Effect of Solar Radiation on Thermal Performance of External Wall Structures Based on Long-Term Measured Data

Mihkel Kiviste, Ralf Lindberg, Virpi Leivo
Tampere University of Technology, Finland

Abstract

This paper discusses some of the factors affecting the energy consumption of different external wall structures in northern climate. The studies have been conducted at the Department of Civil Engineering at Tampere University of Technology (RTEK/TUT) during the past 16 years. As one of the outputs measured data from 6 test buildings (plus six-year data from additional 2 test buildings) has been built up. The level of detail (520 sensors in each building), amount (after each 20 seconds), long-term (measuring period of six and ten years) and coherency (measured at the same time at the same conditions) makes that data unique in Finland as well as in Europe.

Up to 50% differences were found in the measured and calculated heat losses. Possible reasons for such a discrepancy are described and discussed. It has been focused on the effect of solar gains to thermal performance of massive exterior wall structure. Examples from massive external brick leaf (cladding) of the insulated brick wall are demonstrated. The thermal energy from solar radiation stored in the cladding during daytime warms the air in the ventilation gap and has a great momentary impact on the need to compensate heat losses. Due to the high thermal inertia of the brick leaf temperature of the inner surface of the leaf facing the air gap remains relatively high until early evening. This advantage is not available throughout the year, but its impact is much greater than usually believed.

The knowledge from this study forms the base for the design and construction of sustainable external wall structural solutions. The location of the test buildings is showing a significant impact of solar radiation and thermal inertia to the thermal performance of external wall structures in Tampere, Finland. As the average solar radiation increases towards the south, the effect is expected to be greater in Baltic states.

Keywords: Test buildings, external walls, energy consumption.

Introduction

Research in the field of energy need and efficiency of buildings is very actual, urgent and rapidly developing. A great amount of models and simulations on the energy consumption in buildings have been developed and improved. Some review of the current status in research is provided by the following journal papers. The accuracy of energy analysis and for modern, well-insulated Nordic buildings in Nordic climate has been studied (Kalema et al., 2008). Calculations by seven researchers and by seven different calculation programs were compared. Six of these programs were simulation programs (Consolis Energy, IDA-ICE, SciaQPro, TASE, VIP, VTT House model) and one monthly energy balance method (Maxit energy) based on the predecessor of standard EN ISO 13790. The study showed that the differences in input data cause often greater differences in calculation results than the differences between various calculation and simulation methods (Kalema et al., 2008). A Round Robin Test (Tronchin and Fabbri, 2010) was performed to compare, test and validate the several existing typologies of building energy simulation tools, provided that the same data input and typology of calculation model are given. The Round Robin Test included all modern energy calculation methods. The results of test show the relationship between thoroughness of data input and energy evaluation accuracy. The more the input data is affected by uncertainty, the less precise is the energy efficiency calculation (Tronchin and Fabbri, 2010). Therefore, previous research has shown that inaccurate input data leads to inaccurate results in calculation of energy consumption of buildings. Guan (2009) has been concluding that since all building simulation programs require hourly meteorological input data for their thermal comfort and energy evaluations, the provision of suitable weather data becomes critical.

Therefore, the aim of the following experimental study is to solve an urgent scientific demand for: a) accurate measured data and b) appropriate input for building energy simulation programs.

The Department of Civil engineering at Tampere University of Technology (RTEK/TUT) has gathered ten-year (Sept. 1997 – Aug. 2007) long measured data from six test buildings. Six-year (Apr. 2001 – Aug. 2007) data from additional two test buildings is also available. The data was collected from identical-sized test buildings, having different commonly used exterior wall structures in Finland. A computer system (data logger) was used to monitor, check, calculate, integrate, and save the data acquired from approximately 520 sensors in each building were applied in data recording. Measurements were taken with a time interval of 20 seconds. The 20 second values were then integrated over a time interval of 30 minutes and the minimum, maximum, and mean values were subsequently stored to a computer database.

Six test buildings were constructed in a moderately exposed parking area within the compound of Tampere University of Technology (Fig. 1). Later on two more test buildings were constructed. Test buildings shield one another from the outdoor winds. The surrounding of the test buildings can be considered mostly as rural.

