NUMERICAL ANALYSIS OF HEAT AND MOISTURE TRANSFER IN HISTORICAL CERAMIC MASONRY WALL

Dariusz Heim[1], Sebastian Krawczynski[2], and John Grunewald[3]

[1]Department of Building Physics and Building Materials, Technical University of Lodz, Poland
[2]Department of Mechanical and Aerospace Engineering, Syracuse University, USA
[3]Institute of Building Climatology, Dresden University of Technology, Germany

ABSTRACT

Building physics processes in some parts and elements of revitalized historical buildings play an important role in their future energy efficiency and maintenance. The unique character of 100-years-old post-industrial buildings results from masonry-brick façades with precise ornamentation and sophisticated details which should be retained and reconstructed in renovation works. Any changes in wall properties, such as the addition of new layers (insulation, rendering or plaster), are at variance with cultural heritage protection. Therefore, structural and material properties of wall structures and the geometry of external surfaces have to remain unchanged.

Heat and moisture transfer across a single-layer masonry wall is discussed. The modeling, numerical solution and climatic, boundary and initial conditions are described. Simulation results of coupled heat, air and moisture in building-envelope systems show the effect of material properties and boundary conditions on water content in the wall. Two cases differing by brickwork mortar (original lime-sand mix and cement mix) are analysed. The influence of the renovation method on heat and mass transfer is examined. The results show overall hygrothermal processes in renovated brick masonry walls. The method of coupled heat and mass transfer is very useful in the prediction of possible damage-related processes and the estimation of rainwater transfer in the wall.

INTRODUCTION

Recent development of revitalisation projects has revived interest in adequate protection methods used in the modernisation of historical masonry buildings (Kubik 2006). Old post-industrial complexes seem to enjoy special popularity as their attractive, often central location provides an excellent base for new business enterprises. With former textile factories still taking up ca. 20% of the city centre, Łódź has become one of the greatest testing grounds for the renovation of historical post-industrial areas. The shopping and recreation centre Manufaktura, situated on a 27ha site in the city centre, is a spectacular example of a recent revitalisation project. Approximately 50 000 m^2 of brick façades were renovated as part of refurbishment works and the factory buildings were converted into commercial facilities (Fig. 1). It is the biggest revitalisation project in Europe.

Modernisation and conservation works of this size and scale require special attention to building physics processes. The ability to avoid or resolve building problems is important both for the investor and future occupants (potential damage processes and maintenance costs) as well as for conservation services responsible for urban cultural heritage.

Basic problems affecting modernised buildings arise from the change of use. Manufacturing plants that had operated in the Manufaktura complex for approximately a century were closed in 1989 when textile production was discontinued. The abandoned and unheated buildings soon deteriorated or were plundered. Damage processes related to the adverse influence of the outdoor environment on unprotected building elements also intensified in this period. Salvaging the remaining undamaged building fabric by starting conservation and protection works became a top priority. Decisions had to be made to define the properties of the hygrothermal building envelope such as potential internal insulation, protection of external surfaces from rain penetration and replacement of partly or often completely missing components. Importantly, the environmental context, both indoor and outdoor, was transformed significantly. As the buildings were refurbished and given new functions, indoor temperatures, streams of internal heat and moisture gains as well as the quantity and type of air flux changed. However, these changes affected both the indoor and outdoor environment as construction works influence the urban system and, consequently, the local climate, access to solar radiation, ventilation, etc. The scale of airflow disturbances that can be caused by changes in a built-up system are analysed in a case study of the Manufaktura project in, for instance, (Heim et al. 2007).

Figure 1 Manufaktura today – general view

BRICK WALL MODERNISATION

External load bearing walls of the industrial buildings revitalised for the *Manufaktura* centre were built using solid ceramic bricks, 27×13×6 cm, with joints 1cm thick. Wall thickness was increased by half a brick every single or every second storey down and the walls were as thick as 83 cm (three bricks) on the ground floor level. Sections across selected walls before and after modernisation works are shown in Figure 2. The walls do not comply with current standards of heat retention regardless of their thickness but could not be externally insulated because of conservation requirements. Additionally, the natural brick structure of the buildings had to be retained to accommodate the architectural demand for the original character of the interiors. Therefore, the following modernisation measures were taken:

- The external wall face was cleaned by mechanically removing the external layer to a thickness that allowed a smooth surface to be obtained,
- Missing bricks were replaced and brickwork was repointed on the outside as required,
- The external surface of the masonry wall was protected with impregnation compounds.

