Semi-scale experiments for model calibration and verification in water and heat transport in porous media

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Abstract

A semi-scale device is employed for monitoring the drying out process of a building envelope consisting of freshly cast gypsum elements and exterior thermal insulation in the conditions of difference climate. The climatic chamber system includes two climatic chambers connected by a specially developed tunnel for testing large specimens. As for the climatic conditions on the exterior side, the test reference year data for Prague are used. Constant temperature and relative humidity is assumed on the interior side. For monitoring moisture content, the time-domain reflectometry probes are used, for the relative humidity and temperature measurements capacitance sensors are utilized. The measurements are performed for the time period of 92 days. On the basis of the measured data, calibration of the computer code Delphin 4.4.16 is done. The measured values of temperature, relative humidity and moisture content are compared with the calculated data, and a fitting procedure is employed for the identification of model parameters that are not known with a sufficient accuracy. Keywords: semi-scale experiment, hygrothermal performance, computer simulation, multi-layered envelope.

1 Introduction

Determination of hygrothermal performance of building structures belongs to actual topics of building physics. Presently, two basic approaches are applied in
the process of characterization of hygric and thermal performance of building materials themselves as well as their multi-layered systems.

The first possibility is to use a computational analysis combined with laboratory measurements of material parameters. In the process of heat and moisture transport, these parameters include moisture diffusivity, water vapor permeability, sorption isotherms, water retention curves, specific heat capacity and thermal conductivity of the particular materials. The material parameters should be determined in dependence on moisture content and temperature. On the basis of laboratory tests, the necessary input data for the subsequent process of computational analysis of the tested building structure are obtained. The tested building structure is then in a computer experiment loaded by real climatic conditions.

The computer codes used for computational analysis are based on the energy and mass conservation laws and include a system of coupled non-linear transport equations. Using them, it is possible to determine temperature, moisture and water vapor pressure fields in building structures under operation conditions and in long time intervals. However, a serious application of computational analysis presumes calibration and verification of the implemented model, which is not always an easy task, particularly in the case of investigation of a multi-layered structure, where the surface and interface resistances that cannot be directly measured may play a significant role in the process of heat and moisture transport. The further limitation of computational modeling consists in input material parameters, whose entire determination in the whole range of moisture and temperature is not only time consuming but for some types of materials not ever an easy task. The inaccuracies in determined material parameters can then play a very significant role in the final results. Nevertheless, the computational modeling without an exact calibration of the model is often successfully used as a first estimate of hygrothermal function of a studied structure. It finds an application especially in the process of design of new technological solutions or new building materials. Here, the computer codes are helpful in determination of required properties of materials and in giving clear evidence about the performance of designed technological solutions in the estimated conditions of use.

The second way how to describe the hygrothermal behavior of the whole building structure is to measure thermal and hygric parameters in the real climatic conditions using the test house measurements and in-situ measurements. The test house measurements are presently also popular for validation tests of newly developed computer codes for computational analysis of moisture and heat transport in the climatically loaded building envelopes. In the full scale testing of hygrothermal performance of building structures climatically loaded by real conditions, modified laboratory methods for determination of field variables are mostly used. However, an application of in-situ measurements and full test house tests for validation of computer codes of moisture and heat transfer and for investigation of hygrothermal behavior of building structures is accompanied by certain well known problems. The most important of them seem to be the high financial requirements and high time consumption. Other
problems may be found in the accuracy of measured results. For instance, the most often employed resistance method for investigation of moisture content is not very proper for long-term measurements because it is very sensitive to the amount of salts in water. Nevertheless, the field measurements generally give a more reliable information on hygrothermal performance of the whole tested building structure in real climatic conditions than computational analysis without an exact calibration. Therefore, monitoring temperature and moisture fields on building sites will certainly always remain the final and decisive stage of testing the performance of building envelopes. However, it should really be considered as the final step, when all principal problems are already resolved and the risk of failure is minimal.

In this work, a relatively new approach to assess the hygrothermal performance of building structures is presented. The basic element of this approach is a semi-scale experiment designed in [1] and filling the gap between the laboratory measurements of hygrothermal properties and full-scale test house measurements of field variables of heat and moisture transport. This experiment is utilized as a critical experiment for the calibration and verification of the chosen computational model.

