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Modelling and Solving Building Physics Problems using MATLAB/Simulink*

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This article describes in detail an experimental technique and an implementation of a numerical model, in MATLAB/Simulink, used in laboratory classes of the Civil Engineering course at the Faculty of Engineering of Porto University. This work aims to motivate the students to combine laboratory experiments with computer simulation. The present work also illustrates the moisture buffer capacity of building materials. The moisture buffer capacity of building materials in transient conditions was tested in small-scale laboratory tests. Alongside, was a numerical simulation tool for hygrothermal performance analyses of buildings and building materials and both results were compared. The experiment illustrates the importance of materials moisture buffer capacity in the hygrothermal behaviour of buildings; and it is important to have in mind that the majority of students do not have the opportunity to gain 'hands on' familiarity with the interplay between diffusion and sorption, nor do they have the opportunity of seeing, in practice, how it is possible to characterize porous materials in terms of their impact on indoor environment.

NOMENCLATURE

A	Area [m^2]
g	Density of moisture flow rate [kg/m^{2}s]
g_v	Total moisture flux (vapor flux) [kg/m^{2}s]
P_v	Vapor pressure [Pa]
$P_{v,air}$	Ambient water vapour pressure [Pa]
$P_{v,surf}$	Vapor pressure on surface [Pa]
P_s	Suction pressure [Pa]
t	Time [s]
w	Moisture content [kg/m^3]
x	Space coordinate [m]
β_p	Surface coefficient of water vapour transfer [s/m]
δ_p	Moisture permeability [s]
$\lambda_{m,l}$	Hydraulic conductivity [s]

INTRODUCTION

IMPLICATIONS OF MOISTURE in building and construction are of interest to the international community because of their huge economical consequences, including effects on health, maintenance and repair, retrofitting and conservation, as well as on common welfare.

The Civil Engineering undergraduate programme, at the Faculty of Engineering of Porto University includes some laboratory classes in the Laboratory of Building Physics, namely, in the last year of the course, for the students that choose the option of Building Engineering. In these laboratory classes the students have the opportunity to gain 'hands on' familiarity with some theoretical concepts. However some experiments are too time consuming. One possibility is to use computer simulations, which are increasingly powerful, affordable and user friendly.

Simulations, however, leave some students cold—an ideal curriculum should supplement them with lab experiments. One approach is to provide small-scale but realistic processes. Nevertheless, an instructor can tailor simulations to illustrate key concepts of varying complexity.

MATLAB and Simulink [1] were being used routinely since the first year of the Civil Engineering undergraduate programme. Simulink is an especially popular simulation platform because of its intuitive graphical interface. A Simulink diagram consists of interconnected blocks. Each block can model a continuous system, a discrete operation, or a hybrid of the two. Signals connect the blocks and represent variables and parameters that change as a function of time. During a simulation, Simulink calls upon each block repeatedly for the information needed to calculate the signals. A Simulink block can include MATLAB code, so it is possible to use the MATLAB functions within Simulink.

There are many scientific problems in building physics that can be described by PDEs and a lot of software programs available in which one specific PDE is solved. The numerical modelling of Heat, Air and Moisture (HAM) transport processes in buildings is an essential part of studying these phenomena—it might be as a part of research work, building design or for educational purposes.

HAM-Tools, from International Building Physics Toolbox (IBPT), is a building simulation

