Long-term monitoring of the thermal insulation properties of building envelope structures in real climatic conditions

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Abstract. The analysis and non-stationary numerical calculations of in situ temperature measurements are important details with regard to the connection between a window and a window sill. Due to its material and geometric heterogeneity, this connection is significant in terms of both surface temperature and heat flux. The structure under investigation is a panel fragment of the outer shell of an experimental chamber for in situ measurements. The aim of this paper is to compare the temperature obtained both from measurements and numerical calculation. Simulation and experimental measurement obtained in different environments, such as indoor and outdoor climates or experimental chambers, is an effective scientific tool for predicting the physical properties of building envelopes.

1. Introduction

Outdoor test cells and laboratory climate chambers are appropriate instruments for the long-term in situ monitoring of physical parameters of building envelopes and indoor climate parameters. Monitoring of the full-scale structures in non-stationary boundary conditions is a current trend in building physics research [1]. Outdoor on-site test cells are appropriate for energy and hygrothermal assessment of structures, due to their controlled indoor environment. Such cells have been applied in Dübendorf, Glasgow, Cottbus, Limelette, Almeria, Espoo, Delft etc., since 1993 [2, 3]. Outdoor test cells are a reasonable compromise between laboratory testing and full-scale building testing [3].

Results of panel research of an experimental wall structure with a window are presented in this paper [4]. Devices of the type of experimental internal and external chambers with adjustable environments (examples of which are presented in previous papers [5, 6, 7, 8]) are suitable for the comparison of experimentally obtained values with results of numerical calculations [9]. Validation of the simulation is a valuable tool for monitoring the accuracy of numerical calculations.

Thermal comfort and emission efficiency are important factors when choosing heat emission systems in low-energy buildings [10]. Outdoor test cells have also proved useful for laboratory measurements performed in Tallinn, Estonia [11].

Other institutes have full-scale outdoor laboratories, rather than simply cells, for improving research at the level of entire buildings. They mostly focus on green architecture, green roofs, wooden lightweight envelopes, etc. In Zilina, Slovakia, the full-scale monitoring of different kind of building construction, especially wooden constructions has been performed [12].

Surface temperature monitoring is not only useful for the thermal analysis of buildings and direct or indirect implementation in virtual simulations but it is equally relevant for use in the field of building physics. The measuring of surface temperatures on the building envelopes by means of commercial temperature sensors are typically applied for the field of thermal building performance aspects [13]. AdMaS (The Advanced Materials, Structures and Technologies Centre of Brno University of Technology) conducts long-term experiments under real climatic conditions. Similarly, The University Centre of Energy Efficient Building, Czech University of Technology, Prague (UCEEB) conducts long-term monitoring [14]. The main objective of the centre is the development of technologies for the reduction of energy demand and the efficient improvement of natural energy sources with regard to new constructions and reconstructions of existing buildings. This objective is achieved by a holistic approach – expert knowledge from the fields of architecture, construction, mechanical engineering, information technology, and hygiene of indoor environment and the advanced scientific equipment of the centre [14]. Another important aspect concerning building physics is summer overheating. Once again, full-scale monitoring facilities could be useful as an advanced tool for the passive cooling of green buildings [15].

The objective of this paper is to assess the accuracy of the numerical model and the justification of using the temperature field model without considering the transport of moisture. This model can be numerically modified after validation to optimise the window attachment solution.

2. Experimental chambers, monitoring cells, experimental methodology

This paper investigates the measurement and numerical calculation of the temperature values from the winter period of February 2015. The temperature at two locations and the surface temperature in the window aperture are analysed as shown in figure 1. The task was to compare the temperature results in the constructions obtained from experimental measurements with numerical calculations in order to validate the simulation model.

The assessed structure is a section of the external experimental chamber for in situ physical measurements, which is part of a laboratory of the Faculty of Civil Engineering of the Technical University in Košice. The composition of the structure is shown in table 1 and figure. 2. The structural heat transfer coefficient is U = 0.12 W/m^{2}K. The windows are made of a composite plastic material (U$_f$ = 0.9 W/m^2·K) with a 3-fold closed glass system 4-16-4-16-4 Ar (U$_g$ = 0.5 W/m^2·K). The values of the heat transfer coefficient are determined through calculation.