The external walls of the test buildings were constructed of different building materials that include: polyurethane insulated wooden frame wall (T-B 1), insulated cavity brick wall (T-B 2), insulated log wall (T-B 3), plastered massive brick wall (T-B 4), autoclaved aerated concrete (AAC) block wall (T-B 5), and log wall (T-B 6). The ceilings and floors of all the test buildings were composed of two layers of foamed polyurethane elements with an overall thickness of 200 mm. External doors were installed within the eastern wall and the test buildings had no windows. The floor area of each test building was 2.4 m × 2.4 m and the free floor to ceiling height was 2.6 m. Fig. 2 shows the details (section) of the external wall structures of the test buildings.

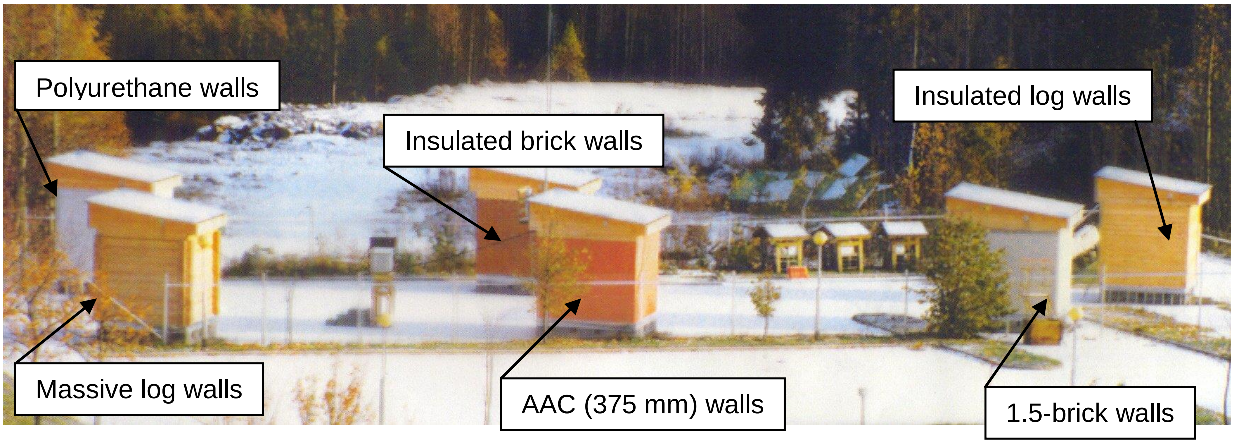

Figure 1. **Test buildings at RTEK/TUT**

All the test buildings are heated with a 1500 W electric radiator (1248 mm × 400 mm heat panel) except for the massive brick wall test building, which is heated by two 1200 W electric radiators (1008 mm × 400 mm heat panels). During the heating season the indoor air temperature inside the test buildings was constantly maintained at 20 °C. Test buildings number 1, 3, and 5 were ventilated by balanced mechanical ventilation systems with heat recovery. Test buildings number 2, 4, and 6 were ventilated by exhaust mechanical ventilation system. The air change rate in all the test buildings was 0.5 h^{-1}. For occupancy simulation, (2 g/m^3) moisture content was constantly added to the indoor air. The additional moisture content was provided by continuously heating water that was kept into plastic containers inside each test building.

A weather observation station was constructed at the test buildings' site that measures the outdoors temperatures, wind speed, and direction, and the relative humidity of the air. The intensity of solar radiation was also measured on-site by a pyranometer (solar meter) that was fixed on the eaves level of test building number 5. The pyranometer measures the global solar radiation to the building surface, which is composed of the direct, and the diffused solar radiation. Wind speed and direction were measured 10 m high from the ground using an anemometer that was fixed to a steel mast at the test building number 5. A three-cup anemometer was used to measure the wind speed whilst a wind streamer monitored the wind direction.