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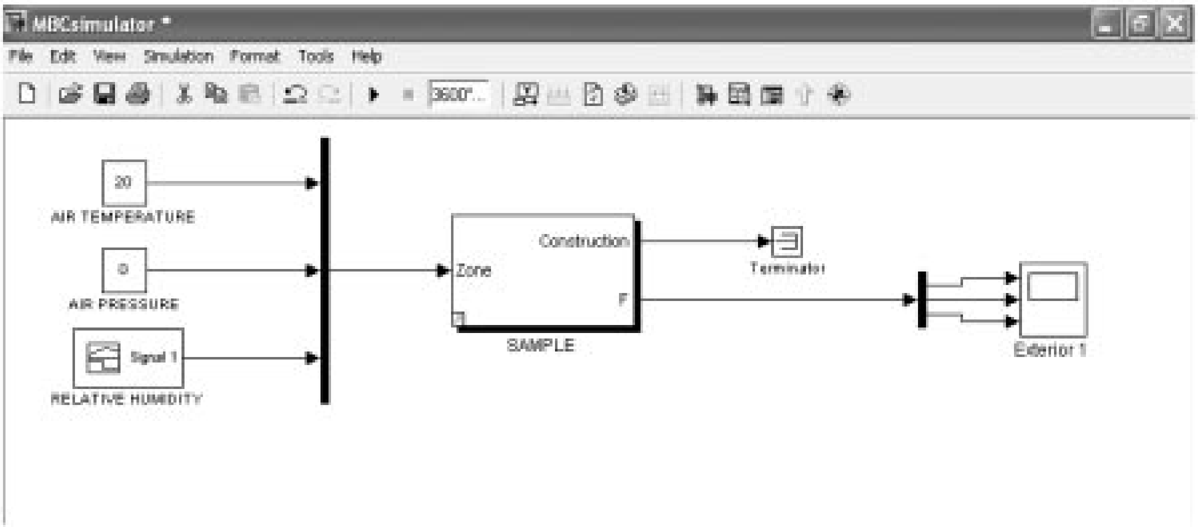

Fig. 1. Numerical model reproducing the laboratory experiments using Simulink.

software that permits simulations of transfer processes related to building physics, i.e. heat and mass transport in buildings and building components in operating conditions. A special problem of building physics, the definition of moisture buffer capacity of building materials, using HAM-Tools simulations, illustrated in Fig. 1, is described in this paper. In a general way, moisture buffer capacity can be defined as a materials ability to exchange moisture with the surrounding environment. Some of the properties that influence the buffer capacity are: moisture capacity, vapour permeability, density and cycle time.

The remaining sections describe this software and illustrate some of the ways it can be used.

MOISTURE TRANSPORT

The subject of moisture transport in porous building materials is usually present in the curricula of most civil engineering undergraduate programs [2–4], especially in the building physics courses. It's a very broad subject and each institution approaches it in very different ways, some based on mathematical modelling, some using laboratory facilities for material characterization, and others using a mix of both approaches.

In the Faculty of Engineering of Porto University, this subject is given more emphasis in the last year of the undergraduate program. But applications of those principles are usually approached in student's assignments in the frame of the Building Engineering option. Until now, those assignments would consist of modelling tasks or basic material properties measurement. Moisture related experiments are usually too much time consuming to be performed in laboratory classes. But a rising interest in the scientific community for the porous building materials ability to buffer moisture when facing an ambient of relative humidity variation, referred as *moisture buffer capacity*, supplied an easy to perform test that at the same time illustrates the moisture transport inside porous materials and the coupling of materials with the

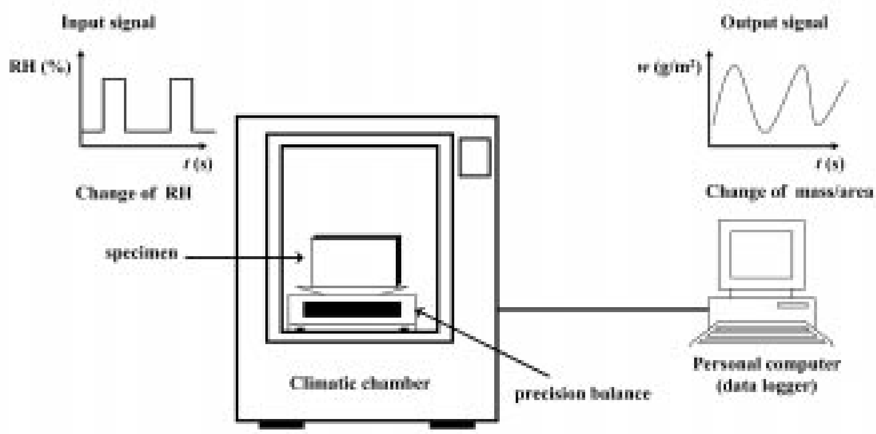

Fig. 2. Sketch of experimental set-up.

surrounding air. The simplicity of the laboratory tests allows for a parallel work of numerical simulation that can be done by the students.