Figure 1. Southern view of monitoring chambers in the laboratory (cells → no. 3,2,1)

In this investigation, we measured values of the temperature in the window opening at the sill site. At the same time, the following parameters of the outdoor and indoor environment were monitored: air temperature, relative humidity, wind and precipitation parameters, solar radiation. The non-stationary numerical calculation of the surface temperature field was realised for part of the porous brickwork made of porous concrete. The subject of the calculation was the temperature results for the sites considered in the construction (see Fig. 2). Heat dissipation over time (for homogeneous and isotropic

constructs) describes the Fourier partial differential heat conduction equation. For the numerical experiment, the Physibel simulation tool, BISTRA module, was used. The non-stationary simulation was based on the Crank-Nicolson's Finite Difference Method. This method meets the criteria of STN EN ISO 10211, Annex A for numerical computational methods.

Table 1. External wall

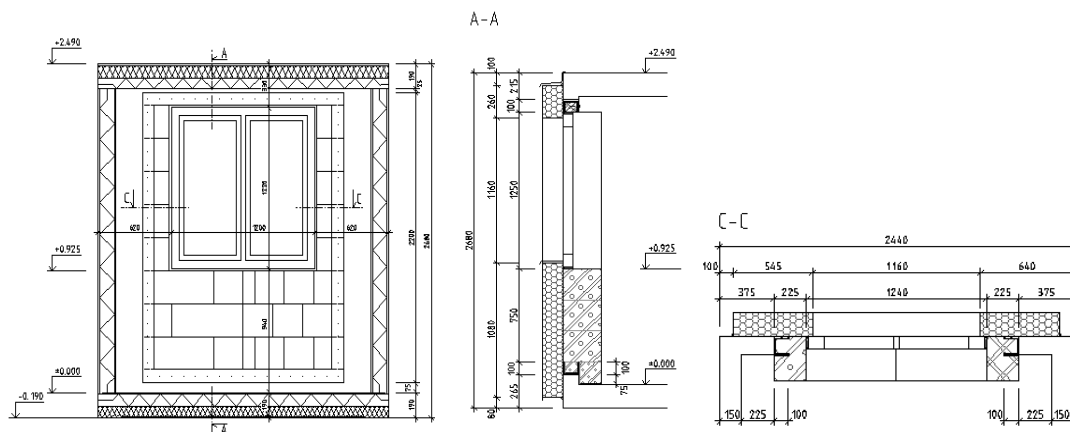| Name of test wall layer	c (J/kg.K)	λ (W/m.K)	ρ (kg/m3)	d(m)
1 – AAC P2 – 350	900.0	0.104	350.0	0.300
2 – adhesive PUR foam	800.0	0.040	35.0	0.010
3 – graphite extrude polystyrene	920.0	0.033	16.0	0.170
4 – adhesive mortar	900.0	0.850	1300.0	0.002
5 – primer	-	-	-	-
6 – silicone plaster	900.0	0.700	1700.0	0.002

Figure 2. View and cut planes, cross section and floor plan of the contact between the wall with and window in the chamber

3. Boundary conditions of the experiment in the test cells

In the selected period, outdoor air temperatures were recorded between -6.5°C and +11°C. Solar radiation also changed from 100 W/m² to 500 W/m². In chamber 1 (south orientation) the average indoor air temperature was 22.7°C (figure. 3).
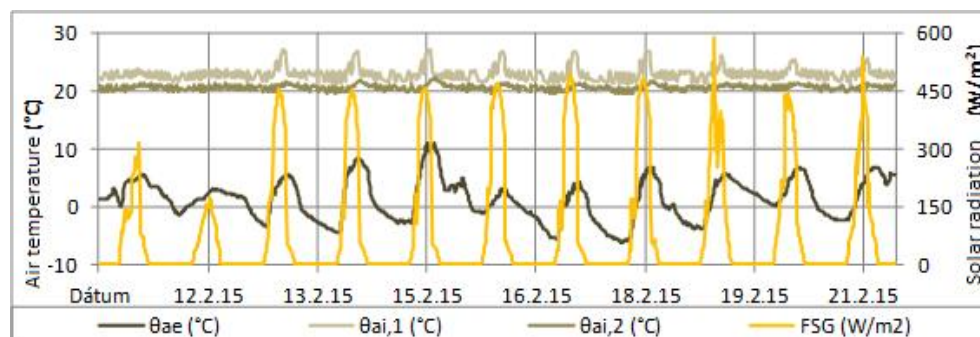

