).

Obtained results for all test buildings are visualized in Fig. 7. The variation in determined *U*-values is mainly caused by different humidity conditions of a building structure (see next chapter). The resulting range is a result of several measurement cycles (up to 5 for any construction); the greatest deviations is obtained for AER, EXP and CER building in year 2013, but still remain high only for AER building in year 2014. This building's type differs from other masonry structures with porous structure of the blocks, which means slower drying; this effect is clearly seen from Fig. 7 – measured *U*-values measured in year 2014 are decreased.

Comparing experimental results with the calculated (designed) it is seen, that walls in PLY building, as well floors and ceilings in all buildings are very close. Measured *U*-value for wall in LOG building is lower than calculated value; this can be explained by low moisture content in timber constructions just after manufacturing, which slightly increases in year 2014 (see Fig. 7).

Very high values of heat transmittance obtained for EXP building can be explained by mistakes in manufacturing process of ceramic blocks, resulting in the highest volume of ceramics and the highest thermal conductivity value.

Based on the experimental result obtained, it is estimated that the *U*-values for all the masonry constructions (especially for aerated concrete) in the first year of operation are very closely linked with the moister content in structures. In the second year heat transmittance decreases, this means also reduction in conduction heat losses from the buildings.

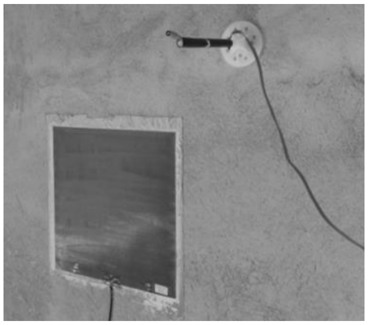

Fig. 6. Heat flux density and temperature measurements.

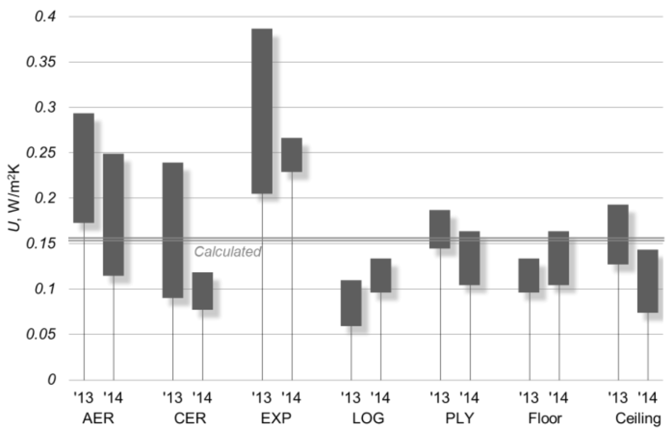

Fig. 7. Measured *U*-values of different constructions for all test buildings in years 2013 and 2014.

VI. Air humidity measurements

Temperature and air humidity in different places of test buildings (in the air as well as in the building structures) are controlled by several sensors (Fig. 4). Characteristic values of air humidity in all buildings (data from sensor located in the middle of a room) for all monitored period are displayed on Fig. 8.

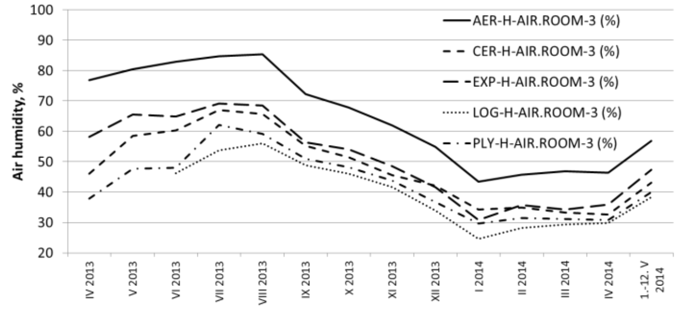

Fig. 8. Measured relative air humidity in the middle of the room.

The highest values are observed for AER type building built from aerated concrete, ever after one year operation under set ventilation conditions (measured air exchange rate 0.5 h^{-1}, see Table 4) the air humidity is highest in comparison with other types of buildings. It should be noted that this difference decreases in time and after another heating season it may be very close to another buildings, it is due to relatively slow drying of construction. It is seen also, that the relative air humidity in the summer is higher than in winter.

