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Degradation Control of Walls with Rising Damp Problems: Numerical and Mathematical Analysis of the Evaporative Process

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ABSTRACT

Degradation in walls of Historical Building with rising damp is a complex problem to solve, due to the thickness and heterogeneity of those walls. The traditionally treatment techniques used (such as watertight barriers, injection of hydrofuge products, etc.) show, sometimes, to be ineffective, justifying the need to find a new approach. Experimental studies validate the effectiveness of a new treatment technique applied to the walls of old buildings – wall base ventilation system.

Building Physics Laboratory of the Faculty of Engineering, University of Porto is developing a model of this technique. The sizing of the treatment system is based on knowledge of the characteristics of the wall, of the geometry of the ventilation system and of the building being dealt with.

In this paper it is described the moisture transfer process between the moving air flux, inside the system, and the wall. A mathematical solution of a partial differential equation describing moisture conservation gave the concentration field near the wall surface and the mass transfer flux was integrated to give values of the Sherwood number as a function of Peclet number. Experimental results were used to validate the mathematical solution and the values obtained are practically the same. It is possible to get a relation between the flux of evaporation inside the system and some sizing parameters which is crucial to control the damp front level.

KEYWORDS

Rising damp treatment; Wall base ventilation system; Moisture transfer.

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1 INTRODUCTION

The mechanisms underlying the moisture transport through buildings are complex. In the vapour phase diffusion and convection have the main important role, while, in the liquid phase, capillary action, gravity and the pressure gradient effect control the moisture transfer.
In practice, moisture transport occurs in the liquid and vapour phases simultaneously, being dependent of several parameters such as temperature, relative humidity, precipitation, solar radiation, wind effect, atmospheric pressure (which define the boundary conditions) and the characteristics of building materials used.

Rising damp coming from the grounds that, by capillarity, climb through the porous materials constitutes one of the main causes of old buildings degradation, especially, its thick walls with heterogeneous composition. Once there are identify the special characteristics of those buildings, it is important to recognize the limitations of traditionally used technologies and to study new solutions for the rising damp phenomenon in historic buildings.

In Building Physics Laboratory (LFC), at Faculty of Engineering of University of Porto (FEUP), has been developed important experimental research about rising damp problems. In recent years, has been validated and experimentally characterized the operation principle of a treatment technique called “Wall Base Ventilation System to Treat Rising Damp - HUMIVENT” that consists on circulating air on the base of buildings walls with high thickness and heterogeneity in its constitution, with a saturation distant relative humidity. Wall base ventilation increases evaporation, which leads to a reduction in the level achieved by the damp front. This is possible only when the groundwater is lower than the base of the wall (see Colombert [1975]).

In previous studies it was possible to conclude, after experimental results analysis, that the wall base ventilation system reduces the level achieved by wet front. Following this work, experimental campaigns were carried out to explore the boundary conditions, geometry, speeds engine, etc., and it was possible to observe that a hygro-regulated system is essential to control the possibility of condensations occurrences in the interior of our system. A hygro-regulated system is a mechanical scheme controlled by probes placed at the inlet and outlet. These probes, in accordance with a pre-programmed criterion, will induce the system to turn on/off.

As a first step, it would be interesting to understand the behaviour of air within the conduct and to calculate the water flow removed from the wall. Therefore, this paper intends to develop a mathematical/numeric model that describes and characterizes the water vapour transport phenomena over the conduct and between the wall and the conduct. The experimental results of the present study are also useful to validate the proposed model and this is illustrated in the section on comparison with mathematical and numerical results.

2 ANALYTICAL AND NUMERICAL ANALYSE

In terms of analysis we consider a wall base ventilation system along which air is flowing, close to the saturated wall ($0<z<L$). Air flow will be taken to be steady, with uniform average velocity u, and if the concentration of water vapour in the air fed to the channel is c_0 and the water vapour saturation in the solid wall is c^*, a moisture transfer boundary layer will develop, across which the water vapour concentration drops from $c=c^*$, at $y=0$, to $c \rightarrow c_0$, for large y.