A major error made during renovation works of historical buildings, also briefly discussed in study (Kubik 2006), is to “seal” traditional, vapour-permeable lime-cement mortar with cement mortar.

The new function of the modernised Manufaktura buildings and the operation period are also relevant to energy performance. The facilities are used both during the day and at night; however, internal air parameters change over a 24h period in contrast to their former industrial function. They are also equipped with indoor temperature-control systems and comprise areas with high sensible heat gains as well as areas where periodically considerable gains of latent heat occur.

Figure 2 Brick walls before (left) and after (right) modernization

HEAT AND MASS TRANSFER MODELLING

Coupled heat and moisture transport in building elements (Häupl P. et al. 1994) can be simulated using advanced numerical model. CHAMPS (Bomberg et al. 2006) or WUFI (Künzel H.M. 1995) are examples of computer software dealing with the effect of driving rain on building envelopes.

CHAMPS is an acronym for coupled heat, air, moisture, pollutant simulation or alternatively for heat, air, moisture, pollutants and salt transport, which is the underlying physical model of the CHAMPS-BES code.

CHAMPS modeling comprises the description of fluxes in the calculation domain or in the field (between volume elements including material interfaces) and at the boundary (between volume elements and exterior or interior rooms) by physical models. Also included are models for storage processes like adsorption, desorption and release.

The description of field flux and storage is usually done by a set of balance equations. These balance equations are of parabolic type and there is no closed analytical solution for this problem. The transport coefficients depend usually highly on the variables of state. They can vary over several orders of magnitude, as for example the liquid water conductivity. Therefore, a numerical solution is the only choice to solve a coupled CHAMPS problem. The numerical solution is done by semi-discretization in space (using a finite/control volume method) and subsequent integration in time.

By defining a set of balance equations one establishes a framework for the solution of a variety of CHAMPS problems. To solve the problem, also the definition of conditions (initial conditions, boundary conditions etc.) is required. Lastly the numerical solution is applied to solve the system of equations.

More information about software and it’s application are available at:

http://energysystems.syr.edu/champs.htm

For the purpose of this study two dimensional model of masonry wall with mortar joints were defined. Hygrothermal parameters inside the wall (in a brick and mortar) were calculated at depth of 1cm and 5cm from outside. The sensors location in a wall is presented in fig. 3.

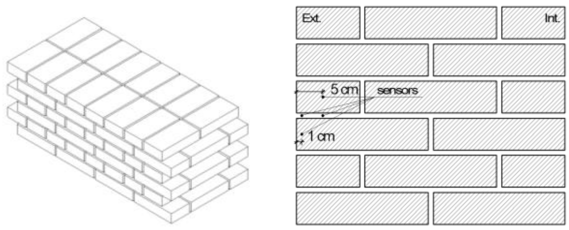

Figure 3 Perspective view and cross section through the analysed wall

CLIMATIC, BOUNDARY AND INITIAL CONDITIONS

Factors used in simulations of hygrothermal processes in building elements include outdoor and indoor climatic parameters. Climatic conditions can be defined by a total of 20 variables. Annual data sets of the following nine parameters describing the conditions of the outdoor climate were examined: temperature, relative humidity, direct and diffuse solar radiation, wind direction and speed, cloud cover and rain density. Sets of climate parameters were obtained using long-term hourly meteorological data. These parameters were worked out based on 30 years measurements data (Narowski & Heim 2008) according to European standard EN ISO 15927-4 „Hygrothermal performance of buildings – Calculation and presentation of climatic data – Part 4 Data for assessing the annual energy for cooling and heating systems".

Standard meteorological data files used in building-energy analysis often give only basic parameters influencing heat and moisture transfer across building envelopes or system elements. Rainwater penetration into building envelopes caused by driving rain is usually not included. These values, however, are necessary for the examination of coupled processes of heat and moisture transfer in building materials and elements.

Three meteorological parameters were used to determine the quantity of rainwater reaching the external wall surface: wind speed and direction, degree of cloud cover, rain type and intensity. Precipitation occurrence as well as its type and intensity were specified in the precipitation file. Additional weather parameters for which data sets were determined comprised wind speed, dry-bulb thermometer temperature, relative humidity, intensity of direct and diffuse solar radiation and total pressure. The distribution of air temperature and relative humidity are shown in Figure 3.