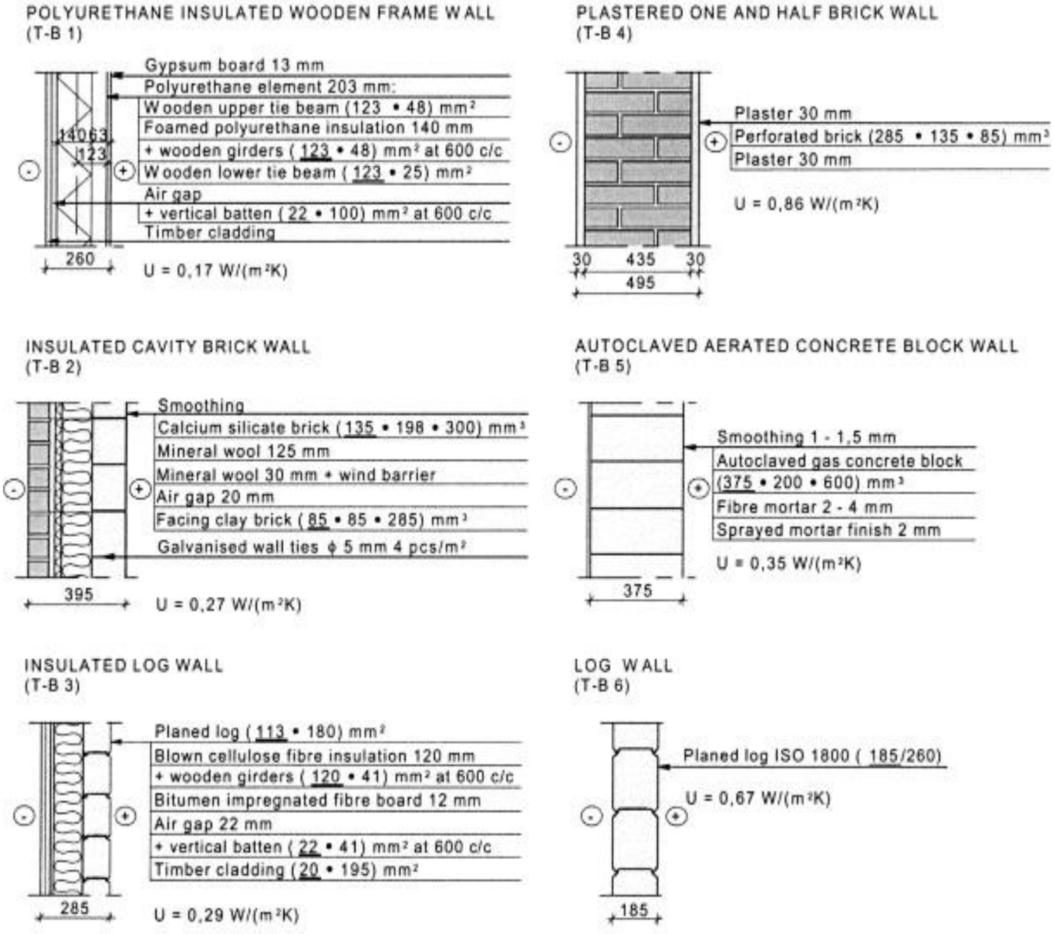

Figure 2. **Details of the external wall structures of the test buildings**

In addition, temperatures inside the wall structures were monitored at different depths in order to determine the temperature distribution in the walls. Airflow rates and temperatures of the supply and exhaust air were continuously monitored. The temperatures were measured with calibrated semiconductor sensors and copper–constantan thermocouples. The indoor relative humidity was monitored with two humidity sensors. The number of semiconductor sensors and thermocouples were about 350 and 170, respectively.

Multiplexers were used to collect the data from the sensors so that readings from each channel were recorded to a computer after every 20 s. Analog-to-Digital and Digital-to-Analog (ADDA) cards were used for data collection and conversion. The minimum, maximum, and average values from the 20 s measured values were saved to a computer hard disc after every 30 min. The relative humidity inside the wall structures of the northern and southern facades were measured to determine the moisture content of the wall materials and the rate of drying after construction. The air tightness of the test buildings was measured by pressurization test method at 50 Pa pressure difference while infiltration was measured using tracer gas.

Results and discussion

Through the analyzed period from September 1998 to May 1999 the measured (light blue bars) heat losses through the external walls of test buildings were up to 50% smaller than calculated (light blue + dark red bars; Fig. 3) (Lindberg et al., 1998; Lindberg and Leivo, 2005).

