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MONITORING THE HYGROTHERMAL REGIME OF THE CHURCH SAINT JAMES IN LEVOČA

Ľudovít Kubičár[1,*], Ján Hudec[1] and Peter Dieška[2]

[1] *Institute of Physics SAS, Dúbravska cesta 9, 84511 Bratislava, Slovakia*
[2] *Institute of Nuclear Science and Physical Engineering, Faculty of Electrical Engineering, STU, Ilkovičová, Bratislava, Slovakia*

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Abstract

A new innovative method of monitoring the hygrothermal regime of buildings is presented. The method is based on measuring the thermal conductivity of porous materials. The thermal conductivity is a function of properties of the matrix and pore content. Air, water vapour, water or ice, can be found in pores depending on the ambient conditions. The impact of the long-term climatic conditions can be monitored by proper placement of sensors into structure of the monument. Then transport of moisture and heat can be investigated and thus the overall energy balance of the building can be determined. The monitoring method is applied to Saint James's Church in Levoča. Two moisture sensors are placed into pillar of the church. Effects of freeze – thaw were found during wither period. Heat flows and moisture transport in the pillar are identified depending on the season.

Keywords: thermal conductivity, porous system, moisture sensor, monitoring, hygrothermal regime

1. Introduction

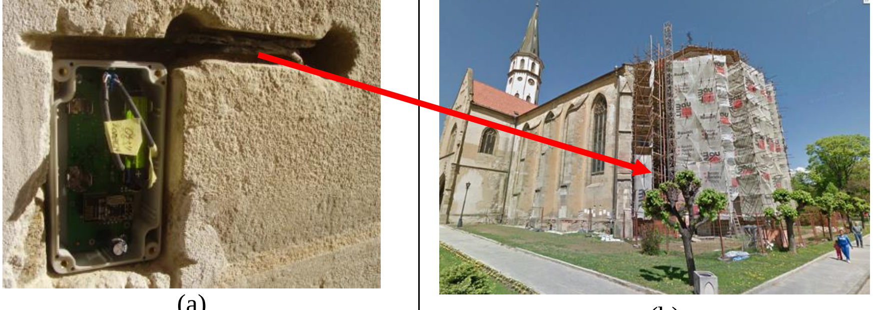
Historical objects consist of components with porous structure. Such structures are attacked by atmospheric humidity, precipitation, wind, solar radiation and groundwater [1]. Moisture can be present in any wall system in three thermodynamic physical states: the solid state (ice), the liquid state, and the vapour state. Hygrothermal behaviour of such system is characterised by the moisture storage function, vapour permeability, liquid conductivity, thermal conductivity, and specific heat capacity. Moisture in the walls has destructive impact which is caused by natural cycles of wetting-drying and freezing-thawing. Any model of the hygrothermal behaviour is based on coupled differential equations for coupled liquid water, water vapour and heat transfer, based on thermodynamical principles. Determination of the moisture content in an object under study, its distribution and variation in time is crucial in the

[*]E-mail: ludovit.kubicar@savba.sk

prediction of porous material decay. Therefore, the moisture monitoring has high priority in the preservation and restoration of historical objects.

Several projects have dealt with historic monument deterioration. Saas and Viles [2] studied the spatial distribution of moisture and its time variation in ruined walls. Kramer et al. [3] analyzed the effect of interior operating conditions on historic building enclosure components. Brüggerhoff et al. [4] studied water circulation in stones in the wall of Saint-Gatien Cathedral in Tours. A group of authors have used hot-ball technique for monitoring the temperature – moisture regime of the Saint Martin's Cathedral in Bratislava [5]. A simplified version of the hot-ball sensor has been used for monitoring the Saint James's Church in Levoča [6]. A set of authors deal with hygrothermal function, representing a transport model for coupled liquid water, water vapor and heat transfer, based on thermodynamical principles [7, 8]. Results have shown that moisture transport through porous structures is a complex process where an entire set of environmental factors must be considered to obtain a clear picture of deterioration processes.

