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A powerful simulator for moisture transfer in buildings

M. Karoglou, A. Moropoulou*, M.K. Krokida, Z.B. Maroulis

School of Chemical Engineering, National Technical University of Athens, Zografou Campus, 15780 Athens, Greece

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Abstract

The seasonal moisture transfer to and from the walls of a building is the most important factor concerning the deteriorating effect of moisture in buildings envelopes. The presented simulator takes into account the (a) moisture transfer mechanisms to and from the building (capillary rise, drying, etc.), (b) wall configuration (materials and size), (c) construction materials properties, (d) seasonal region meteorological data (air temperature, humidity and velocity) and calculates the (a) seasonal wall moisture content along with the corresponding equilibrium moisture height, (b) capillary rising water flow rate, (c) wall drying flow rate, etc. The simulator has been developed in an Excel platform in a user-friendly environment and consists of four units: (a) process model, (b) problem solution algorithms, (c) database and (d) graphics interface. The proposed simulator is a powerful tool in decision-making concerning the building deteriorating evolution and the selection of appropriate protecting strategy, e.g., the plaster selection (material, size, replacing time), contributing to the sustainability of masonries.

Keywords: Capillary rise; Drying kinetics; Decision-making; Plasters; Microstructure

1. Introduction

One of the widespread problems with historic masonries is the damage caused as a direct or indirect result of moisture transfer at the building envelope. In general, moisture causes:

- damage to the exterior walls,
- high heating energy consumption,
- uncomfortable indoor environment.

Thus, the building envelope restoration suffering from moisture problems is one of the critical key issues in sustainable refurbishment and conservation strategies [1]. The incompatible materials and techniques that are used in many cases accelerate the degradation process. There is a growing need for the development of new tools, which will contribute in masonries lifetime increase.

Moisture transfer in buildings is a very complex process and is influenced by many physical phenomena. Controlling the accumulation of moisture in building enclosures has been a topic of growing interest especially over the last 15 years [2]. The prediction of the hygrothermal performance of the building enclosure requires some knowledge of:

1. geometry of the enclosure (building shape and height),
2. boundary conditions (interior–exterior environment, boundary conditions between elements),
3. material properties,
4. physics, chemistry, thermodynamics and mathematics of combined moisture, heat and air transport and
5. performance thresholds.

In the literature, there are many computer-based tools aiming to predict the long-term hygrothermal performance of buildings. These models vary significantly concerning their mathematical sophistication. The model sophistication depends on the degree that takes into consideration the following parameters [3]:

1. moisture transfer dimension: one, two or three,
2. type of flow: time-steady-state, quasi-static or dynamic,
3. quality and availability of information,
4. stochastic nature of data.

*Corresponding author. Tel.: +30 210 7723276; fax: +30 210 7723215.
E-mail address: amoropul@central.ntua.gr (A. Moropoulou).

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A review of hygrothermal models for building envelope retrofit analysis made by Canada Mortgage and Housing Corporation (CMHC) has identified 45 computerized hygrothermal modeling tools. Most of them are not readily available to the public. More information is available for the following computerized hygrothermal modeling tools [4].

The WUFI-StOpStar and its family of predecessor WUFI and WUFI-ORNL/IBP are menu-driven PC programs that calculate the transient behavior of multi-layer building components exposed to a set of climatic conditions (2D Heat and Moisture transfer). The model uses a full retention function, from the sorption isotherm and suction curve, and also can be used for assessing the drying time of masonry with trapped construction moisture, the danger of interstitial condensation, the influence of driving rain on exterior building components, the effect of repair and retrofit measures and the hygrothermal performance of roof and wall assemblies under unanticipated use or in different climate zones [5,6].

The LETENITE-VTT is an enhanced version of the original LATENITE model (2D Heat and Moisture transfer). LETENITE-VTT includes not only the building envelope solver, but also a capability to simulate the interactions between the building envelope and the indoor air by solving the whole building energy and mass balance [7].

The MOIST is a PC program for predicting the one-dimensional transfer of heat and moisture in building envelopes (1D Heat and Moisture transfer). It enables user to define a wall, cathedral ceiling, or low-slope roof construction and to predict the temperature and moisture content (or relative humidity) of the individual construction layers as a function of time of year [8].

The UMIDUS is a PC program for the prediction of heat and moisture transfer in porous building elements (1D Heat and Moisture transfer). Models coupled heat and moisture transfer within porous media, in order to analyze hygrothermal performance of building elements when subjected to any kind of climate conditions. Both diffusion and capillary regimes are taken into account, i.e., the transfer of water in the vapor and liquid phases through the material can be analyzed. The model predicts moisture and a temperature profile within multi-layer walls and a low-slope roof for any time step and calculates heat and mass transfer [9].

The Delphin4 is a two-dimensional model for transport of heat, air, moisture and salt in porous materials (2D Heat, Air, Moisture and Salt transfer). It simulates the behavior of building materials and constructions close to reality, i.e., including climatic boundary conditions. The main goal is the development of building materials with an optimized hygrothermal performance, the evaluation of retrofitting strategies for historical buildings, the estimation of the energy consumption of old and new constructions taking into account moisture-related effects and to investigate damages caused by moisture. It uses a model of coupled heat, moisture and air transport in capillary porous materials, analyzing numerically the heat energy, the moisture and the air transport [10].

EMPTIED is a one-dimensional model for heat and moisture transport, with some considerations for air leakage included (1D Heat, Air and Moisture transfer). It predicts condensation [11].

GLASTA is a one-dimensional model for heat and moisture transport (1D Heat/Moisture). It is based on the Glaster method, but includes a model for capillary distribution within the layers of the assembly, and may be suitable for assessing drying potential [12].

MATCH is a one-dimensional model that accounts moisture transport by diffusion and liquid suction (1D Heat and Moisture transfer). The moisture retention properties have been taken into account. It considers the hygroscopic capacity of building materials. It also contains a detailed description of the two-way interaction, between the transfer of heat and moisture [13].