2 Semi-scale experiment – principles and devices

A semi-scale measuring and simulating system for monitoring temperature and moisture fields was designed in such a way that it simulates conditions, which are as close as possible to the real conditions on building site. However, at the same time, it still maintains its laboratory character. So, the expenses can be kept considerably lower compared to a real test house. Concerning the basic arrangement of the experiment, a system of two climatic chambers imposes conditions of difference climate on a sample of building envelope with a real thickness of all its components which is placed into a connecting tunnel.

As temperature and moisture content are certainly considered as principal quantities from the point of view of hygrothermal performance of a building envelope, the measuring system allows for the point-wise determination of temperature and water content. For a validation and calibration of advanced mathematical models of heat, moisture and salt transport, the knowledge of temperature and moisture fields only may not be sufficient. Therefore, the semi-scale system enables monitoring of relative humidity, capillary pressure, heat flux and salinity as well. More details on the system description can be found in Pavlík et al [1]. The measuring techniques for determination of the above mentioned field variables present a logical extension of advanced laboratory methods to the semi-scale conditions, so that for instance field probes instead of laboratory probes are employed.

In the experiment presented in this paper, the values of temperature, moisture content and relative humidity were monitored. For measuring moisture content, specific devices developed by Easy Test and Polish Academy of Sciences and working on the basis of time-domain reflectometry method have been used [2]. Two-needle sensors (see Fig. 1) designed by Malicki and
Skierucha [3] with an accuracy of dielectric constant reading of ± 2% were switched to cable tester LOM/RS/6/mps with sin²-like needle pulse having risetime of about 200 ps.

![Figure 1: TDR moisture sensor.](image1)
![Figure 2: Ahlborn humidity/temperature sensor.](image2)

For the determination of relative humidity and temperature in the porous space, we employed the ALMEMO measuring system manufactured by Ahlborn. Input ALMEMO connectors are equipped with the EEPROM memory, in which the sensors parameters like the measuring range, linearization of the signal, values of corrections, power supply of sensor and other sensor parameters are saved. These connectors make possible to connect the probes and sensors to ALMEMO central 5590-2 system. The combined capacitance relative humidity and resistance temperature sensors (see Fig. 2) are applicable in the range of humidities of 5-98% with an accuracy of ±2 %, temperature sensors have an accuracy of ± 0.4°C in the temperature range from –20 °C to 0 °C and ± 0.1 °C in the range from 0 °C to 70 °C.

3 Experimental

The studied building envelope consisted from the interior towards the exterior of freshly cast (14 days old) calcined gypsum wall 200 mm thick, gluing material FSP developed by Sakret Ltd. 2-3 mm thick, 80 mm thick thermal insulating mineral wool board Fasrock, Rockwool SA, and the exterior FSP plaster 3 mm thick, which was reinforced by plastic net.

The measuring procedure was divided into several steps: sensors calibration, sample preparation and sensor placing, insulation of the sample in the connecting tunnel, connecting of the climatic chamber system and starting the experiment.

In our measurements we employed probes for the determination of moisture, temperature, and relative humidity, as described above. The TDR sensors measure the properties of the particular porous material itself, so they must be calibrated for each measured material. The calibration consists in a comparison of measured moisture content with a reference method. The specimens of materials involved in the investigated building envelope were dried first in
vacuum drier at the temperature of 50°C, and then moistened to the predetermined moisture content. We employed the gravimetric method as reference method, which is the most often used method for determination of moisture content at present. Simultaneously, we measured apparent value of complex relative permittivity by TDR method. Comparing the results obtained by the two methods, we arrived at the desired calibration curve. As the sensors for monitoring temperature and relative humidity are calibrated by the producer, we have only occasionally verified their functionality using salt solutions with specific relative humidities and temperature resistance thermometer by another producer.

The sensors were placed into the before bored holes and the upper parts of the hole openings were closed by silicon sealing. The probes for monitoring moisture content measure properties of moist material. Therefore, it was necessary to fill up back the bored holes by the gypsum powder and to provide the sensor steel needles with an electrically conducting gel surface layer to achieve a good contact between the measured material and the sensor and to avoid formation of an air gap. The positioning of the sensors was chosen in such a way that measured moisture and temperature fields in the studied structure could be conveniently used for the computer codes verification and calibration.