As there are basically two different forms of boundary layer flows: laminar and turbulent. In laminar flow, the transport of moisture, temperature and momentum across the boundary layers are controlled by molecular diffusion. The Reynolds number, $\mathrm{Re}=uL/\nu$, may be interpreted as the ratio of the flow destabilizing forces (inertia, u) to the stabilizing forces (viscosity, ν). Stable laminar flow is thus characterized by low values of Re. Laminar flow is found for Reynolds number less than approximately 3×10^5 (see Incropera and deWitt [2002]). In our study the Re<10^5, for all experiments.

If we restrict our analysis to those situations for which the moisture transfer boundary layer is thin and if a small control volume is considered, inside this boundary layer, with side lengths δz, δy and unity (perpendicular to the plane of the figure), a steady state material balance on the solute leads to

$$u\frac{\partial c}{\partial z} = D_{\text{m}}\frac{\partial^2 c}{\partial y^2} + D_{\text{m}}\frac{\partial^2 c}{\partial z^2} \tag{1}$$

where D_{m} is the molecular diffusion coefficient, in the cross stream and in the stream wise directions and c is the concentration of water vapour.

2.1 Analytical solution

Noting that the surface y=0, 0<z<L, is a surface of constant concentration, along which $\partial^2 c/\partial z^2 = 0$, it may be shown that the last term on the right hand side of (1) will be negligible, for a boundary layer which is thin in comparison with the length of the saturated wall. Equation (1) reduces then to the equation of diffusion in one dimension (Hall *et al*. [1984])

$$u\frac{\partial c}{\partial z} = D_{\text{m}}\frac{\partial^2 c}{\partial y^2} \tag{2}$$

and for the situation sketched in Fig. 1, Eq. (2) is to be solved with

$$c = c_0 \qquad z = 0 \qquad y > 0 \tag{3a}$$

$$c = c^* \qquad z > 0 \qquad y = 0 \tag{3b}$$

$$c \to c_0 \qquad z > 0 \qquad y \to \infty \tag{3c}$$

The first condition states that the leading edge of the saturated wall is approached by “fresh air” with the bulk concentration of water vapour, c_0. Condition (3b) states that the air is in equilibrium with the saturated water vapour at the wall surface (see Cussler [1997]). Condition (3c) states that the channel is wider (in the y direction) than the boundary layer. For constant u and D_{m}, the solution is

$$\frac{c - c_0}{c^* - c_0} = \text{erfc}\left(\frac{y}{2\sqrt{D_{\text{m}} z/u}}\right) \tag{4}$$

and the flux of evaporation at the saturated wall surface may be obtained from (4) as

$$N = -D_{\text{m}}\left(\frac{\partial c}{\partial y}\right)_{y=0} = \left(c^* - c_0\right)\left(\frac{D_{\text{m}}}{\pi\, z/u}\right)^{1/2} \tag{5}$$

The total rate of evaporation may be calculated taking the width b along the saturated wall surface, perpendicular to the flow direction

$$n = \int_0^L N\, b dz = \left(c^* - c_0\right) bL\left(\frac{4D_{\text{m}}}{\pi L/u}\right)^{1/2} \tag{6}$$

and it is useful to define the coefficient

$$k = \frac{n}{(bL)\ (c^* - c_0)} = \left(\frac{4D_{\text{m}}}{\pi L/u}\right)^{1/2} \tag{7}$$

2.2 Numerical solution

In order to integrate numerically Eq. (1) it is convenient to define the following dimensionless variables:

$$C = \frac{c - c_0}{c^* - c_0} \quad (8a)$$

$$Y = \frac{y}{L} \quad (8b)$$

$$Z = \frac{z}{L} \quad (8c)$$

$$\mathrm{Pe} = \frac{uL}{D_m} \quad (8d)$$

where Pe represents the Peclet number (based on the length, L). In terms of dimensionless variables, Eq. (1) may then be rewritten as

$$\mathrm{Pe}\frac{\partial C}{\partial Z} = \frac{\partial^2 C}{\partial Z^2} + \frac{\partial^2 C}{\partial Y^2} \quad (9)$$