1D-HAM is a one-dimensional model for coupled heat, air and moisture transport in a multi-layered porous wall (1D Heat/Moisture). The program uses a finite-difference solution. Moisture is transferred by diffusion and convection in vapor phase. No liquid/water transport occurs. Climatic data are supplied through a data file with a maximum resolution of values per hour over the year [14].

In this work, a simulator is developed and proposed, for one-dimensional moisture transfer in buildings. The advantage of this work is the development of a general phenomenological model, which describes the mechanism of moisture transfer, capillary rise kinetics and evaporation phenomena, containing simple parameters with physical meaning. These models are based on a large amount of experimental data. The simulator uses the advantages of the Excel software. With the aid of this simulator, it is possible to predict the masonry capillary moisture height knowing some specific hygroscopic properties of building materials for selected environmental conditions.

Moreover, the appropriate restoration plaster can be selected based on the characteristics of the original structure. Therefore, this simulator is an effective tool for decision-making on the compatible restoration materials and techniques for the protection of masonries suffering from moisture problems.

2. Simulator scope

The development of the simulator intends to contribute to the solution of masonry moisture problems effectively. More specifically, aims of this tool are:

- prognosis of the seasonal wall moisture content along with the corresponding equilibrium moisture height,
- decision-making on effective restoration materials and techniques concerning moisture problems,
- increase of masonry service lifetime and
- comparison between alternative restoration materials.

In the market, there are many products which are proposed for the treatment of masonries with rising damp problems, and the decision on what material to apply is not so evident in most cases. Moreover in the last 20 years, some pre-mixed "smart" plasters have been developed, with controlled microstructure suitable for masonries with salt damp problems. These plasters are called macroporous plasters or dehumidifying plasters (in italian Intonaci macroporosi or in german Sanierputze) [15,16]. With the aid of the simulator, various restoration materials can be assessed before their real application. The validity of the simulator results can be tested by pilot-scale application of different plasters at various masonries and environments.

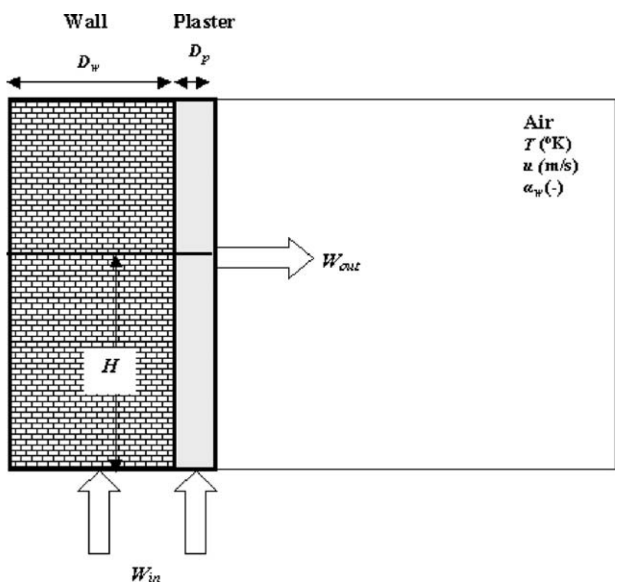

Fig. 1. Masonry system geometry.

3. Process model

Most common masonry systems consist of two layers, the substrate wall and the outer plaster. Wall is constructed either with brick or stone. Wall and plaster are compact and homogeneous, consisting of one material. Supposing that the above masonry system is in contact with ground moisture, while only the plaster layer is in contact with air, its main characteristics are:

a. *Masonry*: The masonry system characteristics are as follows (Fig. 1):

Wall (consisting of one material without the use of joint mortars)

- width D_w (m),
- bulk density ρ_{bw} (kg/m^3),
- capillary equilibrium height H_{cw} (m),
- capillary equilibrium moisture content X_{cw} (kg/kg db).

Plaster of one layer

- width D_p (m),
- bulk density ρ_{bp} (kg/m^3),
- capillary equilibrium height H_{cp} (m),
- capillary equilibrium moisture content X_{cp} (kg/kg db),
- equilibrium moisture content X_{ep} (kg/kg db).

Table 1
Example of materials properties

Code	Materials	Bulk density p_b (g/cm^3)	Sorption b_0 (kg/kg db%)	Drying c_0 (hrs)	Drying t_d (hrs)	Capillary t_c (d)
Bricks						
BRI	Traditional brick	1.53	11.9	4.62	0.19	3.81
BRM	Traditional brick	1.87	1.62	2.62	0.11	1.88
Plasters						
PEM	Suitable for rising damp phenomena with hydraulic lime as binder premixed	1.59	31.3	3.13	0.13	0.04
PMP	Premixed for rising damp phenomena with lime as binder	1.95	16.8	2.19	0.09	0.70
PRL	Premixed for rising damp phenomena/ cement based	1.75	29.8	2.82	0.12	2.11
PTI	Premixed cement-based mortar	1.54	17.3	3.20	0.13	1.97
PTR	Premixed for rising damp phenomena cement based	0.89	121	4.17	0.17	2.27
PZN	Traditional neoclassical building (Athens, 19th century) with lime binder	1.91	33.8	2.77	0.12	3.81
Stones						
SCY	Cyprus quarry	2.04	41.5	2.10	0.09	0.79
SRH	Rhodes quarry	2.45	6.12	1.88	0.08	0.02
SRY	Rethimno yellow quarry	1.79	14.2	2.79	0.12	1.27
SRW	Rethimno white quarry	1.86	18.4	2.10	0.09	0.24
			$b_1 = 3$ (°C)	$c_1 = 0$ (—)		
			$b_2 = 0.36$ (—)	$c_2 = 0.75$ (—)		
				$c_3 = -0.8$ (—)		