This paper discusses methodology of the monitoring of hygrothermal regime using two moisture sensors placed in the porous structure of the pillar of Saint James's Church in Levoča. Such configuration allows determination of the heat and moisture transport in the pillar depending on the season. The hot-ball method is used for measuring thermal conductivity. Thermal conductivity of porous system is a function of properties of the matrix and pore content.



(a) (b)

Figure 1. (a) placement of the moisture sensor in the wall, (b) locality of sensor placement in the pillar of the Saint James's Church.

2. Monitored object history

Saint James's Church in Levoča belongs to the biggest Gothic churches in Slovakia. The church is consecrated to Saint James the apostle, protector of the fighters, the pilgrims and the workers venerated by the whole medieval Europe. Roman Catholic parish Church of Saint James belongs to the most important monuments of sacral arts in Slovakia. It was built in the last quarter of the 14^{th} century. Apart from the church architecture, the works of the medieval wellknown woodcarver Majster Pavol from Levoča as well as the works of the jeweller Jan Szilassy are included into UNESCO list. Geographical position of the church is at 49.1°N, 20.4°E and at an altitude of 570 m. Levoča is located on the northern edge of the boiler Hornádska Basin in a distance of around 50 km from High Tatras Mountains. The climate is strongly influenced by the High Tatras, therefore winters are cold and summers are rainy. The sensors are placed in the south pillar of the church in a depth of 10 and 40 cm at a height of 2 m above ground. Pillar's width is 1m (Figure 1). The pillars are built of sandstone blocks. The church is built on the wet ground.

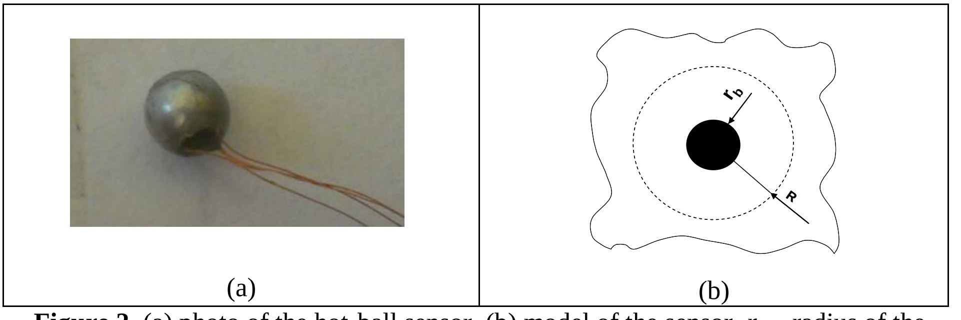


Figure 2. (a) photo of the hot-ball sensor, (b) model of the sensor, r_b – radius of the sensor, R – penetration depth.

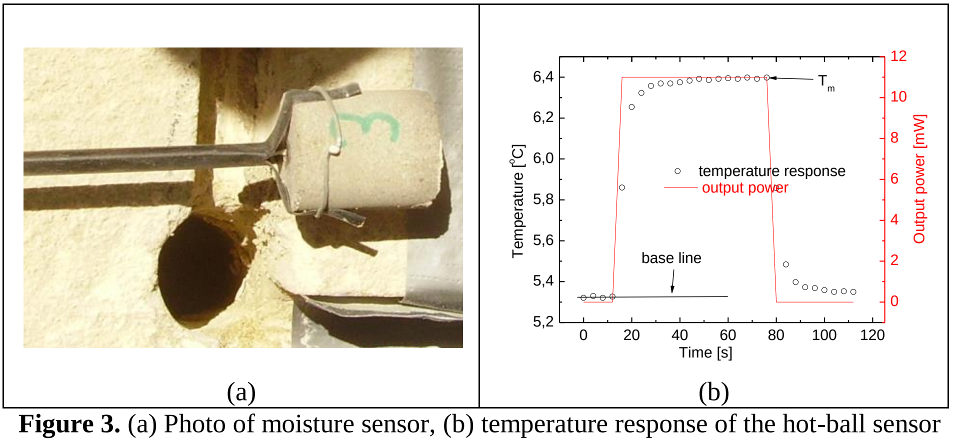


Figure 3. (a) Photo of moisture sensor, (b) temperature response of the hot-ball sensor when heater is producing constant heat output q, material: sandstone.