EXPERIMENTAL ILLUSTRATION

The recent work of several researchers [2–5] and the conclusions from the NORDTEST Workshop on Moisture Buffer Capacity [6], inspired the specific tests that are presented in this paper. In these tests, several specimens of rendering materials are submitted to transient conditions of air humidity and/or temperature. Based on the suggestions of the NORDTEST Workshop on Moisture Buffer Capacity, Summary Report [6], a laboratory test was prepared, where a specimen is submitted to a square wave in relative humidity, and constant temperature. This experiment simulates the cyclic variations in moisture loads and relative humidity levels that can be found in bedrooms, for instance, where during the night, there will be an increase in relative humidity due to vapor production by occupants.

A group of students performed the referred experiments using spruce samples ($430\,\mathrm{kg/m^3}$ of density) of $20 \times 20\,\mathrm{cm^2}$, 10 mm thickness and a seal of aluminium foiled around the edges, leaving only two open surfaces, $A = 0.08\,\mathrm{m^2}$.

The specimens used in the tests were stabilized inside a climate chamber at 23ºC and 33% relative humidity. Afterwards, the experiments were performed for a 4-day period with a square wave of relative humidity with step cycles of 8 hours with 75% RH followed by 16 hours at 33% RH, and a constant temperature, 23ºC.

To perform these experiments, a climatic chamber was used, allowing for the control of temperature and relative humidity. Both the moisture content and the temperature of the chamber can be independently controlled to constant values or to cycles of change. A precision balance was located inside the climatic chamber and the mass change registered continuously by a personal computer [7] (see Fig. 2).

NUMERICAL SIMULATION

The laboratory tests described in the previous section were simulated by students using the building software program HAM-Tools [8]. 'HAM' stands for Heat, Air and Moisture transport processes in a building and building envelope that can be simulated by this program, and 'Tools' describes the modular structure to obtain simulations of transfer processes related to building physics, i.e. heat and mass transport in buildings and building components in operating conditions [8].

The International Building Physics Toolbox, is a software library specially constructed for HAM system analysis in building physics [8, 9]. As part of IBPT, HAM-Tools is open source and publicly available on the Internet [10], any student can use the contents of the toolbox. The library contains blocks for 1-D calculation of the heat, air and moisture transfer through the building materials. The toolbox is constructed as a modular structure of standard building elements using the graphical programming language Simulink. All models are made as block diagrams and are easily assembled