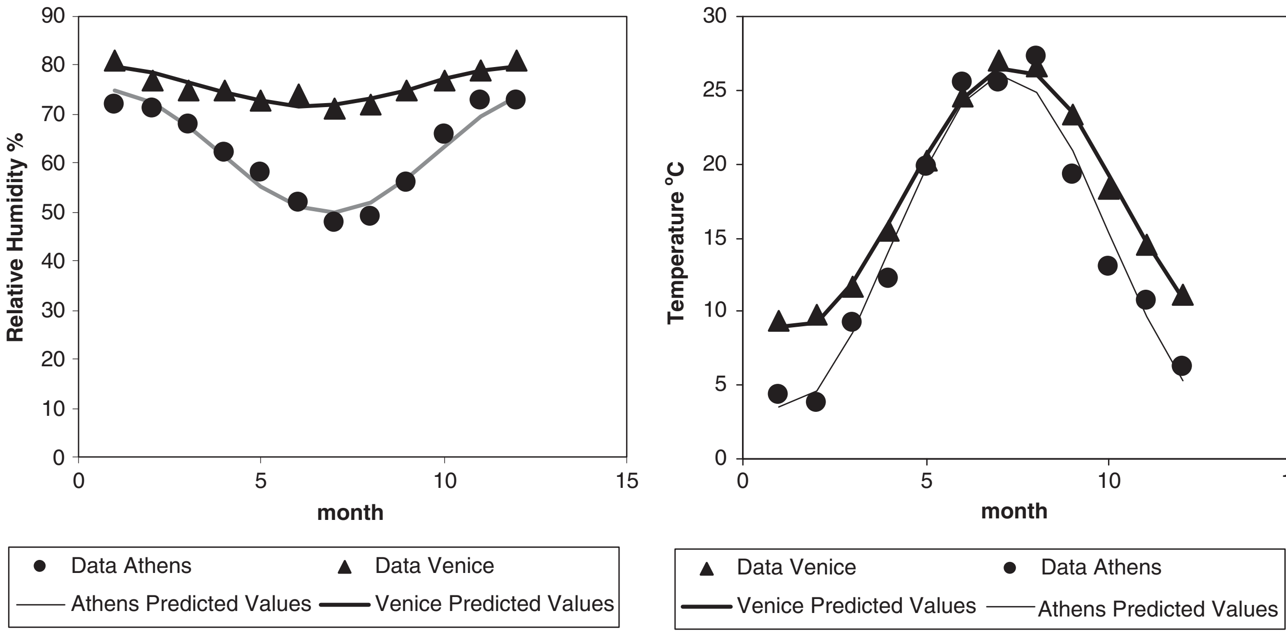

Fig. 2. Real and predicted meteorological data for two cities: Athens and Venice.

b. *Environment*: Air conditions

- air temperature T (°K),
- water activity α_w (—),
- air velocity u (m/s).

The main moisture transfer mechanisms taken into consideration are capillary suction and drying process. The physical parameters included in the model are described in Fig. 1. Rising damp is the main moisture source, as described by flow rate, W_{in}. Moisture evaporation phenomenon occurs only at the system outer layer, the plaster, which is in contact with air and is described by drying rate, W_{out}. The system is at equilibrium state with the environment, and the equilibrium moisture storage depends on the environmental conditions (air temperature, water activity and air velocity).

The two layers have different theoretical moisture equilibrium height due to their different microstructural characteristics, while moisture height (H) in wall and plaster system is the same. Moisture transfer phenomena to indoor environment, as well as the effect of system interface on moisture height are ignored, but they can be easily added in the future, with a simple mathematical modification of the proposed model.

3.1. Wetting phase

A first-order kinetic model is used for describing capillary rise phenomenon, which relates the moisture capillary height to time, as follows:

$$\frac{dH}{dt} = \frac{1}{t_c}(H_e - H), \tag{1}$$

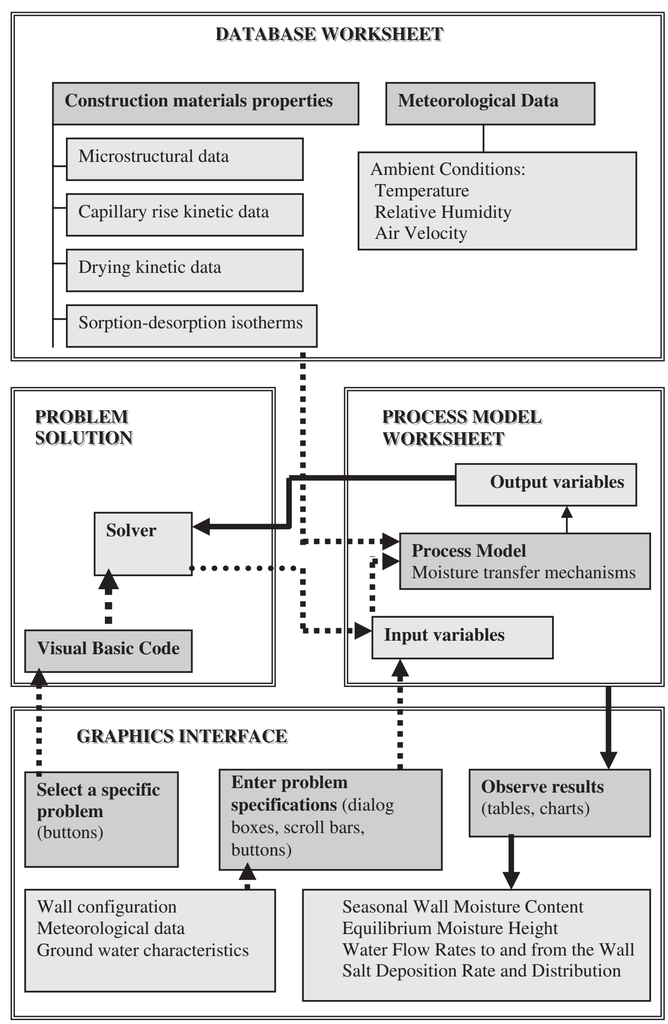

Fig. 3. Simulator architecture.

where t_c (d) is the capillary rise time constant [17]. H_e is moisture equilibrium capillary height, which is calculated using Jurin Law at steady state for vertical rise [18] by:

$$H_e = \frac{2\gamma}{\rho g r}, \tag{2}$$

where r (μm) is the average radius of the material, γ (dyn/cm) the surface tension of the liquid, ρ(g/cm^3) the water density, and g (m/s^2) the acceleration gravity force.