As the test buildings are well ventilated, the measured air humidity depends mainly on moisture content in building structures. However, humidity measurements in the structures or near its surfaces are also very important, e.g. data from humidity sensors located under the window sill (Fig. 9) and between mineral wool layer and main material (Figs. 10, 11) allows to better understanding of drying processes and moisture transport in building constructions [13]. As is seen from the graphs on Fig. 9, the relative air humidity in AER and EXP buildings are very high and can reach even 100% in the autumns under the windows sill. Measured relative humidity near mineral wool layer for CER, LOG and PLY buildings (Fig. 11) is very high throughout the year (more than 65%); and it is 100% even after one year of exploitation for AER building, but it should decrease in the next years.

The moisture has a significant negative influence on building structures, not only in terms of increasing of thermal transmittance, but also on condensation and mould growing. More information about mathematical modelling and analysis of condensation risk and mould growth in test building is summarised in [14].

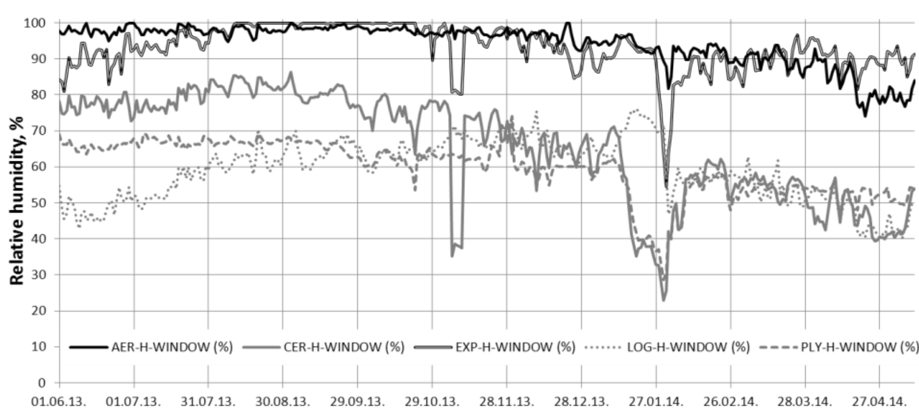

Fig. 9. Measured relative air humidity under the window sill.

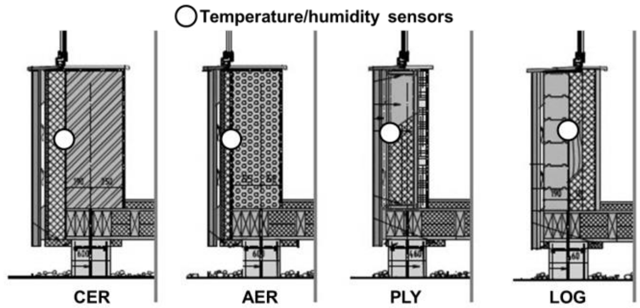

Fig. 10. Location of temperature and humidity sensors between a layer of mineral wool and ceramics blocks (CER), aerated concrete blocks (AER),plywood (PLY) and timber (LOG).

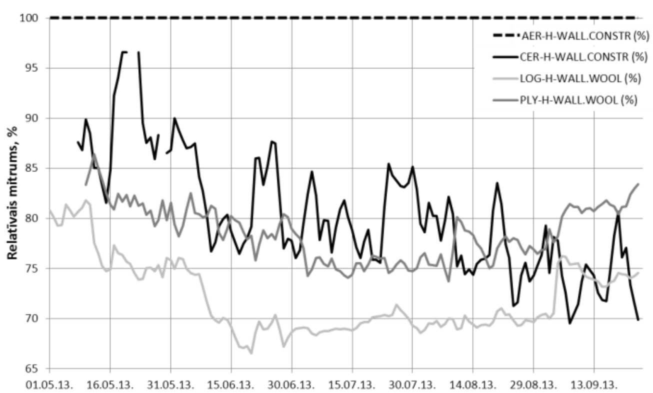

Fig. 11. Measured relative air humidity for sensors shown on Fig. 10.