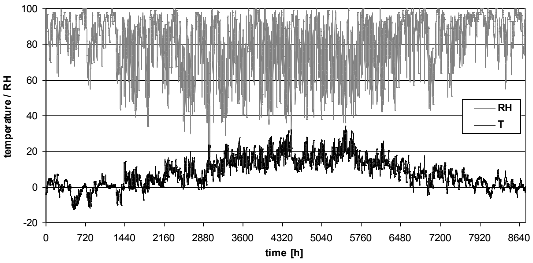

Figure 3 External temperature and relative humidity yearly history

Two use profiles that condition two operation patterns of the internal heating and cooling system were used to describe indoor climate. Ideal control of indoor air parameters, determined in keeping with the profiles shown in Figure 4 for temperature and relative humidity was assumed. Profiles 1 and 2 show day-time and evening/night-time functions, respectively. As the climatic data set consisted of nine parameters, only the problem of heat and moisture transport for driving rain and solar radiation should be solved to calculate the boundary conditions.

Effects of pollution were not analysed at this stage. On the other hand, initial conditions were determined using the results for the so-called start-up days when the hygrothermal condition of the building envelope stabilises.

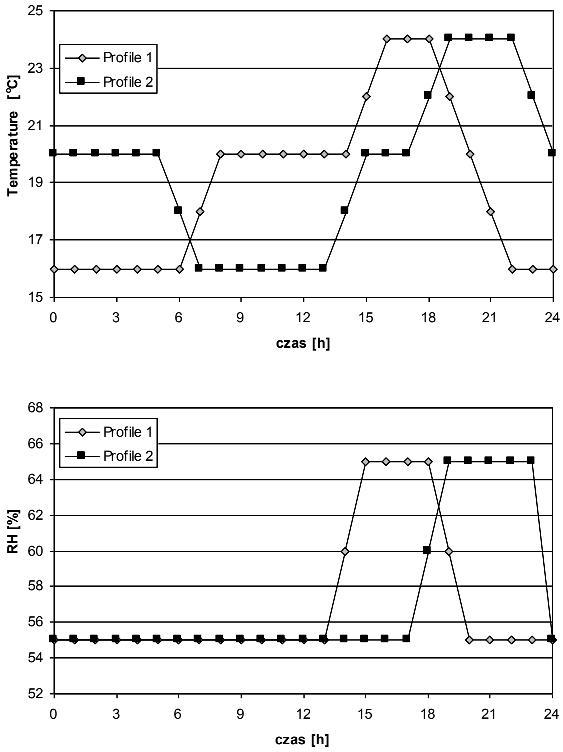

Figure 4 Occupancy profiles – heat and moisture daily history – internal conditions

MATERIAL SELECTION

A 55cm-thick external wall built using the traditional English bond with two alternate courses of bricks was examined. One type of brick (historical brick) and two variants of mortar were analysed:

- lime-cement mix throughout the course and
- cement mix to a depth of 2 cm from the external surface and lime-cement mix in the remaining part.

The basis parameters of the materials are listed in table 1. The lime-cement mix is an existing, historical mortar left inside a wall during restoration.

Table 1

Basic properties of materials used in simulation*

MATERIAL	1	2	3	4
historic brick	1 700	0.85	0.36	0.32
lime-cement mix	1 800	1.05	0.27	0.25
cement mix	2 100	1.34	0.22	0.20

1 – Bulk density [kg/m^3]
2 – Thermal conductivity for dry material [W/m^{2}K]
3 – Porosity [m^3/m^3]
4 – Maximum liquid moisture content [m^3/m^3]

*All values come from CHAMPS Database

Calculations were conducted for two variants according to the procedure shown in Figure 4. An initially dampened masonry wall, which reflects the actual humidity condition on the day of the year chosen as the beginning of the analysis, was used.