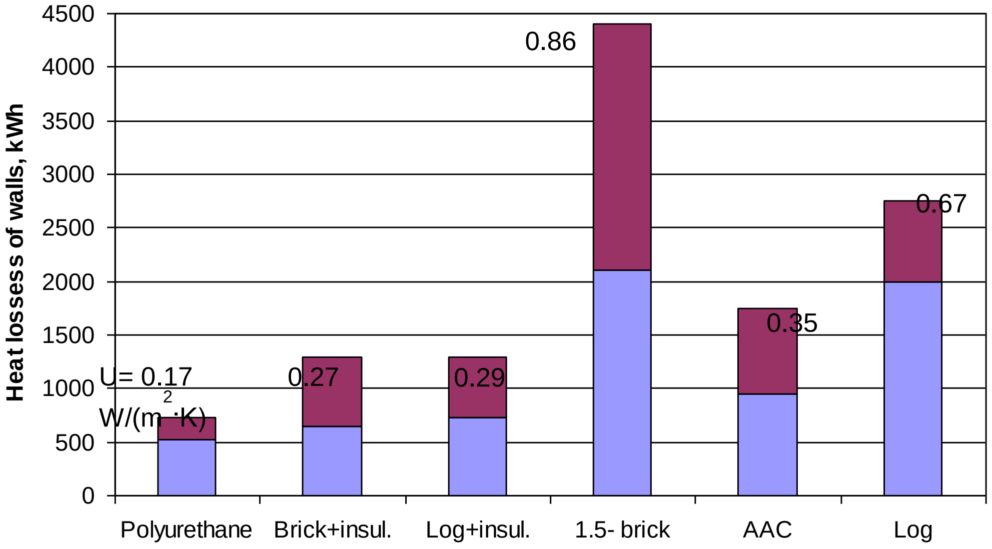

Figure 3. **Measured (light blue bars) and calculated (light blue + dark red bars) heat losses of the walls of test buildings at TUT from Sept. 1998 to May 1999** (Lindberg et al., 1998)

There are three main reasons for the difference between measured and calculated energy consumption: (1) the material properties from which the U-values are calculated, (2) the areas of the walls, and (3) the solar radiation energy stored in the external part of the exterior walls (Lindberg and Leivo, 2005; Lindberg et al., 2008).

(1) The U-values are calculated from the thermal conductivity (λ) values of the materials. The design thermal conductivity values can be obtained from declared values, measured values or (in the absence of before mentioned) tabulated values (EN ISO 10456:2007). Measured thermal conductivities of materials form a distribution as all other material properties. For the calculation of a U-value, a design thermal conductivity λ value at the upper end of the distribution is chosen. It is clear that when the aim is actual energy consumption, the real thermal conductivity of materials should be used. The difference between the average thermal conductivity and the thermal conductivity value used to calculate the U-value is quite large with some of the thermal insulation materials used.

(2) The amount of heat energy lost through an exterior wall is linearly dependent on the wall area. In the exterior wall of a building, the area can be based on internal or external dimensions, or some area in between. Differences between the areas are large due to the thickness of the insulation. Traditionally areas based on the external dimensions of insulations have been applied. A principle from the viewpoint of design allows providing sufficient heating power for each room with view to the coldest possible situations. Various calculation models apply the areas based on external dimensions. Analysis of the measurement results shows that actual consumption should be evaluated based on dimensions close to internal dimensions. For instance, the higher energy consumption at an outside corner is reduced by the decreasing temperature difference around the corner area. The internal section of the corner has a lower temperature than inside air while the external sections have a higher temperature than the outside air. This smaller temperature difference thereby reduces energy consumption (Lindberg et al., 2008).

(3) A key factor is the effect of the solar gains of the massive exterior wall structure in saving heating energy. In principle the effect can be found from Fig. 3 i.e. the ratio between calculated and measured heat losses is larger with

massive solid external wall structures (1.5-brick (T-B 4); AAC (T-B 5); log (T-B 6)) and external walls with massive external leaf (brick + insulation (T-B 2)). The effect of solar gains is lost in exterior wall structural solutions, where thin and lightweight material (timber cladding) is applied as an outer leaf (polyurethane T-B 1; log + insulation T-B 3).