When the ground conditions and the masonry characteristics are kept constant, Eq. (1), for 1 day time period, integrates as follows:

$$W_{in} = \frac{H_{ew} - H}{t_{cw}} \rho_{bw} D_w X_{cw} + \frac{H_{ep} - H}{t_{cp}} \rho_{bp} D_p X_{cp}, \tag{3}$$

where W_{in} (kg/md) is the wetting rate of masonry due to capillary rise phenomenon, H_{ew} and H_{ep} (m) are the capillary equilibrium heights of wall and plaster, respectively, ρ_{bw} (kg/m^3) is wall bulk density, ρ_{bp} (kg/m^3) plaster bulk density, D_w(m) wall width, D_p (m) plaster width, X_{cw} and X_{cp} (kg/kg db) are capillary equilibrium moisture content of wall and plaster, and t_{cw} and t_{cp} (days) are capillary time constants of wall and plaster, respectively.

3.2. Drying phase

A first-order kinetic model is used for describing drying kinetics as follows:

$$\frac{dX}{dt} = -\frac{1}{t_d}(X - X_e), \tag{4}$$

where dX/dt is the drying rate, X (kg/kg db) the material moisture content at time t (h), t_d (h) the drying time constant and X_e (kg/kg db) the equilibrium material moisture content.

The drying and the capillary time constants are consistent with the process control terminology for

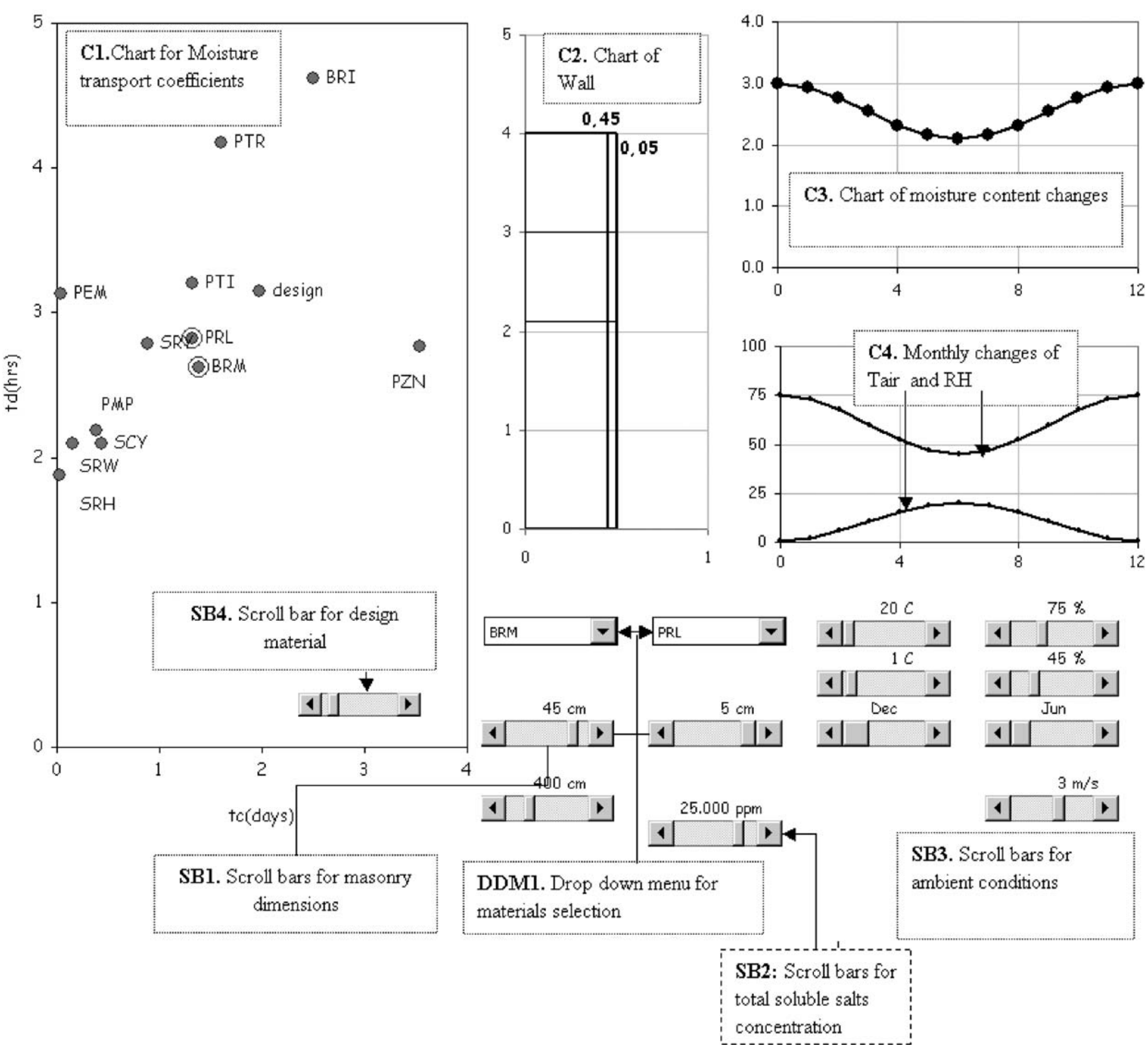

Fig. 4. Graphics interface and comments.

first-order dynamic systems and its value has physical meaning denoting the required time to remove the two-third of the total moisture.

The drying time constant depends on drying air conditions and material characteristics. Various empirical or semi-theoretical models have been proposed in the literature [19]. A simple power-law model seems adequate for most purposes. It incorporates the effect of drying air conditions, i.e., air velocity u (m/s), temperature T (°K) and water activity a_w(—):

$$t_d = c_0 T^{c_1} a_w^{c_2} u^{c_3}, \tag{5}$$

where c_0, c_1, c_2 and c_3 are adjustable empirical constants.