RESULTS

Annual courses of water content changes in the wall resulting from the influence of outdoor and indoor environment parameters are shown in Figures 5-7. A two-directional heat and moisture exchange was used in the analysis. Changes in individual parameters are given for four characteristic wall points (brick and mortar) at two different depths, 1 and 5 cm, to visualise the results. A strong influence of driving rain on the dampness of external wall surfaces (characteristic extreme values are noticed in the case of the mortar, Figure 5) is visible in the profiles. Deeper sections of the historical mortar are susceptible to smaller amplitudes of water content changes. However, water content is higher in the deeper parts of the mortar than in the wall face part throughout most of the year in all the cases (Fig. 5-7). Water content is also considerably higher when a barrier of non-permeable cement grouting is used on the external side of the joint (Figure 6, 7). An instantaneous distribution of water content in Figure 8 illustrates the influence of the reduction in moisture transfer through the cement mix (water content distribution in the wall at the beginning and at the end of the study period). Dampening process in individual masonry wall parts after 8 400 hours indicates a significant moisture concentration within the joints and the inability to evaporate through the external surface. Thus the cement mix plays the role of a "stopper" that retains rainwater absorbed earlier in the wall. The results obtained after the analysis period corresponding to a full calendar year suggest that the process may intensify in subsequent years and the wall may biodegrade. The influence of individual use profiles and changes in indoor environment parameters turned out to be less significant (Figures 5 and 7). This results from the large thickness of the building envelopes analysed in the study and their ability to absorb and give up moisture.

CONCLUSIONS

The history of water content during the whole year shows the basic effects of water transport in different physical states. They are: water absorption at outer surface, penetration into a deeper parts of the wall, exchange between materials inside a wall, evaporation and drying. The unique, different properties of three materials combined into one building components bring on uncharacteristic phenomenon. The biggest disadvantages of using cement mortar at the outer part of the joints between old, porous brick is so-called "cork effect". The rain water relatively easy penetrate the parts of brick elements. Then, the mass is transfer into the hygroscopic and absorbable historic, lime-cement mortar located in a middle part of the wall. At the same time the possibly water evaporation at external surface is stopped by a impermeable cement mortar closing joints from outside. This increasing effect can lead to dangerous water concentration in a low temperature wall region. Additionally, during winter the water freezing in a boundary of cement and lime-cement mortar can cause stress and mechanical damages of the wall.

The study is part of a research project investigating the impact of the local climate on historical buildings. The results were obtained using coupled, two directional models of heat and moisture transfer in porous media. They show the scope and scale of the influence of moisture on brick walls in modernised historical buildings with regard to weather conditions, use profiles and specific material properties. The results will be used to predict the performance and stability of such construction systems depending on the degree of exposure to changeable parameters of the local climate.

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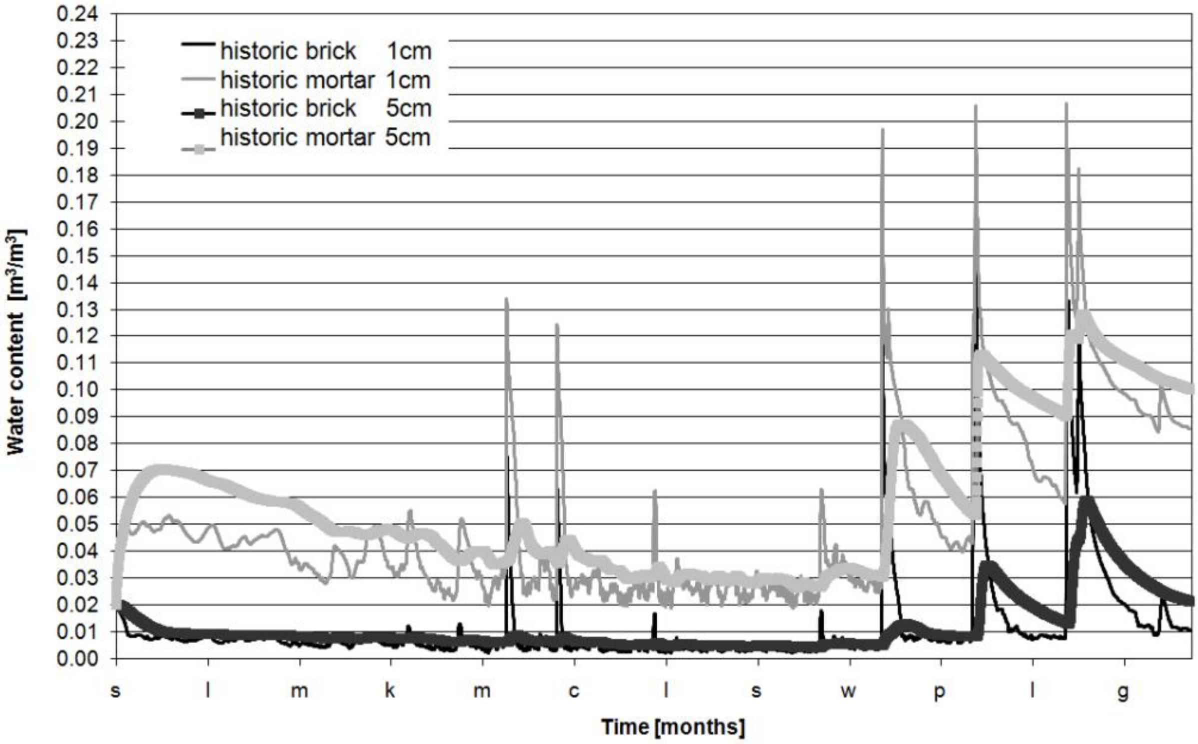