3. Experimental technique

3.1. Thermal conductivity sensor

We use the hot-ball method for measuring thermophysical properties [9]. The method uses a small ball that generates a transient temperature field and simultaneously measures the temperature. The ball's temperature is a measure of the thermal conductivity of the surrounding material. The diameter of the ball ranges from 2 mm to 3 mm. A photo of the hot ball sensor is shown in Figure 2a.

The hot-ball sensor consists of two electrical components: a resistor and a thermistor. The electrical components are placed inside the ball. The resistor is used as a heat source for generation of the temperature field and the thermistor for measuring the temperature response to this heating.

The working equation for the hot-ball sensor is based on a model which assumes a constant heat power q generated by a ball of radius r_b (Figure 2b). For long time approximation i.e. when temperature response is stabilized, one obtains equation

$$\lambda = \frac{q}{4\pi r_b T_m} \tag{1}$$

that is used for calculation of the thermal conductivity of surrounding medium within a sphere R [10]. Here q is overall heat production and r_b is radius of the hot-ball, T_m is stabilized value of the temperature response due to heating q (see Figure 3b). Thus the sensor determines thermal conductivity locally.

The principle of measurement by the hot-ball method is as follows. A heat source, in the form of a small ball, starts to produce heat at a constant rate, while simultaneously measuring its own temperature. The heat penetrates a sphere with radius R during the temperature stabilization phase (Figure 2b). The measurement procedure consists of measuring the ball's temperature before, during and after the period of heating (Figure 3b). Temperature measurement before the heating indicates the temperature of the surroundings and provides a baseline; measurement during heating is the basis of determining thermophysical parameters. When the ball's temperature reaches a plateau, the heating is stopped.

3.2. Moisture sensor

Thermal conductivity sensor measures locally. Radius of the hot-ball sensor r_b ranges from 2 to 3 mm. The sensor's signal reflects the characteristics of the surrounding material within the radius R around the ball (Figure 2b). The radius R ranges between 10 and 30 mm. If you want to measure thermal conductivity of the wall structure of thickness around 100 cm, then installing a hot-ball sensor (thermal conductivity sensor) into the wall is a serious technical problem. Therefore, in real conditions, we drill a hole with a diameter of 20-30 mm into the wall into a depth where hygrothermal mode is the most interesting. The moisture sensor is then made of the core hole (Figure 3a).

The moisture sensor (Figure 3a) is composed of a cylindrical body with a diameter and length around 30 mm [11]. A hole is drilled in the axis of the cylinder, where the hot ball is inserted and fixed by epoxy resin. The sensor body is made from a core taken from the borehole drilled out from the porous structure in which the moisture will be monitored. The cylinder is inserted back in the borehole exactly at the same position which ensures that the properties of the sensor and the porous material are identical.

Accuracy of moisture measurement is limited by many factors [10, 11]. There are many layers between the active components (heater, thermometer) and moisture sensor's body. They represent the thermal resistance. Therefore the moisture sensor has to be calibrated for practical use. We assume the thermal conductivity is a linear function of the moisture [5]. Using equation (1) we can write:

$$M = A + B\frac{q}{T_m} \tag{2}$$

where M is moisture and A, B are calibration constants. Calibration procedure consists of measuring of the sensor's signal q/T_m in a monitoring regime versus time assuming the completely dried sensor is successively submerged into distilled water. In a period of 24 hours the sensor mass is checked. Calibrated moisture sensor made of a core of drilled hole is fixed back into the hole. The sensor fixation must meet the conditions of macro-homogeneity of the porous system. Then joint layer between the sensor's body and the porous surrounding material must represent a small (negligible) deviation from macro-homogeneity of the porous surroundings. Fine grained plaster or concrete mixture is used for joint material that after hardening creates the appropriate porous structure.