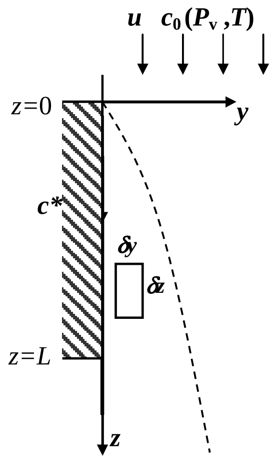

Figure 1. Moisture transfer boundary layer.

and the appropriate boundary conditions are

$$C \to 0 \qquad Z \to -\infty \qquad \forall Y \quad (10a)$$

$$C = 1 \qquad 0 \le Z \le 1 \qquad Y = 0 \quad (10b)$$

$$\frac{\partial C}{\partial Y} = 0 \qquad Z < 0 \vee Z > 1 \qquad Y = 0 \quad (10c)$$

$$C \to 0 \qquad \forall Z \qquad Y \to +\infty \quad (10d)$$

$$C \to 0 \qquad Z \to +\infty \qquad Y \ge 0 \quad (10e)$$

Equation (9) is to be solved numerically, subject to the boundary conditions (10a-e), over a large range of Pe of practical interest.

2.2.1 Discretisation

Equation (9) was solved numerically, using a finite-difference method in a non-uniform grid. The method is similar to that described in detail by Alves *et al.* [2006]. A second-order central differencing scheme was adopted for the discretisation of the diffusive terms on the right hand side of Eq. (9) and the convective term, on the left hand side of Eq. (9), was discretised using the CUBISTA high-resolution scheme of Alves *et al.* [2003], which preserves boundedness and higher-order accuracy, even for highly advective flows.

The discretised equation resulting from the finite-difference approximation of Eq. (12) reads:

$$\mathrm{Pe}\frac{C_{i+1/2,j} - C_{i-1/2,j}}{(\Delta Z_i + \Delta Z_{i+1})/2} = \frac{C_{i+1,j}(\Delta Z_i) - C_{i,j}(\Delta Z_i + \Delta Z_{i+1}) + C_{i-1,j}(\Delta Z_{i+1})}{\Delta Z_i\ \Delta Z_{i+1}\ (\Delta Z_i + \Delta Z_{i+1})/2} + \frac{C_{i,j+1}(\Delta Y_j) - C_{i,j}(\Delta Y_j + \Delta Y_{j+1}) + C_{i,j-1}(\Delta Y_{j+1})}{\Delta Y_j\ \Delta Y_{j+1}\ (\Delta Y_j + \Delta Y_{j+1})/2} \quad (11)$$

It is important that the $C_{i+1/2,j}$ and $C_{i-1/2,j}$ values are adequately interpolated from the known grid node values in order to preserve boundedness of the solution. The CUBISTA high-resolution scheme (Alves *et al.* [2003]) was therefore adopted, since it gives numerical stability and good precision. Details on the application of the CUBISTA scheme to evaluate the $C_{i-1/2,j}$ and $C_{i+1/2,j}$ face values are given in Alves *et al.* [2006].

The resulting system of linear equations was solved iteratively using the straightforward successive over-relaxation method (Ferziger and Peric [1996]. The implementation of the boundary conditions was as described in previous papers (e.g. Alves *et al.* [2006]). For the situation under study, an orthogonal mesh is adequate and care was taken to ensure proper refinement in the regions where the highest concentration gradients were expected.

The converged solution obtained in each grid yields values of $C_{i,j}$, from which the overall moisture-transfer rate from the saturated wall, n, was calculated. The total rate of evaporation may be calculated taking the width b along the saturated wall surface, perpendicular to the flow direction,

$$n = -\sum_i b(z_{i+1} - z_i) D_\mathrm{m} \left(\left.\frac{\partial c}{\partial y}\right|_{i,1} + \left.\frac{\partial c}{\partial y}\right|_{i+1,1} \right) \Big/ 2 \quad (12)$$

and the value of n was used to obtain the average Sherwood number,

$$\mathrm{Sh} = \frac{kL}{D_\mathrm{m}} = \frac{n}{bL\,(c^* - c_0)} \frac{L}{D_\mathrm{m}} \quad (13)$$

which in dimensionless discretised form reads

$$\mathrm{Sh} = -\sum_i (Z_{i+1} - Z_i) \left(\left.\frac{\partial C}{\partial \mathrm{Y}}\right|_{i,1} + \left.\frac{\partial C}{\partial \mathrm{Y}}\right|_{i+1,1} \right) \quad (14)$$