Figure 5 Water content history for wall with historic brick and historic mortar (profile 1)

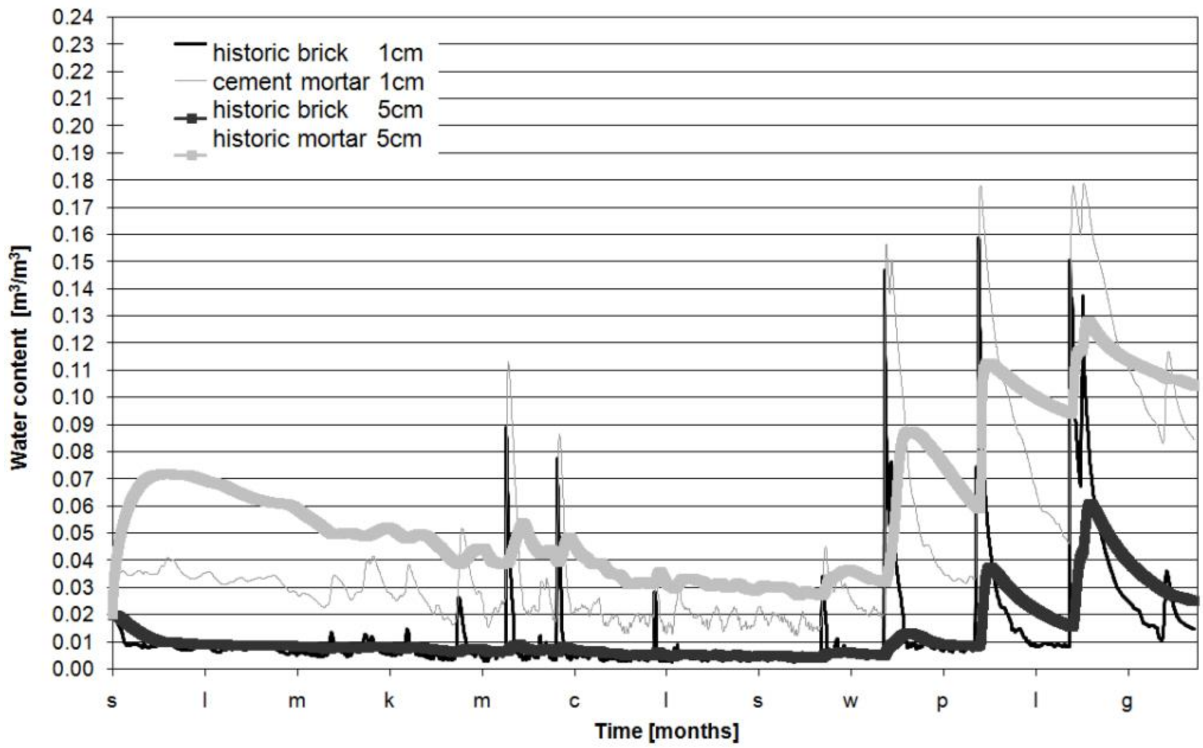

Figure 6 Water content history for wall with historic brick and cement mortar (profile 1)