VII. Energy consumption measurements

After one year project running, there is collected huge amount of data from all types of sensors. The most interesting and representative results it is possible to get by analyzing the heating and cooling energy consumption for different test buildings.

In the beginning of heating season, couple of months after the test buildings are built, energy consumption in buildings AER and EXP was higher than in another three buildings with practically the same consumption. Graphs in Fig. 12 show the increasing of difference in heating energy consumption for all test buildings in the beginning of heating season in year 2013. Comparing the energy consumption, the difference between AER and CER buildings is 134%; it means one-third more heating energy consumption. The main reason is the increased conduction heat losses (see chapter V) through walls in AER building due to higher moisture content. Increasing of *U*-value for walls also in EXP building has an effect on heating energy consumption, which is 25% higher.

Comparing the cooling energy consumption in several summer days (Fig. 13) it is seen, than the same buildings which consumed more heating energy (AER and EXP), now look very energy efficient. It can be explained by two factors:

- highest thermal transmittance for those buildings (Fig. 7), which means more intense heat losses form the room and
- drying of relatively humid structures (see Fig. 9), which requires an additional energy for evaporation.

The role of a heat capacity is very important to reduce peaks of temperature fluctuation, especially in summer days when a solar radiation influences the indoor temperature very significantly. The effect of rapidly increasing of indoor temperature during direct solar radiation called also "overheating"; an example of this process is shown in Fig. 14, where temperature in the test buildings are not controlled, but only ventilation system is on. As it is seen, the maximum temperature inside LOG building is 5°C higher than in AER building.

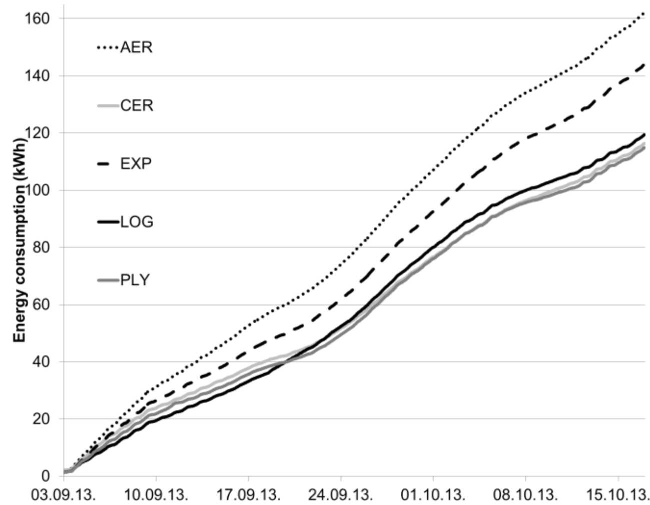

Fig. 12. Heating energy consumption in different test buildings (indoor temperature T_{in}=19°C, air exchange rate n=0.45 h^{-1}).

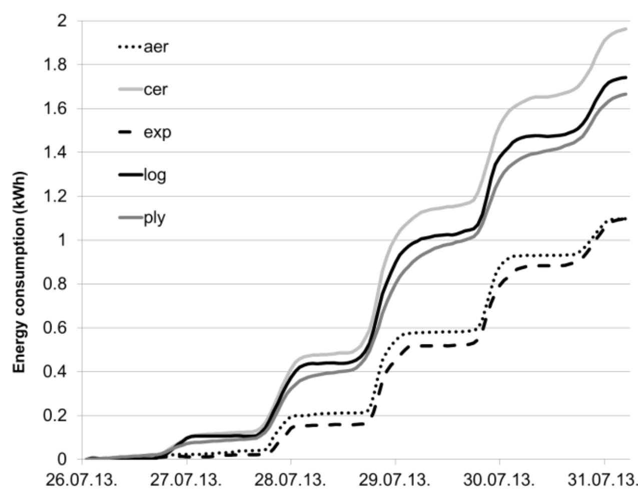

Fig. 13. Cooling energy consumption in different test buildings (indoor temperature T_{in}=24°C, air exchange rate n=0.45 h^{-1}).