In the installation of the specimen into the connecting tunnel, its thermal and hygric insulation from the tunnel walls had to be performed in order to achieve one-dimensional heat and moisture transport in the envelope. For that reason, the specimens were insulated using extruded polystyrene boards in combination with mineral wool, the front sides of the insulation were covered by polyurethane foam. The preparation of the specimen, placing of the sensors and experiment arrangement are illustrated in Figs. 3-5.

Figure 3: Sensors positioning.  Figure 4: Insulated specimen in the tunnel.

The measurements were performed continuously for 92 days. The climatic conditions on the exterior surface of the wall were chosen according to the climatic data for the test reference year for Prague provided by Czech Meteorological Institute on hourly basis. The measurements began with the
climatic data for June 1 and were stopped with the climatic data corresponding to September 1. On the interior side, constant temperature and relative humidity conditions (21°C, 50%) typical for residential houses according to Czech standards were simulated.

Figure 5: Connected climatic chamber system.

4 Computational modeling

The semi-scale experiment described in the previous Section was simulated using the computer code Delphin 4.4.16, developed by J. Grunewald [4] at the Institute of Building Climatology of the Technical University of Dresden. In the computer implementation of the analyzed experimental situation, the computer generated mesh was adjusted to the positions of the sensors in the measured envelope so that the same data could be obtained both in the experiment and in the calculations, see Fig. 6.

The climatic loading of the studied structure was in the computational analysis the same as in the semi-scale experiment. The data for temperature and relative humidity which were measured in the exterior chamber during the experiment were used to avoid possible problems with inertial effects in setting the temperature and relative humidity conditions in the chamber. Although the climatic conditions in the climatic chambers did not meet perfectly the input data from the real test reference year in all the time intervals, particularly when the climatic conditions were changed too rapidly, the performed experiment as well as the computational analysis provided a sufficiently accurate view of the hygrothermal performance of the tested structure.

The input material parameters determined in the dependence on moisture content were taken from [5, 6]. The initial conditions for calculations were chosen as data measured in semi-scale experiment at the time t = 0.
On the basis of a comparison of measured and calculated data, the fitting process was started, because relatively large differences between the corresponding data sets were observed. In the fitting procedure, the following exterior and interior surface transport coefficients, driving the moisture and heat transport between the climatic chambers and the sample, were identified as giving the best agreement between the experimental and computational data: the interior heat surface transport coefficient 8 W/m²K, exterior heat surface transport coefficient 25 W/m²K, interior water vapor transport coefficient 3.0E-10 s/m and exterior water vapor transport coefficient 1.84E-10 s/m. Also, the water vapor diffusion resistance at the interface between the gypsum wall and the mineral wool insulation appeared as important, its optimal value was found to be 5.5E9 m/s.

5 Results and discussion

Figs. 7-9 show selected characteristic temperature, relative humidity and moisture content profiles determined both in the semi-scale experiment and in the computational simulations.

From the hygrothermal performance point of view, we can see that at the beginning of the experiment, the overhygroscopic moisture was observed in the whole tested structure which was a consequence of the initial high moisture content in freshly cast gypsum. Due to the applied climatic conditions, the tested structure was drying out during the whole studied time period.

After three months, no overhygroscopic moisture was observed in the gypsum wall. The seemingly high volumetric moisture content of 17% in gypsum observed in Fig. 9 does not mean any presence of liquid water in the material but hygroscopic water adsorbed in the porous system. This is in a good agreement with the measured desorption isotherm of gypsum in [5] showing a very high hygroscopicity of the material.
The relatively long time necessary to dry out the envelope even in the warmest part of the year is a finding which is important particularly for the supposed future application of gypsum-based materials in building envelopes. It is apparent that gypsum elements should not be applied in an envelope before previous drying.
Comparing the experimentally measured and calculated temperature, relative humidity and volumetric moisture profiles in Figs. 7-9, we can see that the agreement was reasonably good, particularly taking into account the long time used in the analysis, the high number of profiles and the input data uncertainty. Therefore, the model can be considered as well calibrated and can be utilized for service life prediction based calculations of the studied system.

6 Conclusions

The application of semi-scale arrangement in a critical experiment for computational model calibration and verification in simulating heat and moisture transport in multi-layered systems of building materials in this paper was found to be a perspective way for future applications. The relatively low cost of the experiment in a combination with the reasonable accuracy of measured temperature, moisture and relative humidity fields in long time intervals makes good prerequisites for a widespread use of the technique.

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References