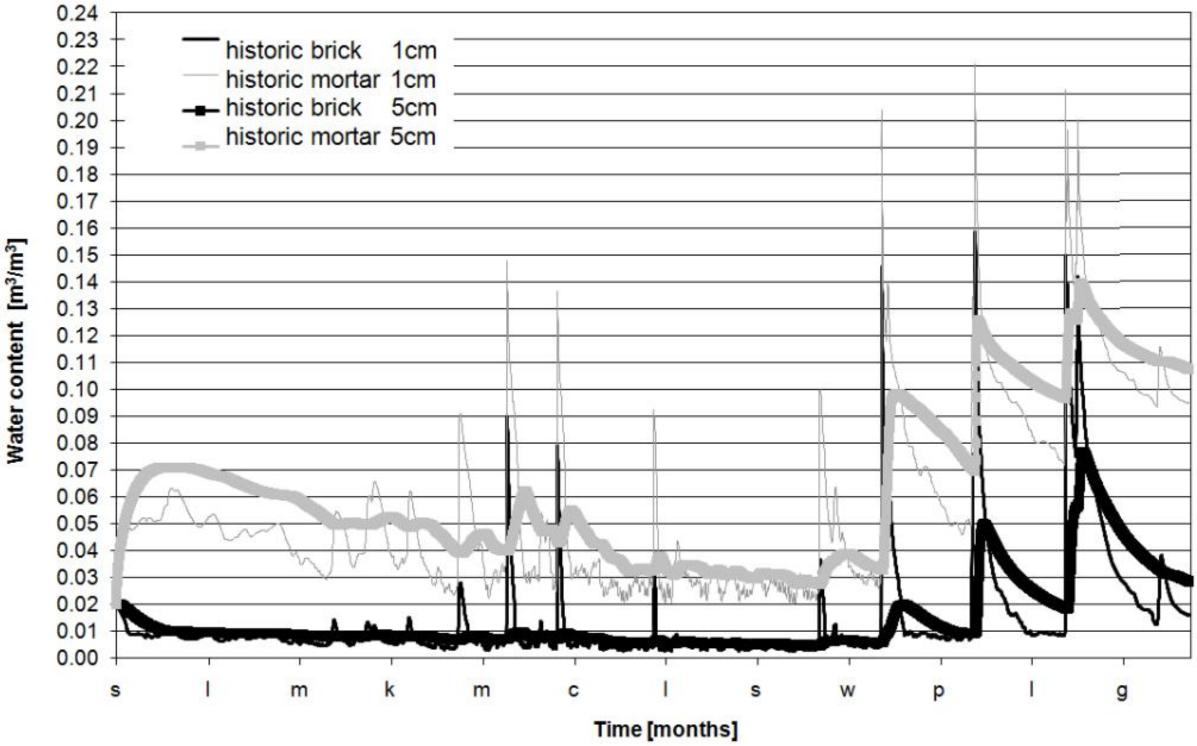

Figure 7 Water content history for wall with historic brick and historic mortar (profile 2)

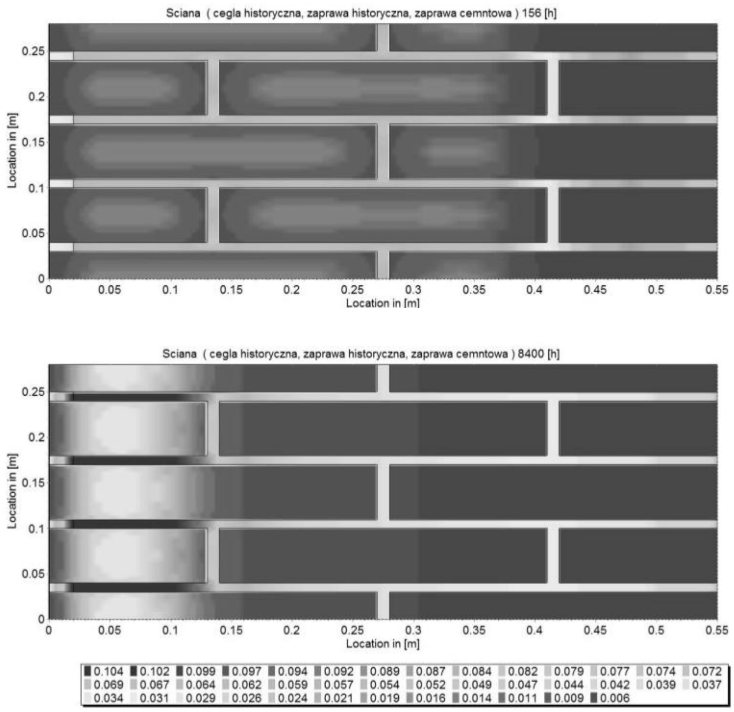

Figure 8 Water content in selected parts of analysed wall (in m^3/m^3) on 6^{th} and 350^{th} day of a year (vertical cross-section)