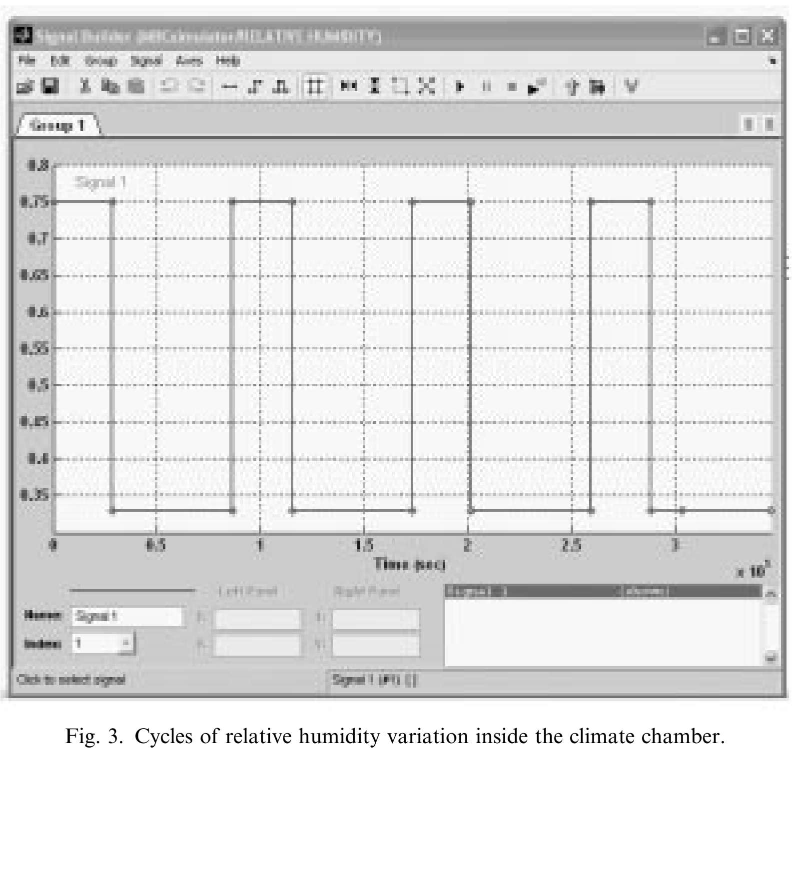

Fig. 3. Cycles of relative humidity variation inside the climate chamber.

in a complex system through the well-defined communication signals and ports. Results can be seen during the simulation on the Simulink's Scope block.

The students used the brief manual of International Building Physics Toolbox in order to familiarize themselves with the technique of creating new HAM models [8] using the software library.

To perform the intended simulation, the numerical model presented in Fig. 1 was put together around the core block named 'sample' which was adapted from the 'construction' block from HAM-Tools. This block is rather complex, but most of its features weren't used at all since the simulation is isothermal. For this simulation in particular, the parts of the model involved were as follows.

Moisture flow inside the material:

$$g = \lambda_{m,l} \frac{\partial P_s}{\partial x} - \delta_p \frac{\partial P_v}{\partial x} \tag{1}$$

Moisture balance:

$$-\frac{\partial g}{\partial x} = \frac{\partial w}{\partial t} \tag{2}$$

Moisture flow to the surface:

$$g_v = \beta_p (P_{v,air} - P_{v,surf}) \tag{3}$$

As part of the simulation work, the students had to assemble the model, as well as prepare each block. On the 'sample' block only small changes were made. The boundary conditions on the surface of the sample were produced by 'source' blocks created by the students. In Fig. 3 the 'relative humidity' block is presented, as it was created using Signal Builder from Simulink library. The communication with MATLAB to make the results available was done using a 'scope' block. In the Simulink diagram, the students needed also to specify the material properties of the specimens used in their experiments, the calculation time and solver used in the model.

We suggest, for an easier understanding of the influence of the parameters under study, that each group of students uses different building materials to explore the importance of some of the variables that can interfere with the final results, such as the materials themselves, relative humidity level, temperature level, amplitude of relative humidity variation and the use of coatings.

RESULTS AND DISCUSSION

The experiments performed on the specimens were intended to obtain a characterization of moisture buffer capacity (MBC) of spruce.

The reproducibility of the experimental values of daily mass variation was tested for three different panels of spruce and repeated measurements of mass variation did not differ by more than 12%.

Figure 4 shows the mass variation observed in specimens of three different samples of spruce. The result of each experiment is presented in a single number format, which represents the peak-to-peak difference in specimen weight expressed as kg of water per square meter of exposed surface area.