Fig. 4 shows the dependency between the outer surface temperature of the external brick leaf of the insulated brick wall (T-B 2) and the measured solar radiation at the site during late February 2005. Correlation between the measured solar irradiance at the site and the measured surface temperature of the brickwork is evident. Fig. 4 also illustrates that the effect of solar radiation to outer surface of the structure is much stronger than to ambient outdoor temperature. The average ambient outdoor temperature during the period was $T_{out,ave}$ = -9.3°C, and the average surface temperature during the same period was $T_{surf,ave}$ = -5.2°C, which is 44 % less than the outdoor temperature (Lindberg et al., 2012).

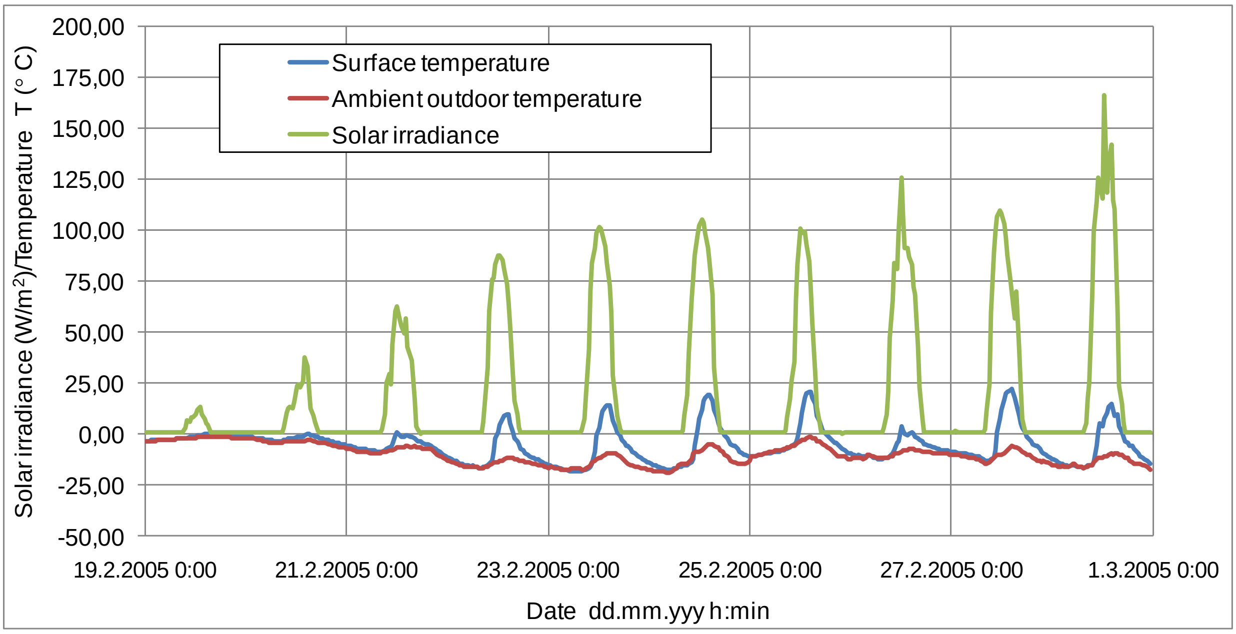

Figure 4. **Measured solar irradiation at the site, the ambient outdoor temperature and the measured outer surface temperature of brick leaf in late February 2005** (Lindberg et al., 2012)

Figure 5 shows the measured temperature distribution inside the wall structure during a 24-h period on 27 February 2005. The maximum measured outdoor temperature of the day was $T_{out,max}$ = -6.4 °C at 15:02 (Figure 4). Meanwhile, the measured surface temperature of the outer brick leaf was $T_{surf,out}$ = + 17.9 °C (at 15:02, Figure 4) and the temperature of the inner surface of the brick leaf $T_{surf,in}$ = +14.7 °C. Temperature difference between the ambient air and inner brick surface was ΔT = 21.1 °C. This temperature difference has a significant effect on the actual heat loss through the insulation layer, as shown in measured temperature distribution curves (Fig. 4).