Body size of the sensor is given by penetration depth R. This ensures that the temperature field generated by the hot-ball is not affected by outside body surfaces. Thus, the measurement runs in an infinite medium that, in our case is represented by sensor body shown in Figure 3a. The measurement process shown in Figure 3b for rocks takes from 80 to 150 seconds. Stabilization of the temperature to its original value takes from 30 to 80 seconds after switching the heating off. For monitoring the moisture transport in porous structures we have repetition rate from 30 to 120 minutes.

Measurement strategy is as follows: porous system, in our case the sandstone block, is in a quasi-thermodynamic equilibrium. This means that the temperature and moisture variations in time are neglectable during the measuring process. Locally generated heat flux by hot-ball into the system introduces a small disturbance. From the temperature response to this disturbance we calculate the thermal conductivity and moisture of a porous system using calibration data. Heat flux from the hot-ball ranges from 5 to 20 mW into 4π space. Magnitude of the corresponding temperature response (rise of the temperature at the hot ball surface) ranges from 0.5 to 2 K during time interval from 5 to 10 seconds. Then the disturbance quickly dies down. We say that disturbance is well localized in space and time. Thus the recorded information corresponds to local thermodynamic equilibrium.

The accuracy of the moisture determination is given by the calibration. In our case, we use a linear approximation $M = A + B\lambda$, where A and B are constants determined from the dry and water-saturated state. In the real case, the thermal conductivity may be non-linear function of moisture. Therefore, the extent of non-linearity contributes to the moisture error. Reducing the measuring range of the moisture sensor to 30-80%, we can increase the accuracy of moisture determination. Moisture range 30% to 80% in our meteorological conditions is most common.

4. Results and discussion

Hygrothermal data collected in the period from October 29, 2014 to August 16, 2015 at a depth of 10 and 40 cm are shown in Figure 4. After reaching the hygrothermal equilibrium around the sensor, we have found a high level of moisture in the sandstone blocks, namely 36% at 10 cm and above 60% at 40 cm. Data represent the cycle winter - summer. Red lines indicate 0°C. The cycle includes a period of frost, when temperatures fell well below 0°C and hot summer period, when the ambient temperature rises above 30°C. During the winter period the pillar structure, passed by a set of cycles freeze - thaw. In summer there were repeated periods colder and warmer days. Middle pillar (sensor at 40 cm) has more than 20% higher moisture compared with the subsurface region of the pillar (sensor at 10 cm). Windows drawn in Figure 4 indicate data sequences in which a detailed analysis has been performed.