The equilibrium material moisture content X_e depends on air temperature T and water activity a_w. Various empirical or semi-theoretical models have been proposed in the literature, but a modified Oswin model proved to be the most appropriate for process design calculations [20]:

$$X_e = b_0 \exp\left(\frac{b_1}{T}\right)\left(\frac{a_w}{1-a_w}\right)^{b_2}, \tag{6}$$

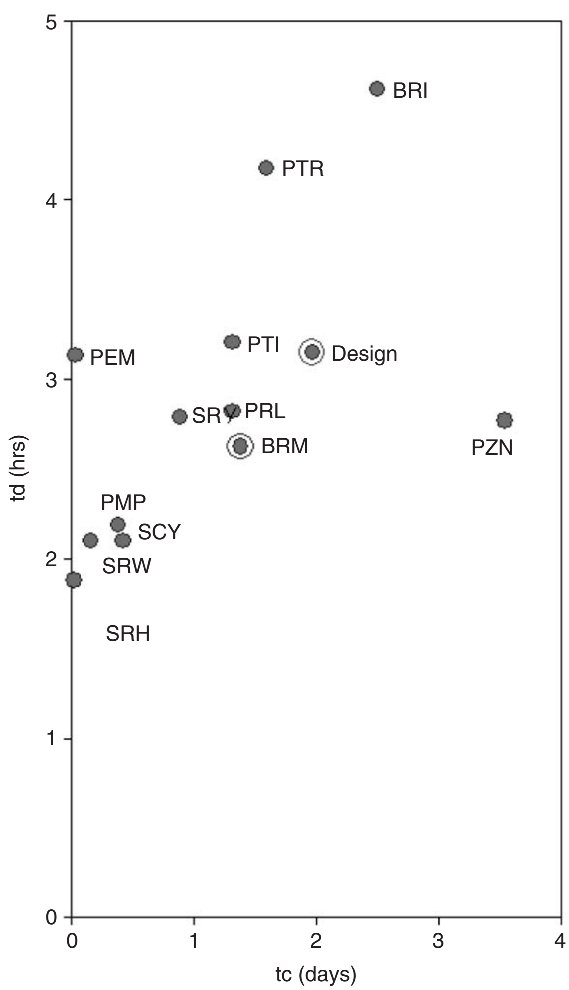

Fig. 5. Chart C1, where BRM is cycled as substrate material.

where b_1, b_2 and b_3 are adjustable empirical constants, dependent on the material characteristics.

By integration of Eq. (4) for 1 day time period, the drying rate of masonry W_{out} (kg/md) due to evaporation phenomenon can be estimated using the equation

$$W_{out} = \frac{X_{cp} - X_{ep}}{t_{dp}} \rho_{bp} D_p H, \tag{7}$$

where H (m) is the moisture height of the masonry system, ρ_{bp} (kg/m^3) bulk density of the plaster, D_p (m) plaster width, X_{cp} (kg/kg db) the capillary equilibrium moisture content of plaster, X_{ep} (kg/kg db) the equilibrium moisture content of plaster and t_{dp} (h) is the drying time constant of plaster.

As far as meteorological data are concerned, real data can be used or general equations fitted to experimental data of temperature and relative humidity. Mean values of temperature and humidity can be expressed as cosine function (Eq. (8)). This function incorporates parameters such as minimum and maximum temperature and humidity values and constant frequency per month.

$$T = \frac{T_{min} + T_{max}}{2} - \frac{T_{max} - T_{min}}{2} \cos\left(2\pi \frac{j_m - j_{T_{min}}}{12}\right),$$
$$RH = \frac{RH_{min} + RH_{max}}{2} - \frac{RH_{max} - RH_{min}}{2} \times \cos\left(2\pi \frac{j_m - j_{RH_{min}}}{12}\right), \tag{8}$$

where T is the average temperature (°C), RH the average relative humidity (—), T_{min} the minimum temperature values (°C), T_{max} the maximum temperature value (°C), RH_{min} the minimum relative humidity value (—), RH_{max} the maximum relative humidity value (—), j_m the number of month, $j_{T_{min}}$ the number of the month at which the minimum temperature value occurs and $j_{RH_{min}}$ the number of the month at which the minimum relative humidity value occurs.

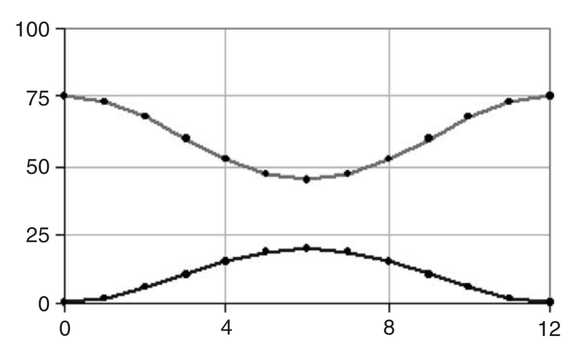

Fig. 6. Ambient conditions (chart C4).

4. Simulator architecture

The simulator has been developed on Microsoft Excel spreadsheets, which offer sufficient process hospitality. They are connected easily and are on-line with charts and graphic objects, resulting in powerful and easy-to-use graphical interface. Excel also supports mathematical and statistical tools. Databases are effective and easily assessed. In addition, Visual Basic for Applications (which is included in the new version of Excel) offers a powerful object-oriented programming [21].

Four different units can be distinguished, developed in different sheets.

1. Databases worksheet: This sheet contains all the data needed for calculations in the form of Data lists. The data could be extended or modified via appropriate dialogue boxes. The following databases are developed:

Construction materials properties:

- microstructural data,
- capillary rise kinetic data,
- drying kinetics data,
- sorption–desorption isotherms.