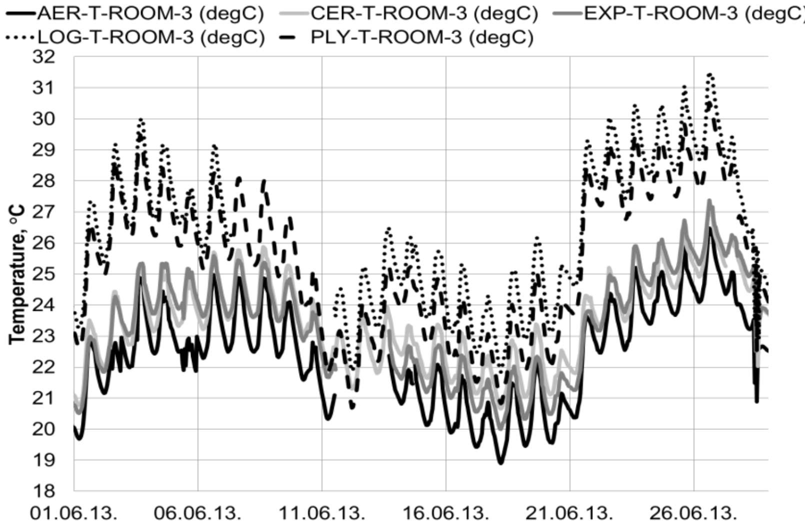

Fig. 14. Overheating of light-weight test buildings (LOG and PLY) without cooling.

VIII. Mathematical Modelling

A. Modelling approach

Only limited number of test houses can be built, but the possible construction envelopes are many, therefore a verified mathematical model can be used to provide the information of how different structures behave in Latvian climate conditions. There are ways to approximately evaluate building performance as it is carried out in [15], however the precision is unsatisfactory and the physical mechanism of what is causing the error remains hidden. The goal of this study is to get understanding of processes that happen inside the room and building envelope. As discussed above, this is affected by several physical quantities such as temperature, humidity, air velocity, thermal radiation etc. It is important to take into account all of them, however, to verify model it is better to go step by step and test as few quantities at time as possible.

To do that, a period of time, when there is constant outside temperature is considered. Such periods were found in experimental data where more than three hours the outside air temperature change no more than 0.2°C off the average value 5.1°C (Fig. 15).

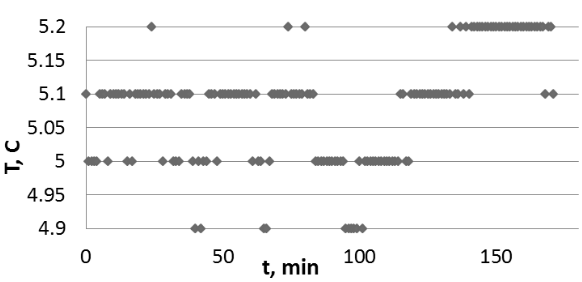

Fig. 15 Outside temperature used for modelling.

This assumption makes the case stationary from outside, however the heat pump louvers move in circles to better mix air and therefore the problem is still transient. In this study it is important to find out if the stationary study when louvers are kept constant can approximately predict temperature distribution as well as transient case.

The roof construction is not taken into account, because it is ventilated and the loft is not heated, therefore temperature there is close to outside temperature.

For this period of time the moisture inside the construction is not changing considerably and therefore is not taken into account. Temperature inside the construction has achieved quasi stationary condition. Further information on this approximation is described in [16].

B. Governing equations and boundary conditions

To get full understanding on physical processes inside building structure, equations that govern the heat transfer, air movement and moisture transport must be considered. Equations for air movement make the modelling task more difficult, because the air movement is turbulent and turbulence model must be used, as it is impossible to model the turbulence to smallest length scales for such large dimensions. Two equation *k*-ω shear stress transport turbulence model was used because of its performance for wide variety of flows [17]. As mentioned before, moisture is considered to be constant for this case and therefore is not taken into account.

Boundary conditions for solid–fluid surfaces are non-slip, for outer surfaces there is third type boundary conditions that has outside temperature (5.1°C as mentioned above) and heat transfer coefficient that account for thermal resistance for natural convection $\alpha=25\ W/m^2\cdot K$.