Due to the high thermal inertia of the brick leaf temperature of the inner surface of the leaf facing the air gap remains relatively high until early evening though the outer surface temperature of the leaf had already decreased significantly. At 21:00, the measured ambient outdoor temperature was T_{out} = -13.1 °C, temperature of the outer surface of the brick leaf $T_{surf,out}$ = -7.5 °C and the measured temperature of the inner surface of the leaf $T_{surf,in}$ = -3.6 °C. The difference between the surface facing the air gap and the ambient air was still ΔT = 9.5 °C.

The ventilation gap air is generally assumed to be of the same temperature as outdoor air and, therefore, the external leaf (cladding) is ignored in the calculations. Previous examples are showing that this assumption is wrong with external wall structures with massive outer leaf due to its thermal inertia. The thermal energy from solar radiation stored in the cladding during daytime warms the air in the ventilation gap and has a great momentary impact on the need to compensate heat losses. This advantage is not available throughout the year (not during the time period from November to January), but its impact is much greater than usually believed.

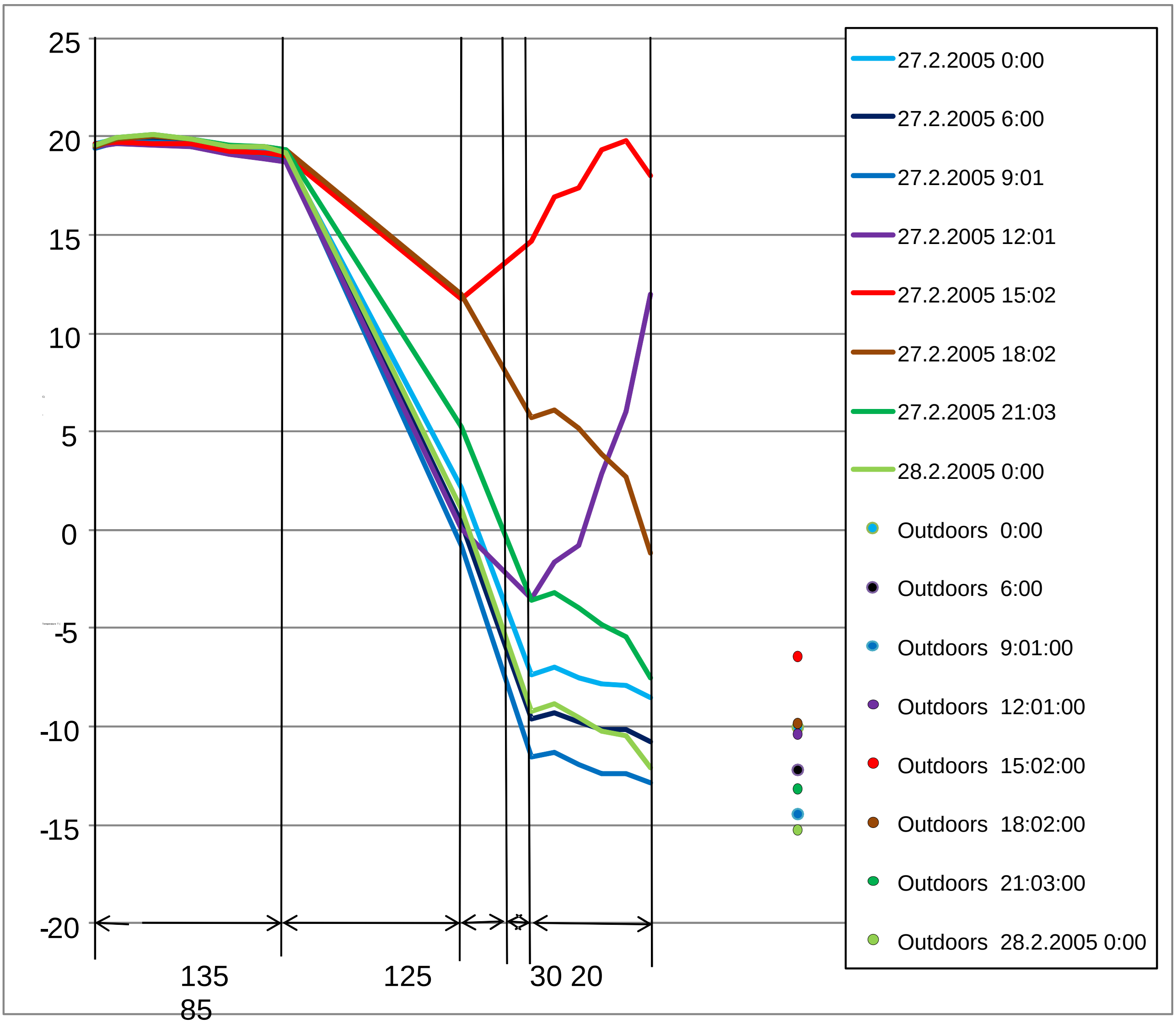

Figure 5. **Measured temperature distribution across the wall during 24 hrs period in late February 200**5 (Lindberg et al., 2012)

Fig. 4 and 5 have shown that the outer surface temperature of the walls is much different from outdoor air temperatures during sunny days. That difference could be significant in any sunny day from late February until September. In that sense, outer surface temperature is much more accurate input for the building energy simulation. Applying outer surface temperature would result in much more accurate calculations of building energy consumption.

The knowledge from this study forms the base for the design and construction of sustainable external wall structural solutions. The principles also apply for roof structures to which the effect of the solar radiation is even greater. In this respect as an innovation, efforts should be made for applying phase-changing materials (PCM) in light-weigth structures of buildings (e.g. wooden frame walls). PCMs, which by melting and solidifying at a certain temperature, are capable of storing and releasing large amounts of energy. Heat is absorbed or released when the material changes from solid to liquid and vice versa.

The northern location (latitude 61°25´N) of the site of test buildings shows that the solar radiation and the thermal inertia of the different structural sections of an external wall have a significant effect on the actual heat loss and energy consumption. As the average solar radiation increases towards the south, the effect of solar radiation on building structures is expected to be greater in Baltic states. For the time being much of the gathered data is still under-utilized. Further analysis on the long-term hygrothermal behavior of different external wall structures is still needed.