3 EXPERIMENTAL STUDY

The “HUMIVENT” technique consists of ventilating the base of the walls using a natural ventilation process or by installing a hygro-regulated mechanical ventilation device. The experiments were designed to show how these walls are affected by rising damp in view of different boundary conditions.

In our laboratory, LFC-FEUP, the relative humidity profile of 20 cm thick and 2 m length stone (limestone) walls was measured. In order to assess the effect of the insertion of a wall base ventilation system, a ventilation channel was placed on both sides. The ventilation box outlines the wall and as a 20cmx30cm section. A mechanical ventilator was placed at one end of a tube, leaving the other end free. This ventilation system functioned continuously throughout the testing period, so as to ensure that the temperature and relative humidity within the system were similar to the conditions inside the laboratory. The air velocities used were between 0.08 m/s and 0.63 m/s to avoid turbulence and consider that a low speed is adequate.

To assess moisture transfer inside the walls, probes were inserted at different heights and depths to measure relative humidity and temperature. The range of temperature and relative humidity’s obtained were 9.6ºC-24.8ºC (wall), 9.2ºC-28.8ºC (inlet), 8.9ºC-28.5ºC (outlet) and 94.2%-95.2% (wall), 20.4%-85.3% (inlet), 22.7%-87.6% (outlet). These probes were then connected to a data acquisition and recording system.

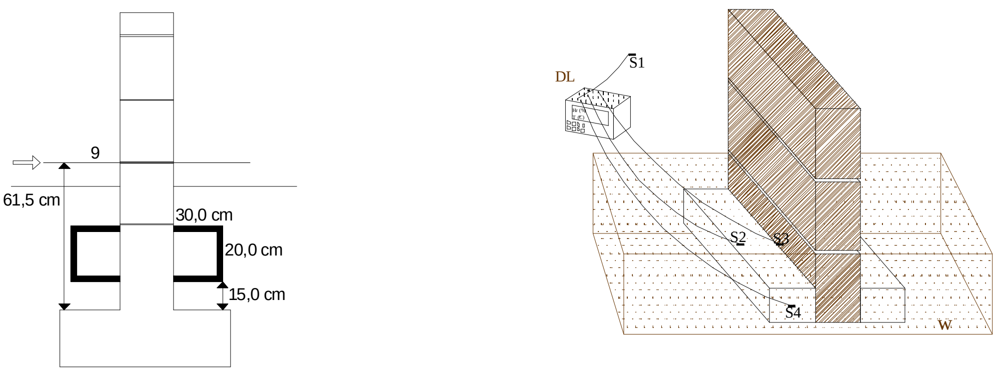

Figure 2. (a)-Relative damp variation at Level 9 and (b)-Physical model and location of probes (Freitas and Guimarães [2008]).

The configuration used is schematically represented in Fig. 2a, as are the relative humidity profiles in the section located at Level 9, 61.5 cm above the base of the wall (see Torres and Freitas [2007]). The boundary condition with system waterproofing was used. Probes were placed to obtain readings of the temperature and relative humidity at the entrance and exits of the ventilation systems (see Fig. 2b).

4. RESULTS AND DISCUSSION

4.1 Numerical results

The numerical solution of Eq. (9) gives the concentration field and from it, the instant rate of evaporation of the saturated wall, *n*, is obtained integrating the diffusion/dispersion flux over the whole saturated wall. This integral may be evaluated numerically, for each set of conditions, from the discretised concentration field that is obtained through the numerical solution of Eq. (9). It is convenient to express the rate of evaporation in terms of the Sherwood number, $\mathrm{Sh} = kL/D_\mathrm{m}$, where $k = n/\left[A(c^* - c_0)\right]$ is the moisture transfer coefficient for the saturated wall and *A* is the exposed area.