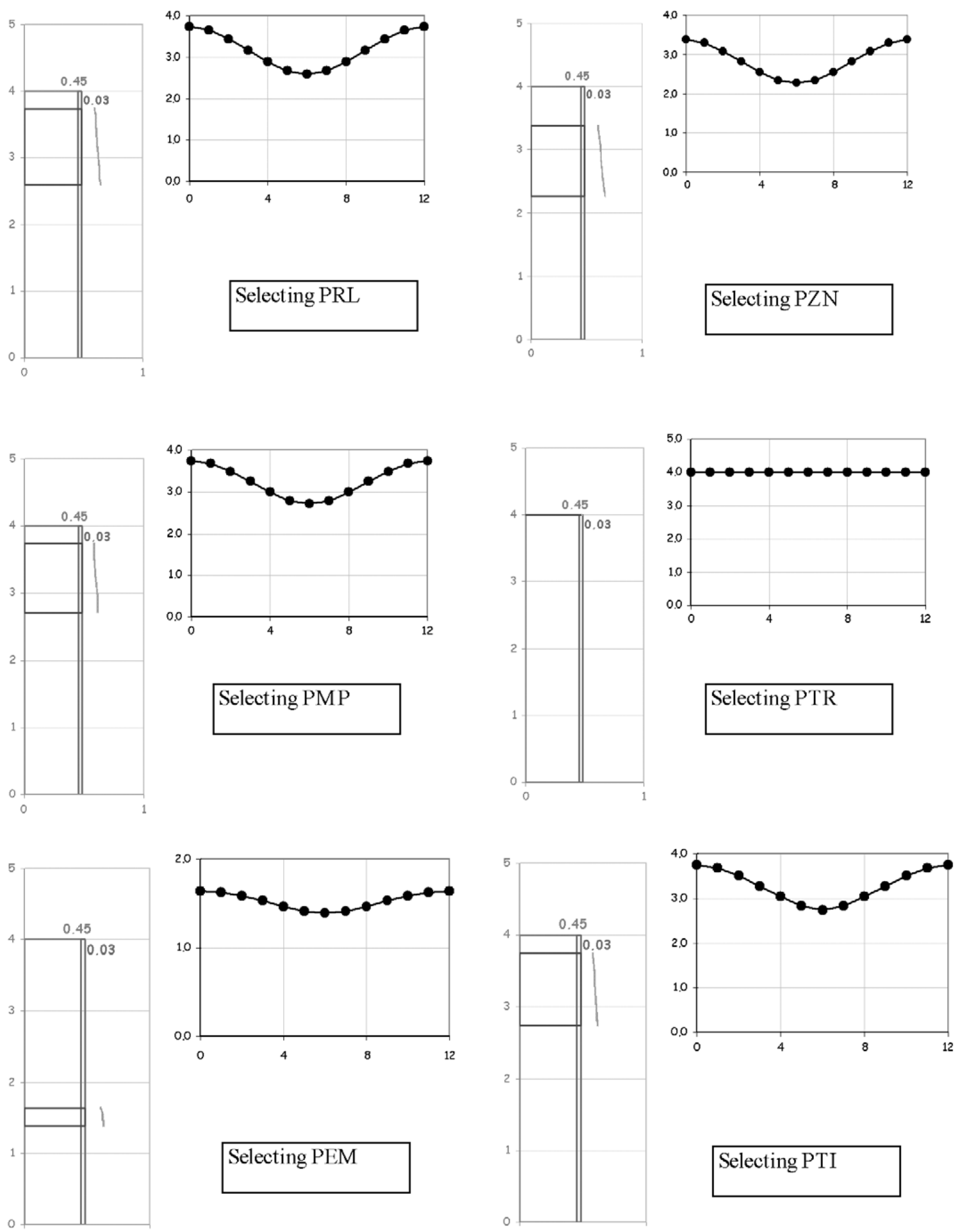

Fig. 7. Various BRM–PLASTERS systems and charts C2, C3 for each.

Table 1 shows the main characteristics of materials at the database worksheets for 12 different materials, such as bricks, stones and plasters.

Meteorological data:

- monthly changes of relative humidity, temperature and air velocity.

In Fig. 2, the real mean values of Relative Humidity and Temperature for Athens and Venice and the predicted values based on Eqs. (8) using the minimum and maximum values of Relative Humidity and Temperature are shown [22,23].

2. *Process model worksheet*: This is the heart of the system calculations. It contains the process model, as described in Eqs. (1)–(8). The model solution uses only worksheet functions. When any changes in input variables occur, the solution is obtained automatically on this worksheet.

3. *Problem solution algorithms*: The solution of different problems is based on the operational program of the above process model worksheet, and uses the Solver of Excel via Visual Basic program to obtain the solution.

4. *Graphics interface worksheet*: This is the only method for man–machine communication. The graphic interface will essentially consist of three parts:

- *Problem formulation*: The specifications and the required data for the problem to be solved are entered by the user or estimated from the databases. Data are inserted via dialogue boxes or buttons for changing some important magnitudes. The specifications will consider the wall configuration, i.e., the type and dimension of the masonry, the ground water characteristics, meteorological data, etc.
- *Problem type selection*: The type of problem (design or operational) to be solved is selected via buttons.
- *Results presentation*: The results will be obtained automatically and are presented in the form of tables or graphs.

The simulator architecture is summarized in Fig. 3 and its typical Graphics interface worksheet is shown in Fig. 4.