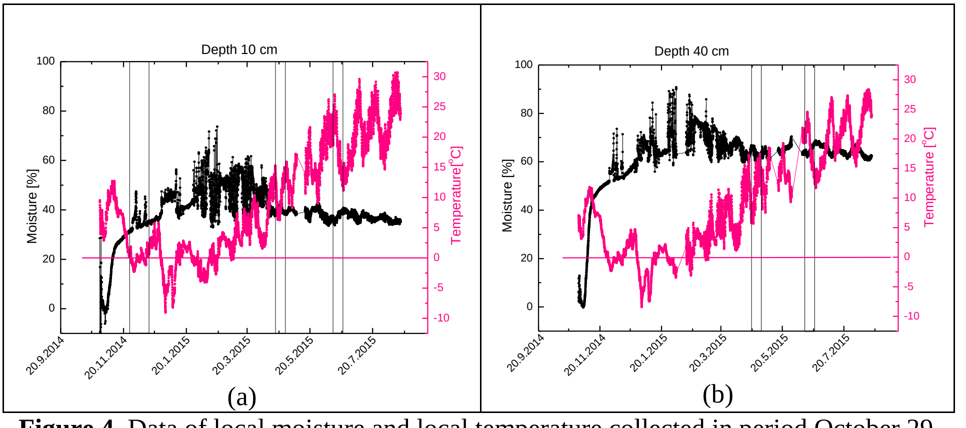


Figure 4. Data of local moisture and local temperature collected in period October 29, 2014 – August 16, 2015; red line - 0°C; windows indicate a detailed data analysis.

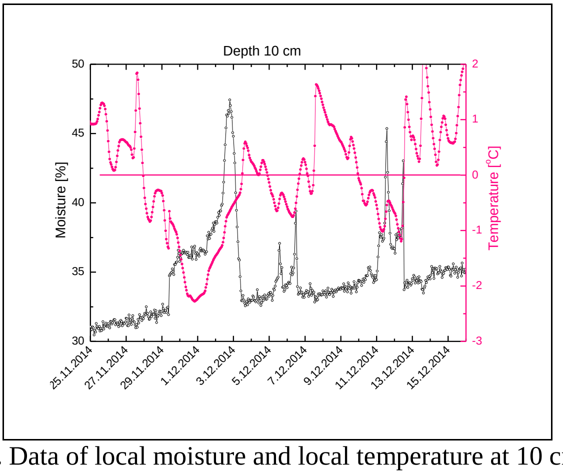


Figure 5. Data of local moisture and local temperature at 10 cm depth.

Temperature fell below 0ºC in period November 29, 2014 – February 15, 2015. Red line in Figure 5 indicates 0ºC. During winter time the effects of freezing–thawing were found. Effects of freezing-thawing for saturated porous structures can be found only in materials having higher porosities [12]. Sandstone used in pillars has porosity around 10% and its change of thermal conductivity ranges around 7%. Detailed characteristics of pore structure are given in [6]. When water freezes below 0ºC its volume increases by around 9%. This has destructive impact on pore structure providing full saturation. We will look in detail for the period November 27, 23:00 December 3, 12:00, when the first freeze thaw cycle occurred (Figure 5). Clearly the period of the water undercooling, the period of formation of nuclei and the thawing period can be identified. An apparent increase of the moisture starts during the formation of nuclei. This is due to the physics of the sensor, based on the measurement of thermal conductivity. Pores content changes its physical state from liquid (water, $\lambda = 0.58\ W\cdot m^{-1}\cdot K^{-1}$) to solid (ice, $\lambda = 2.2\ W\cdot m^{-1}\cdot K^{-1}$). A typical peak was observed during melting process. Similar changes were observed in the measurement of thermophysical properties of Sander sandstone [12]. The next cycles are blurry because the freezing process started from the mixed liquid – solid states that depend on pore size [12].

The analysis of data in the windows shown in Figure 4 allows us to determine the heat and moisture transport in the volume of the pillar. The sensors are located so as to be able to estimate a thermodynamic state of the pillar in the middle (sensor at 40 cm depth) and at the subsurface (sensor at 10 cm depth). For this purpose we have chosen two windows with the corresponding data sequences. The first period from April 19 to 27 (winter period) corresponds to the state when the pillar structure is definitely cooler than the surrounding atmosphere but the pore content contains liquid and the period from June 16 to 20 (summer period), when the pillar material is already overheated by sun radiation. Figure 6 shows data differences in temperatures and in moisture between the localization at 40 cm and 10 cm within the winter period in Figure 6a and in summer period in Figure 6b. Temperature differences indicate heat flows while moisture differences characterize intensity of the moisture transport. For winter period rather strong peaks of heat inflow into pillar structure existed in the middle of the day (Figure 6a) while peaks of heat outflows are found for summer period. Clearly, cool pillar structures absorb intensively heat during days even small outflows exist during nights (Figure 6a). If the structure of the pillar is well preheated, then the process of heat absorption and heat radiation is opposite. During the nights there is an intense heat radiation, whereas during days low rate of heat absorption was identified (Figure 6b). Large temperature differences generate flows of moisture in both in the summer as well as in the winter. Transport is most intense in the middle of the day when there are peaks of temperatures. Of course, in winter, there are differences in moisture larger compared with the summer period when the drying process is more intense (compare Figure 6a with Figure 6b). In any case, definitive conclusions can be formulated only after several annual cycles.