Conclusions

The Department of Civil Engineering at Tampere University of Technology (RTEK/TUT) has gathered ten-year measured data from 6 test buildings (plus six-year data from additional 2 test buildings).. The level of detail (520 sensors in each building), amount (after each 20 seconds), long-term (measuring period of six and ten years) and coherency (measured at the same time at the same conditions) makes that data unique in Finland as well as in Europe.

The analysis of the results have been revealed up to 50% difference between measured and calculated heat losses. Three main reasons for the difference were found: (1) the material properties from which the U-values are calculated, (2) the areas of the walls, and (3) the solar radiation energy stored in the external part of the exterior walls. Examples from massive external brick leaf (cladding) of the insulated brick wall are demonstrated. The thermal energy from solar radiation stored in the cladding during daytime warms the air in the ventilation gap and has a great momentary impact on the need to compensate heat losses. Due to the high thermal inertia of the brick leaf temperature of the inner surface of the leaf facing the air gap remains relatively high until early evening. That difference could be significant in any sunny day from late February until September. Due to the same effect the outer surface temperature is much higher than outdoor air temperature. Therefore, outer surface temperature could be much more appropriate input in order to increase the accuracy of calculations of building energy consumption.

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Mihkel KIVISTE. Postdoctoral researcher, PhD (Civil Engineering), Tampere University of Technology, Structural Engineering, P.O. Box 600, FI-33101 Tampere, Finland, mihkel.kiviste@tut.fi, tel. +358 41 7740803, fax. +358 3 3115 2811. Interests of fields of research: concrete structures, building physics, buildings and energy. Working previously as a lecturer in Estonian University of Life Sciences, Tartu, Estonia.

Ralf LINDBERG. Professor, Dr. Tech. (Civil Engineering), Tampere University of Technology, Structural Engineering, P.O. Box 600, FIN-33101 Tampere, Finland, ralf.lindberg@tut.fi, tel. +358 40 566 5151, fax. +358 3 3115 2811. Interests of fields of research: concrete structures, building physics, buildings and energy.

Virpi LEIVO. Research Scientist, M.Sc.(Civil Engineering), Tampere University of Technology, Structural Engineering, P.O. Box 600, FIN-33101 Tampere, Finland, virpi.leivo@tut.fi, tel. +358 40 1981961, fax. +358 3 3115 2811, Main research area: building physics, buildings and energy.