As shown in Fig. 4, the Graphics interface contains charts (symbolized as C in comments), drop down menus (symbolized as DDM in comments) and scroll bars (symbolized as SB in comments). The Graphics interface is user friendly. It consists of the following parts:

4.1. Problem specifications/problem type selection

With the use of DDM1 and SB1, the following five parameters are specified: the masonry construction material (now is selected as BRM, brick), the restoration plaster (now is selected as PRL), the masonry width (now is 45 cm), the plaster application width (at the moment is 5 cm) and the masonry height (currently 400 cm). The selected materials are marked automatically in chart C1

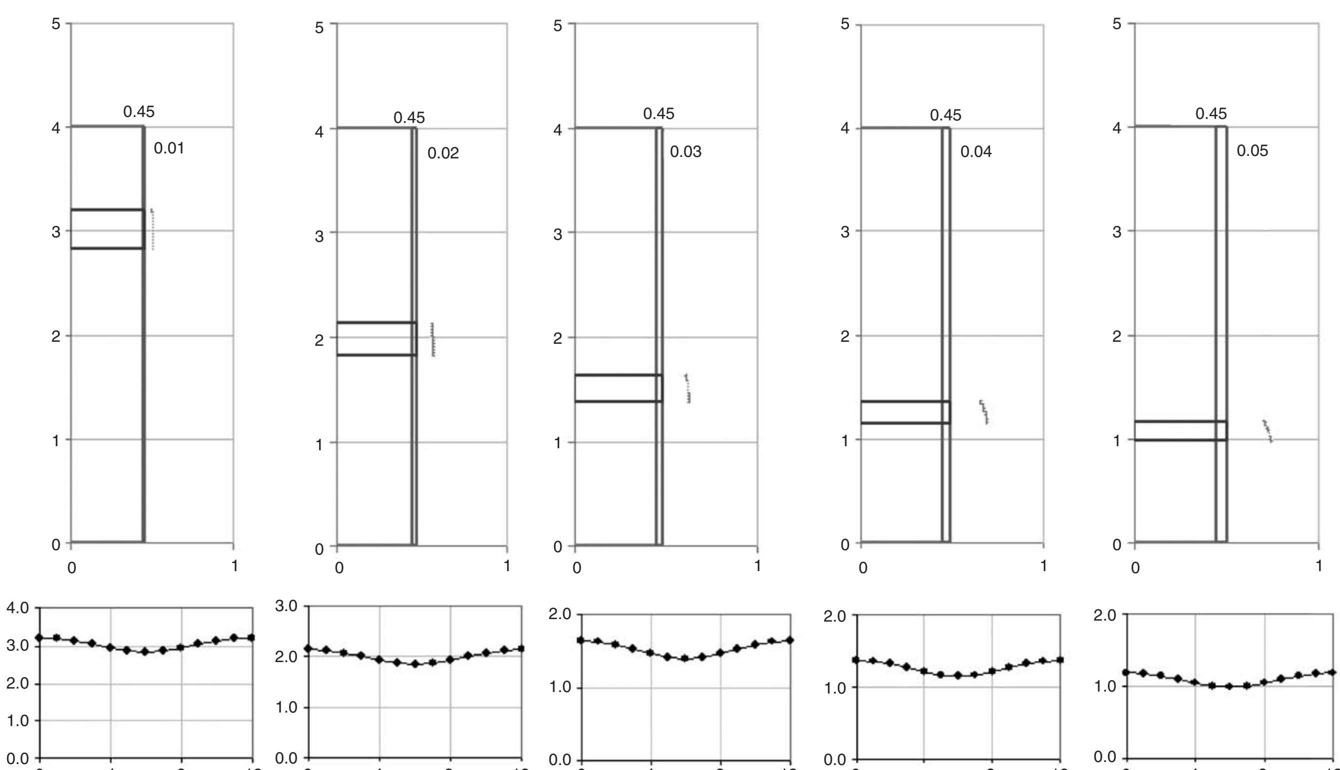

Fig. 8. Change of moisture height for masonry system BRM–PEM using different width of plaster (charts C2 and C3).

with circles. The group of materials that are shown in the chart C1 are presented in Table 1.

The selected masonry dimensions are presented in chart C2. With the use of SB2, the ground water total soluble salts concentration in ppm can be selected. The SB3 are used for input of ambient conditions. With SB4, the user can select a new material named as design material with characteristics of his choice. Also, month of year, temperature, relative humidity and air velocity can be selected. The changes of air temperature and relative humidity per month are shown in chart C4.

Chart C1 describes the time constant t_d (h) of drying kinetic to capillary height constant t_c (days) for all materials of the database. This specific chart gives a first idea about moisture performance of building materials and contributes decisively on the selection of the more hygrometric compatible restoration material.

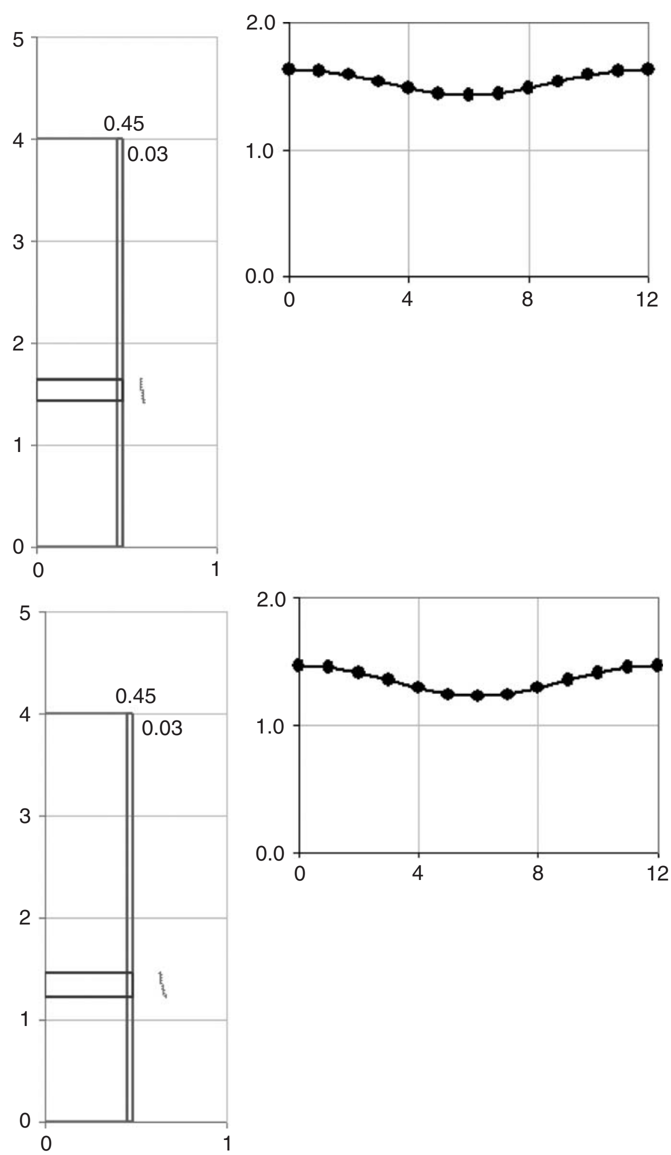

Fig. 9. Effect of air velocity on moisture content (charts C2 and C3).