For the range of Peclet numbers numerically analysed the plot of Figure 3 reveals two asymptotes:

$$\mathrm{Sh} \to \left(\frac{2}{\pi}\right)^{1/2} (\mathrm{Pe})^{1/8} \qquad \text{for } \mathrm{Pe} \to 0 \tag{15}$$

and

$$\mathrm{Sh} \to \left(\frac{4}{\pi}\right)^{1/2} (\mathrm{Pe})^{1/2} \qquad \text{for } \mathrm{Pe} \to \infty \tag{16}$$

The numerical solution obtained is

$$\mathrm{Sh} = \left[\frac{2}{\pi}\mathrm{Pe}^{1/4} + \frac{4}{\pi}\mathrm{Pe}\right]^{1/2} \tag{17}$$

and the numerical values do not deviate by more than 3% from the value given by Eq. (17), over the entire range of values of Pe. Figure 3 shows that for Peclet numbers greater than 50 the numerical and analytical solutions do not deviate by more than 1%; and it is not surprising, since for thin concentration boundary layer, the asymptote given by Eq. (15) is not a relevant parameter.

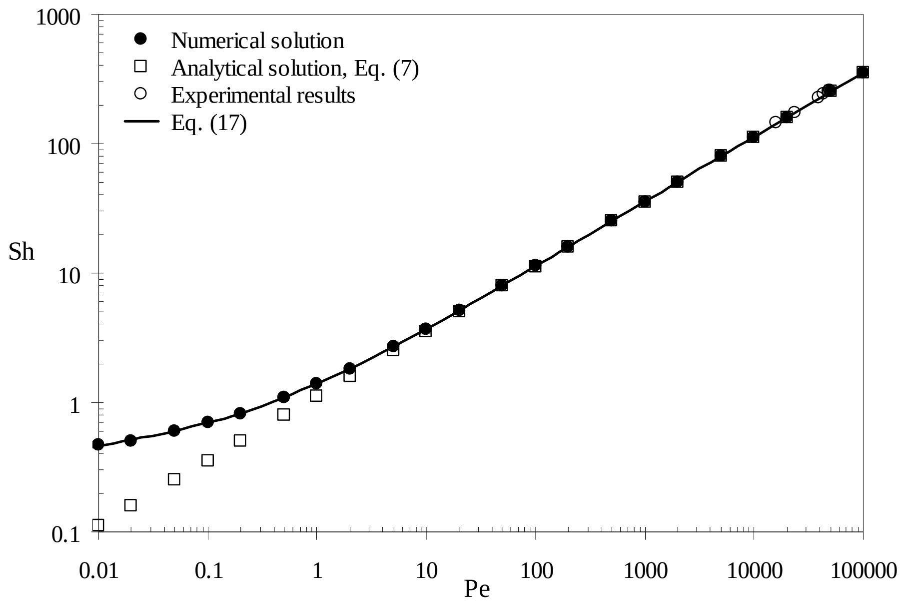

Figure 3. Dependence of Sh on Pe.

4.2 Experimental results

An example of experimental values of Sherwood numbers obtained for seven different air velocities are plotted as a function of Peclet number in Fig. 4. The values of Sh obtained are in good agreement with the numerical predictions, given by Eq. (17), with an error lesser than 4%. The water vapour concentration in the outlet stream, c_{out}, was continuously measured by data loggers, and when steady state was reached, the evaporation rate of the saturated wall could be found from:

$$n = Q(c_{out} - c_0) \tag{18}$$

where Q is the measured air volumetric flow rate. From Eq, (18) with Eq. (17) and $n = kA(c^* - c_0)$, the following equation is obtained

$$c_{out} = c_0 + \frac{D_m}{Q} b(c^* - c_0)\left[\frac{2}{\pi}\left(\frac{uL}{D_m}\right)^{1/4} + \frac{4}{\pi}\left(\frac{uL}{D_m}\right)\right]^{1/2} \tag{19}$$

and if we used the analytical solution (Eq. 7), instead Eq. (17), the following equation is obtained

$$c_{out} = c_0 + \frac{D_m}{Q} b(c^* - c_0)\left(\frac{4}{\pi}\frac{uL}{D_m}\right)^{1/2} \tag{20}$$