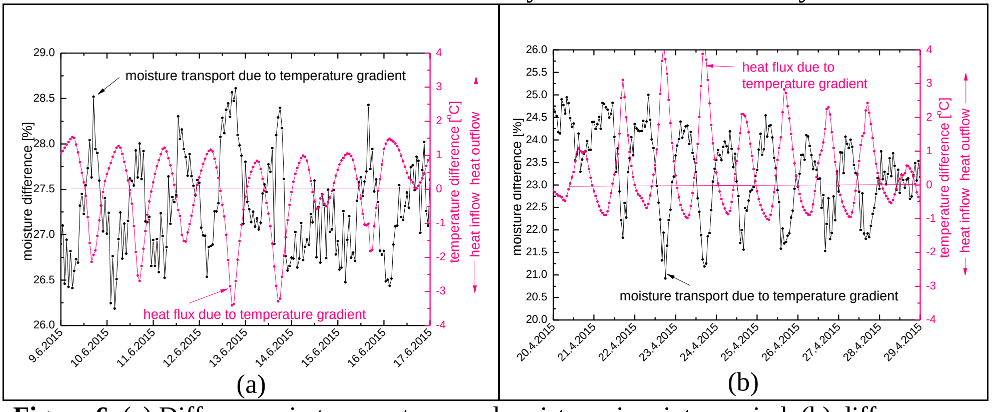


Figure 6. (a) Differences in temperatures and moistures in winter period, (b) difference in temperatures and moistures in summer period. The differences are calculated as temperature/moisture at 40 cm minus temperature/moisture at 10 cm. Data sequences are taken from windows shown in Figure 4.

Holes in the wall were drilled several weeks before the sensors are installed. Data indicate that considerable wall volume around the hole is dried. A period of 1.5 month is required to establish homogenous distribution of moisture in the wall. It appears that moisture can be effectively controlled by the formation of moisture gradients in the wall through a set of holes. A similar behaviour was found in monitoring Saint Martin Cathedral in Bratislava and Saint James's Church in Levoča in different location [5, 6].

5. Conclusions

New innovative technique for monitoring the hygrothermal regime is described, which is based on measuring the local thermal conductivity. Hot-ball method is used for measurement of the thermal conductivity. A sensor is designed and constructed for monitoring the moisture, which uses the sensing element of the hot-ball. Moisture sensor is made of a core of the hole that is drilled into the wall of the object we want to monitor. Body of the moisture sensor has porous structure. The sensor is inserted back in the borehole exactly at the same position which ensures that the properties of the sensor body and the wall structure are identical. Moisture sensor provides information on local temperature and local moisture. Monitoring method is applied at the Saint James's Church in Levoča. Hygrothermal data are collected in the period from October 29, 2014 to August 16, 2015. The sensor is mounted in the pillar into the sandstone block at a depth of 45 and 10 cm, 2 m above the ground. Hole in a block dried the porous structure of the sandstone before the sensor is mounted back into the hole. Thermodynamic equilibrium of the sensor and the sandstone block stabilized within 1.5 month. High level of moisture in the sandstone blocks was found, namely 36% at 10 cm and above 60% at 40 cm. We identified effects of freezing–thawing depending on the ambient temperature. We have identified heat fluxes and moisture transport between the centre of the pillar and the subsurface layer of the pillar.

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