The numerical solutions for this condition were worked in Simulink with HAM-Tools, and the values obtained are shown as a full line in the plot of Fig. 5. The experimental values of mass

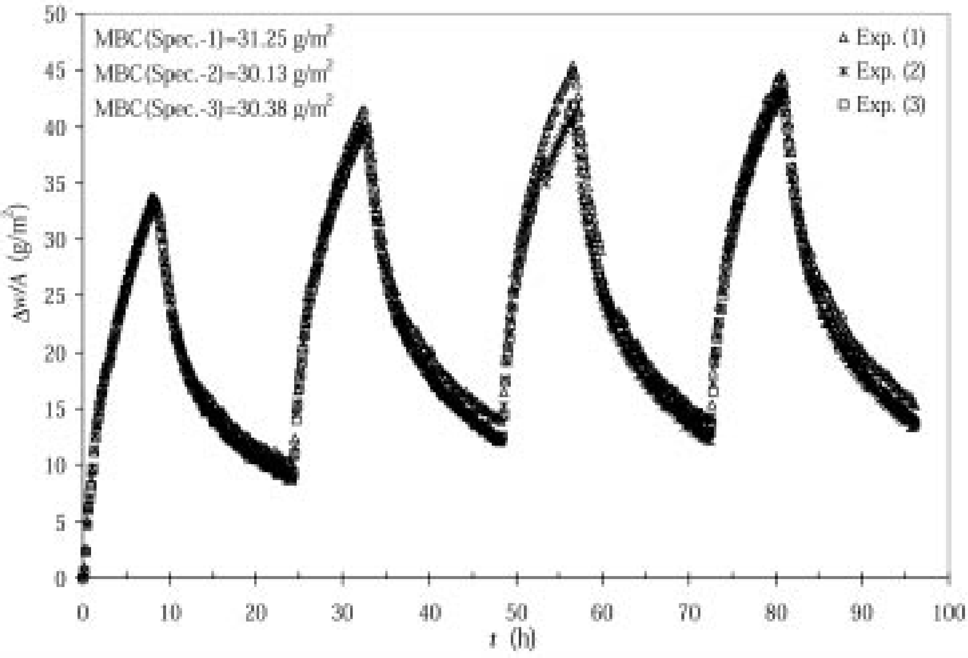

Fig. 4. Experimental mass variations of spruce (three different experiments).

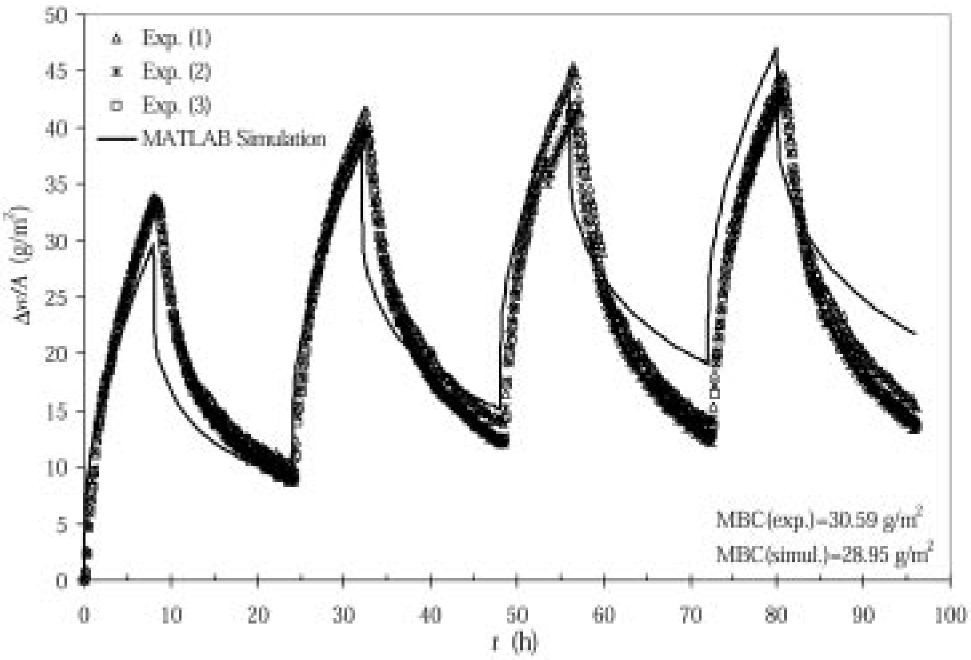

Fig. 5. Comparison between numerical simulations and experimental results.

variation differ, in mean, at most by 10% from the corresponding numerical solution obtained in the present work.