4.2. Results presentation

The results are presented in the form of charts. The variation of moisture height per month is represented in chart C3, while the minimum and maximum height of moisture front, in chart C2.

5. Case study

The simulator resolves the two following typical problems:

- *The operational problem*: Given the masonry characteristics and air conditions, the moisture height of the system can be defined.
- *The design problem*: Given the air conditions and the wall characteristics, the appropriate plaster can be chosen.

Some typical problems solved by the simulator are indicated below.

5.1. Case study 1: keeping constant the wall configuration characteristics

BRM is selected as substrate material. This material, as it is shown cycled in C1, has mean values of t_d and t_c compared to other materials (Fig. 5).

The ambient conditions selected are T varying between 1 and 20 °C, the relative humidity between 40% and 75% and air velocity is equal to 3 m/s (Fig. 6).

For the selection of the appropriate restoration plaster, various masonry systems are presented in Fig. 7.

As it is shown in Fig. 7, the PEM, which is a macroporous plaster, seems to be the better plaster,

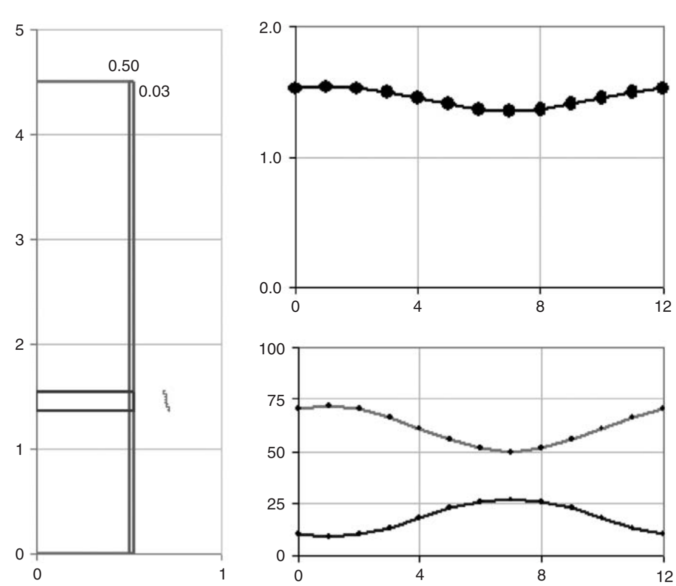

Fig. 10. Masonry BRM–PEM at city center of Athens (charts C2, C3 and C4).

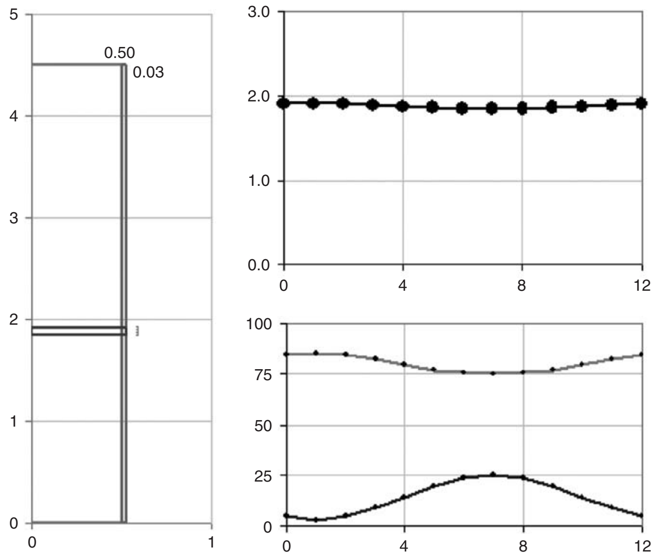

Fig. 11. Masonry BRM–PEM in Venice (charts C2, C3 and C4).

because it reduces the moisture height under 2 m. The PMP, PRL and PTI present almost the same behavior, although, as it is shown in Fig. 4, they present different t_d and t_c values.

5.2. Case study 2: knowing the plaster to decide on the application width

It is decided to apply PEM plaster at the same BRM wall as in case study 1. The question that now arises is what plaster width should be applied. In Fig. 8 is shown how the moisture height is modified using different PEM plaster width.

It is noticeable that the higher the width of the plaster, the greater the decrease of the moisture height.

5.3. Case study 3: scenario analysis

Knowing the required characteristics of plaster, the simulator can predict the variations of moisture height due to the impact of the environment at the masonry.

If for the case study 1, the masonry system BRM–PEM is selected and the air velocity increased from 3 to 5 m/s, then the graphs C2 and C3 for this system are as shown in Fig. 9.

As can be seen from Fig. 9, air velocity increase causes reduction in moisture content.

5.4. Case study 4: masonries located at different cities

Two masonries with the same characteristics are located at the city center of Athens and Venice. The masonry consists of brick BRM and plaster PEM. If the masonry is situated at the city center of Athens, then it has the following characteristics (Fig. 10).

If the same masonry is now situated at Venice, the masonry moisture content is higher, taking into consideration only the variations of environmental conditions (Fig. 11).

6. Conclusions

The proposed simulator is a powerful tool in decision-making concepts concerning the building deteriorating evolution and the selection of appropriate protecting strategy, e.g., the plaster selection (material, size and replacing time). By using this tool, the assessment of the effectiveness of restoration materials before their real application can be made, contributing to the extension of masonries lifetime, and also the reduction of cost and time waste of restoration works.

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