For air inlet there are constant mass flux with constant inflow direction for stationary study and changing inflow direction for transient simulation, see [18] for more information. Part of the air is taken back into the heat pump via feedback that is also as a constant mass flux boundary. The difference between inflow and feedback is directed to ventilation opening. The mass fluxes are calculated to ensure $0.45\ h^{-1}$ air exchange as measured and discussed above.

Ansys/CFX finite volume method based program packet has been used for numerical simulations.

C. Numerical results and model validation

First the stationary results were calculated. The temperature and velocity fields can be seen on Figs. 16 and 17 for planes in the middle of room, perpendicular to ceiling and walls.

As it can be seen in Fig. 17, the solution is symmetrical as expected, because with roof construction removed, the model is perfectly symmetrical.

General airflow directions show that buoyancy is working properly and velocities near the cold wall is downwards that make the numerical results physically consistent.

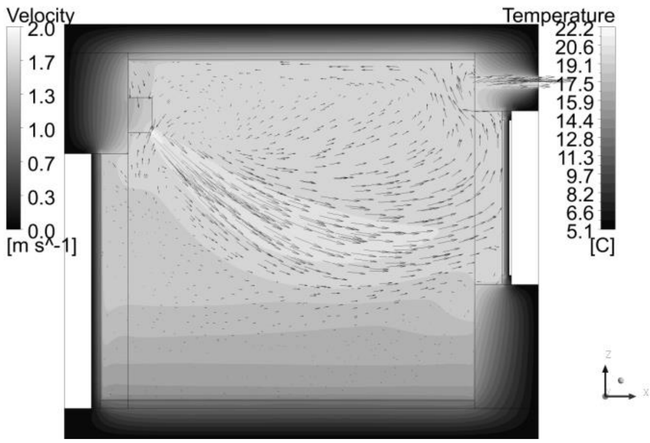

Fig. 16. Temperature and air velocity fields.

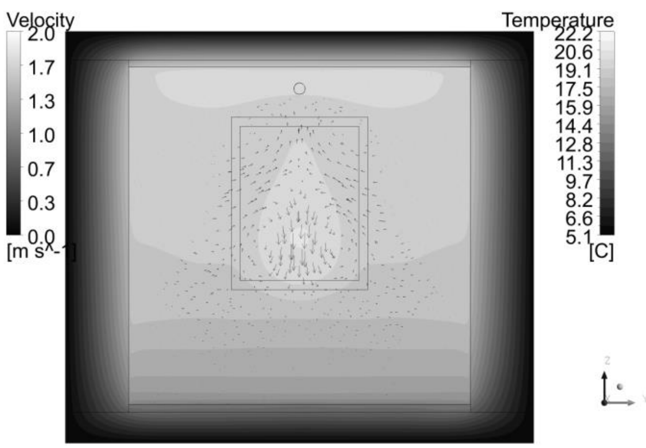

Fig. 17. Temperature and air velocity fields in the middle plane.

Stationary results were used as initial conditions for transient study and 6 cycles of heat pump were calculated with cycle being 51.6 s as measured and shown in [18]. To get meaningful results for transient study Courant criterion must be satisfied (1).

$$C = \Delta t \sum_i \frac{\overrightarrow{u_i}}{\Delta x_i} \le C_{\max} \, , \tag{1}$$

where C – Courant number, u_i – velocity, Δx_i – mesh size, Δt – time step, $C_{\max}$ – maximum Courant number. Maximum Courant number must be below unity for explicit discretization schemes, but can give meaningful results also for higher values for implicit schemes.

For a chosen mesh the time step was chosen to be 0.05 s and the computational time for 1 minute of simulation time were approximately 48 hours. The maximum Courant number value were approximately 4 and RMS value approximately 0.2. There were also calculations made with smaller time step of 0.01 s for first 30 s to ensure that solution is not timestep dependent.

It can be seen on Fig. 18 that mixing in transient case is better than in stationary and that after six cycles temperature values has leveled, however, cycles is not yet repeating each other. This can also happen because of limited time steps that solution was saved during simulation that was every 2 s of solution time.

For further investigation, transient average values for line in the middle of room where temperature sensors are (Fig. 4) considered. Calculated temperatures both, for stationary and transient average cases are compared with experimental average data, see (Fig. 19). Transient average case repeats the experiment well unlike the stationary case.