Figure 3. Measured outside and inside boundary conditions measured in February 2015

The temperature of the inside air (20°C) and the temperature of the ambient air (-13°C) are taken as the standard values for the inside and ambient temperatures. Almost identical results to chamber 1 were identified for A2/7 and A2/5 (see figure 4). Values were significantly different in the morning or when

the daily temperature reached the extreme values. Generally, the largest differences between the measured and calculated values occurred on days with a higher intensity of solar radiation.

4. Results and discussion

A ten-day period in February 2015 (11/02/2015 – 21/02/2015) was chosen for the further analysis. This winter season was selected in order to examine a fulfilment of the requirements for the minimum inside surface temperature during the heating season. Hourly measured values of ambient air temperature of Kosice in February 2015 were used. The temperatures measured in the experimental chamber during the monitored period were used as the inside temperature boundary condition. The average inside air temperature of chamber 2 (north orientation) was 20.6°C and for chamber 1 (south orientation), it was 22.7°C (Fig. 3).

The progression of the calculated and measured temperature values over a given period of time for the points considered (inner surface, A2/15 and A2/11) are shown in figures 4 and 5.
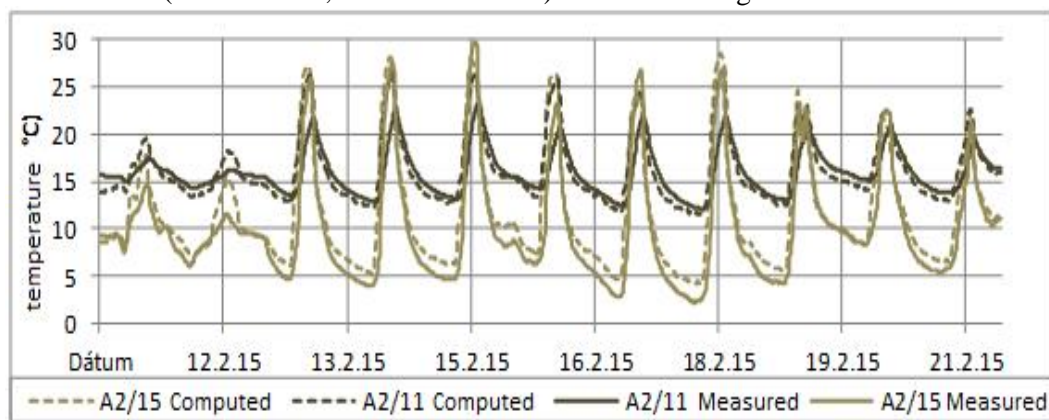
Figure 4. Measured and computed results for monitoring chamber 1 in 02/2015