For our values of air velocity the Peclet numbers were between 6000 and 50000. In this range of Pe values the Eqs. (19) and (20) given practically the same results, which show that the effect of axial molecular diffusion can be negligible compared with transverse molecular diffusion. In Fig. 4 it is possible to see that the agreement between the theoretical and experimental results is excellent over the entire range.

During the five months of experimental research the new treatment technique extract approximately 80 kg of water. Actually, our group are studying if these values can cause bad consequences in terms of long-term deterioration of the wall materials. As we know the salts dissolved on water and the behaviour of these salts in terms of crystallization/dissolution aspect, the target, in the future, will be sizing the new system of rising damp treatment to avoid crystallization/dissolution problems.

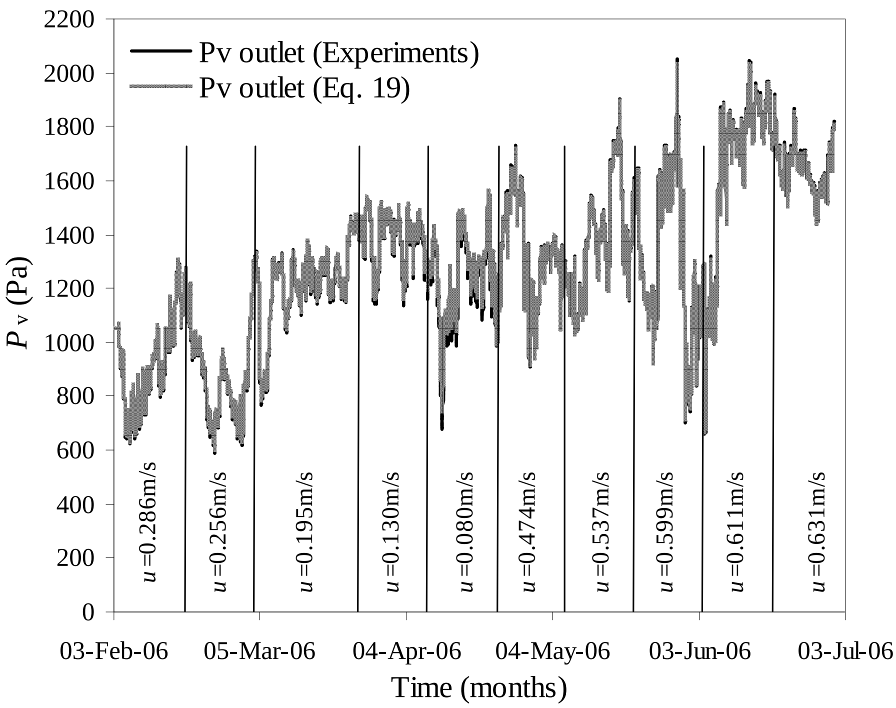

Figure 4. Comparison between the experimental values of water vapour in the outlet stream and the prevision given by Eq. (19).

5. CONCLUSIONS

The mechanisms of moisture transfer are complex, particularly regarding with rising damp in historic buildings. Once, the rising damp is one of the main causes of degradation of these buildings, it became important to study the factors related to this phenomenon. The placement of vapour-impermeable layers on the wall surface increases the level reached by rising damp.

Wall base ventilation is a simple technique that has a great practical potential and the experimental results performed at LFC-FEUP have shown that the placement of a wall base ventilation system on both side of the wall reduces the rising damp level.

The problem of moisture transfer between a saturated wall surface and the air flowing along it, lends itself to a simple full theoretical analysis, under an appropriate set of conditions. The elliptic equations resulting from differential moisture balance has been solved numerically over a wide range of values of the relevant parameters. It was found that the resulting Sherwood numbers are accurately represented by the equations presented above, Eq. (17).

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