Figure 6 presents a sensibility analysis made with a spruce specimen covered by a thin layer of varnish. The varnish layer plays an important role in the performance of water vapour transfer resistance and with numerical simulation it is simple to show the influence of the varnish layer in a moisture buffer capacity, by changing the value of the surface coefficient of water vapor transfer (the water vapor transfer coefficient recommended [11] is 2.5×10^{-8} s/m).

The civil engineering students, with this simple experiment, have the opportunity to see the results obtained from different perspectives. For example,

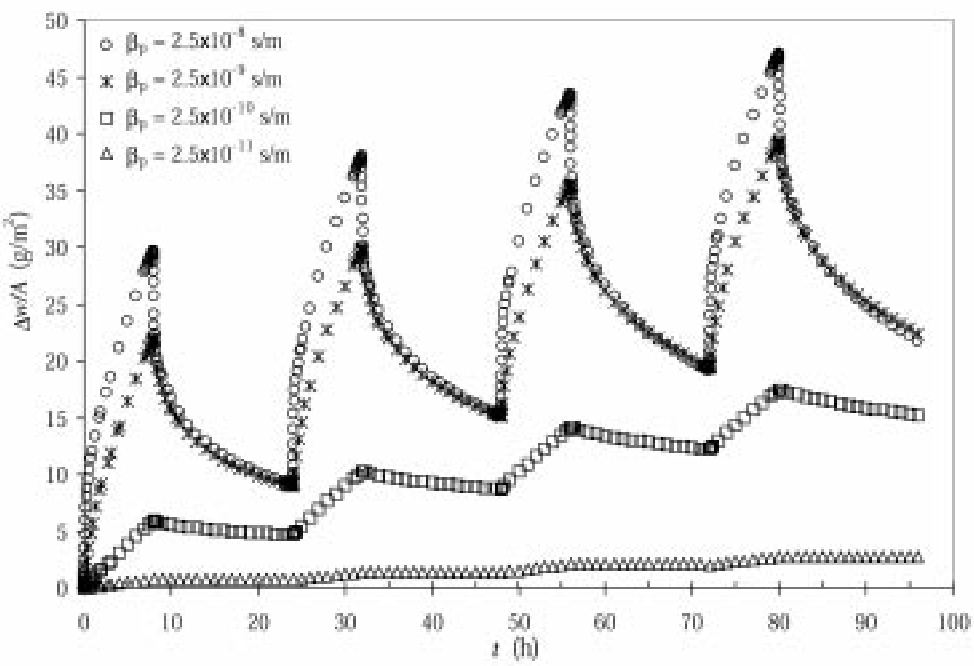

Fig. 6. Numerical analysis of the influence of varnish layers over a spruce specimen.

if the experiments are made with different building materials it will be possible to show the importance of paintings, temperature differences and relative humidity gradients.

SOFTWARE REQUIREMENTS

The Simulink HAM blocks described here require MATLAB Version 7.0 (Release 14), Simulink Version 6 or above and HAM-Tools compatible version. The HAM-Tools is a library of Simulink models specially constructed for thermal system analysis in building physics. The library is the part of IBPT (International Building Physics Toolbox) and available for free downloading on www.ibpt.org. The other licenses are to be purchased from The Mathworks Inc.

CONCLUSIONS

Students can perform simulation and work with physical systems from within a single software package, which is conceptually simpler, more flexible and less expensive.

The undergraduates could observe that a moisture buffering effect exists. This effect has been shown both in numerical simulations and in laboratory experiments. They could observe the response of building materials, facing a daily cycle of relative humidity variation.

Laboratory classes are very important for students to familiarize with theoretical concepts and students feel that laboratory classes help them understand the moisture transport phenomenon. We believe that this experiment coupled with a simple numerical simulation is an excellent learning experience and is very motivational.

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