Chamber 2 is orientated to the north – the effect of direct solar radiation is excluded. For A2/5, the largest difference between the measured (11.39°C) and the calculated (12.34°C) temperatures amounted to 0.95 K; this occurred on 15/02/2015 at 12:00. For A2/7, the largest difference between the measured (-1.15°C) and the calculated (2.22°C) temperatures amounted to 3.37 K; this occurred on 18/02/2015 at 00:48 (see figure 5).
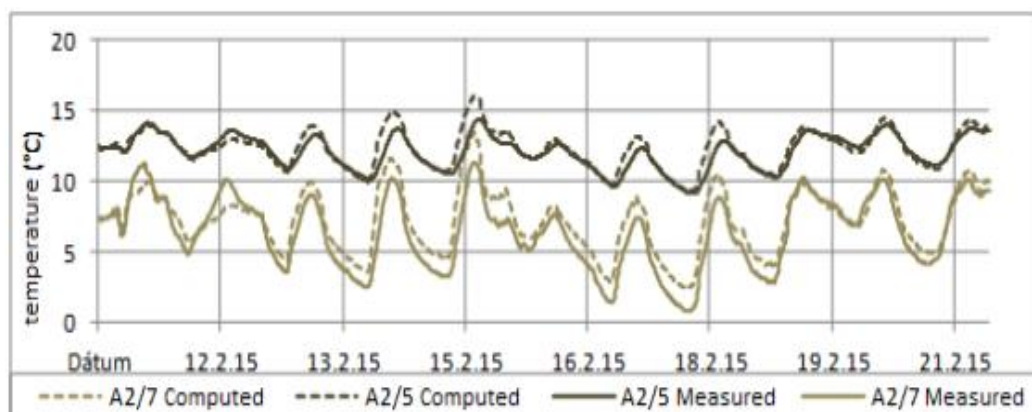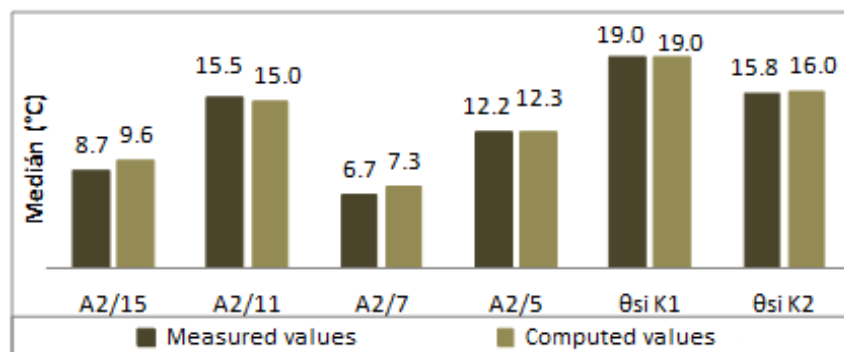
Figure 5. Measured and computed results for monitoring chamber 2 in 02/2015

The process see above note of the calculated and measured internal surface temperature shows a high consistency (figures 4 and 5). The mean internal surface temperature over eleven days is 19.33°C when obtained through calculations and is 19.31°C according to measurements. The greatest differences

between the measured and calculated temperatures for A2/11 and also A2/15 are recorded at the time with the highest solar radiation. Values are significantly different in the morning and when there are daytime temperature extremes, i.e. daily minimum and maximum air temperatures (figure 4). The differences between the measured and the calculated values are caused by the neglect of several factors that affect the heat dissipation in the building structure. A simulation tool is used that analyses the temperature field without interfering with the effects of air and moisture transmission on heat dissipation, the effects of moisture content on thermal conductivity and the thermal capacity of the building material. Thus, it is shown that it is not possible to accurately describe temperature changes in the construction in this way. By using a complex simulation tool and including a correct starting humidity condition, a better match of calculated and measured values can be achieved.

The highest deviations (0.6 K) between these values are at point A2/7, unexpectedly, these values occurred in the same chamber. Variations of values in chamber 1 are from 0.9 K (A2/15) to 0.5 K (A2/11). As expected due to its orientation, we identified the highest compliance in chamber 2. The mean of median differences is 0.6 K, while in chamber 1, it is 0.75 K. Detailed analysis provides a comparison of medians and average values of measured and calculated temperature in the points (figure 6).

Figures 6. Measured results and comparison of medians and averages see above note of computed and measured values in the points A2/15, A2/11, A2/5 and A2/7

In the averages and medians see above note it can be seen that in both there are very similar differences in the compared values. The best match (difference of 0.1 K) of the measured and calculated values is at point A2/5 (chamber 2).

5. Evaluation of thermal instability of chosen detail

Data for hourly weather changes in Kosice was used for further analysis. This data concerns the measured outdoor air temperature and the measured intensity of global and diffused solar radiation during the month of February 2015.

The calculation was performed for three external environments:

I. constant outside temperature for Kosice, θ_e = -13.0°C

II. measured outside air temperature in Kosice without the influence of solar radiation

III. measured outside air temperature in Kosice including the influence of solar radiation

For the purposes of simplification, the internal air temperature was assumed to be 20.0°C. The temperature was constant as the experimental chamber has a quasi-stationary environment. The temperature was maintained at θ_i = 20.0°C and had a relative humidity of 50%. The boundary conditions of the analysis that were entered into the calculation of the temperature fields are shown in figure 3.