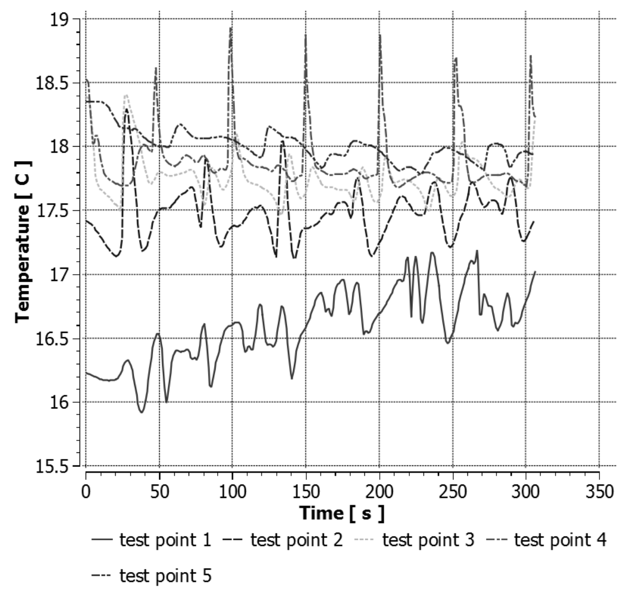

Fig. 18. Temperature dependence on time from transient calculations at test points.

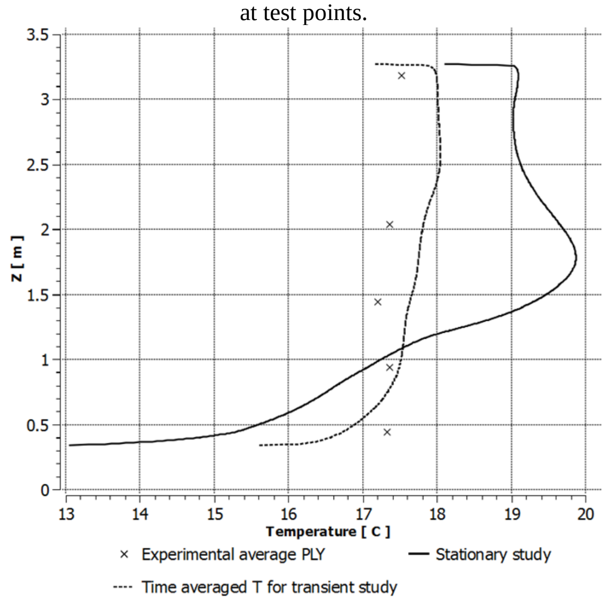

Fig. 19. Vertical temperature distribution.

D. Error estimation

To evaluate the precision of numerical model the overall heat balance is calculated. It is done by (2) and (3) for convective gains/losses and heat flux respectively:

$$P_c = C_p \rho \int_S T\vec{u} d\vec{S} \,, \quad (2)$$

$$P_q = \int_S \vec{q} d\vec{S} \,, \quad (3)$$

where C_p – heat capacity at constant pressure, T – temperature, P_c – power, ρ – density, q – heat flux, P_q – power.

The calculations results and error estimation are given in Table 2, the total error in energy balance is about 5%.

Table 2. Heat balance calculations.

Convective heat gains, W	
Inflow	697
Convective heat losses, W	
Ventilation	-55.6
Feedback	-537
Heat flow losses, W	
Window	-15
Wall	-71.1
Floor	-15.8
Ceiling	-25
Door	-13.1
Total losses, W	-732.5
Error, %	5

IX. CONCLUSION

Long-term monitoring of various physical parameters in 5 different low energy test buildings in Latvian climate show, that:

- Calculated and measured heat transmittance for building structures may vary mainly due to different moisture content. Therefore, heating energy consumption for such buildings differs up to 34%.
- After one year of operation, wet constructions dry out and room's air humidity decreases; it means decreasing in heating energy consumption for the next heating seasons.
- Thermal mass of a building structure is very important factor, which affects increasing of indoor temperature in buildings without cooling systems in summer time.

More information about actual research results in the test buildings is possible to find of project's web site [19].

Mathematical model gives good agreement for simplified case when outside temperature is not changing. To increase precision, overall heat conservation must be introduced for solver.

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