The calculation was performed using the Physibel simulation program. Three methods were selected:

1 - stationary calculation method

2 - non-stationary calculation method without the influence of the sun

3 - non-stationary calculation method with the influence of the sun

Use of the above methods allows a comparison of the results of the surface temperature values of the structure obtained by calculation for the individual states of the different conditions. The sun has a significant influence on the interior surface temperature of the structure. The largest difference between the stationary calculation and the dynamic calculation, taking into account the influence of the sun, is the value of 3.15 °C. This difference suggests the possibility of optimising the thickness of the thermal insulation system with favourable economic results. Therefore, a progressive solution for calculating the parameters of constructions is important in addition to being scientific and practical. In the paper, the detail of the window sill is solved, as it is in present form in the experimental chamber. Even on the basis of the results presented, it is obvious that if the inner window sill is installed, the surface temperature would change.
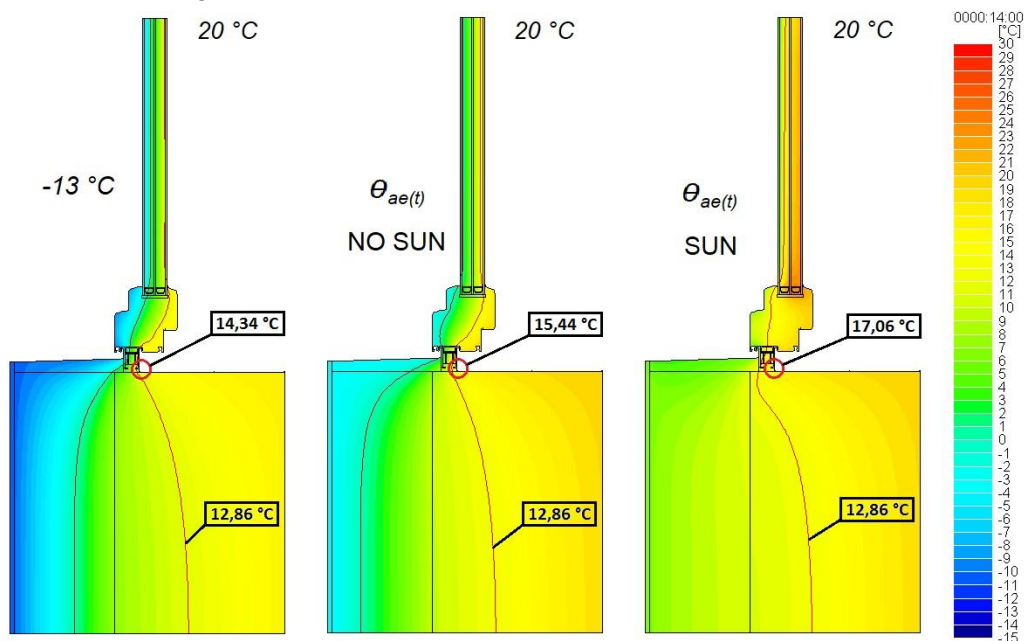

Figure 7. Differences over surface temperature values at the assessed point for individual states

The advantage of experimental chamber is the possibility of verifying the computational results and tuning the model. Validation of the model enables the obtaining of accurate data from simulation programs without the need for further verification. In this way, we can analyse the influence of the way of window profile setting, the impact of the interior sill construction, the influence of the change of the material and the height of the window sill, changes in the thickness of the external sill insulation, and changes to the surface modifications of the outer components of the structure. Thus, the verified model can calculate details of any standard buildings (historic buildings, panel systems, wooden houses) in which it has greater practical importance than it has for nearly zero energy buildings.

6. Conclusion

Validation of the simulation model is the key to solving and predicting the real physical thermal-humidity behaviour of building elements, details, building structures and their environment. Comparison of the results of calculations and measurements confirms the accuracy of the simulation model, given the consistency of the measured and calculated data. If we do not consider sunlight in such cases, we would not obtain comparable results for the south-facing wall. However, differences persist and are mainly due to the material properties, the geometric precision, the initial and boundary conditions used and the consideration of the temperature field without regard to the transport of water and air. An advanced and validated simulation model allows the solving of various types of numerical experiments with defined precision in order to optimise critical building details.

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