Influence of a Refurbishing on an Old Residential building's Wall in Paris in Summer: Mass and Heat Transfer Approach

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Abstract: The implementation of thermal insulation in old residential building walls could compromise the hygrothermal behavior of this kind of construction. A bad installation of insulation, especially when it is place inside, could compromise the health of the wall with accumulation of moisture in the interfaces of two materials during cold periods. In summer time, insulation could have consequences on the quality of indoor air conditions. Thus, the evaluation of heat and mass transfer through the wall is an important and critical task. The aim of this study is to evaluate through a hygrothermal time-dependent 2D-model, the behavior of two kinds of multilayered renovated walls. Modelings are made under real external conditions (for a building located in Paris). COMSOL Multiphysics® is the modeling tool adopted, with the PDE interface which allows the coupling of mass and heat equations.

Keywords: Mass transfer, Heat transfer, Moisture, refurbishing, multi-layered wall

1. Introduction

Old buildings, like in Paris, were built with uninsulated thick walls made of porous materials with high thermal inertia, giving to these buildings a thermal potential in the quality of indoor conditions during summer time. Besides this thermal characteristic, the materials used in old buildings are mostly hygroscopic, which means that they are materials that absorb and release water vapor from the indoor air. Thus, walls in old buildings moderate the amplitude of the indoor relative humidity. These mechanisms also participate in the improvement of the indoor air quality and are energy saving, meanly in summer time.

French thermal regulation and the Factor 4 approach have resulted in the implementation of thermal insulation to reduce energy consumption during winter.

From an installation point of view, thermal insulation poses two major difficulties. When it is put inside, the living area surface is reduced. And when it is put outside, thermal insulation implementation is in most cases restricted, because a very large part of the old buildings in Paris are classified, and facades must be preserved.

From a hygrothermal point of view, the properties and the behavior of old buildings are affected by the installation of thermal insulation devices, mainly when they are placed inside. For this reason, it is important to evaluate heat and mass transfer through the old wall with insulation.

As mentioned before, most building materials are porous, with a solid matrix and pores. In this kind of media, the main mechanisms of moisture transfer are vapor diffusion (linked to Fick's law) and liquid conduction of water (linked to Darcy's law). Thus, every material has an isothermal curve that covers the hygroscopic and capillary region. The isothermal curve is a hygric property which shows the moisture content in the material as a function of relative humidity (Figure 1).

To assess the implications of insulation measures in old buildings, modeling time-dependent heat and mass (moisture) transfer through the wall becomes an important task. The aim of this study is to evaluate the hygrothermal behavior of a 2D-multilayered renovated wall, for two kinds of configurations: outside and inside thermal insulation, under real external conditions (for a building located in Paris). COMSOL multiphysics is a modeling tool which allows coupling heat and mass transfer equations through coefficients in the non-linear Partial Differential Equation (PDE) module [7, 1, 8].

2. State of the art

In physics buildings, heat and moisture transfer processes are described by means of a macroscopic model based on the conservative energy and mass governing equations, where temperature gradients and the moisture variation are the driving forces [9, 6, 2, 4]. Hence, the moisture variation in the mass transport equation could be described in terms of vapor pressure, moisture content or relative humidity [2, 4].

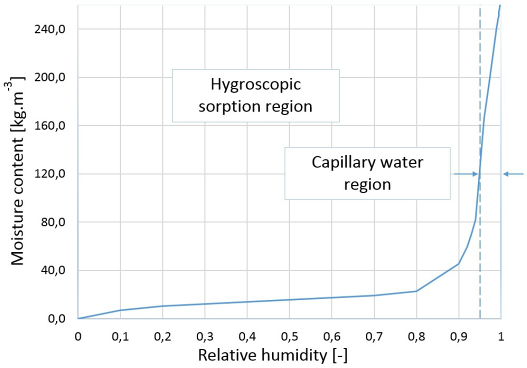


Figure 1. Equilibrium moisture content of limestone

Dos Santos *et al*. developed a heat, air and moisture transfer model (HAMT) that predicts the behavior of a building component and the effect of mass transport over the thermal flux [2]. Künzel proposes a method which connects the vapor pressure with the relative humidity, in order to ensure continuity at the interfaces in a multilayered component [4]. WUFI is a commercial software developed by Fraunhofer-institut based on Kunzel's model that simulates 2D dynamic heat and mass transfer for construction elements. However, this software restricts access to governing equations and does not allow changes to specific calculation parameters [7, 8]. In this field, other simplified lumped approaches have been developed, including the effective moisture penetration depth model (EMPD). This model is used to calculate the hygrothermal behavior of materials assuming that only a thin layer near the indoor surface, known as humidity buffer, interacts with the indoor air. Therefore there are no exchanges between outside and inside [3].

In this paper, heat and moisture transport model is expressed by means of partial derivatives equations, where gradient temperature and relative humidity variation are the driving forces.

3. Hygrothermal Model

The following partial differential equations (PDE) describe respectively heat and moisture transfer through a multilayered wall:

$$\frac{dH}{dT}\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right) + h_v\frac{\partial}{\partial x}\left(\delta_p\frac{\partial\left(\varphi p_{sat}\right)}{\partial x}\right) \quad (1)$$

$$\frac{dw}{d\varphi}\frac{\partial \varphi}{\partial t} = \frac{\partial}{\partial x}\left(D_\varphi\frac{\partial \varphi}{\partial x}\right) + \frac{\partial}{\partial x}\left(\delta_p\frac{\partial\left(\varphi p_{sat}\right)}{\partial x}\right) \quad (2)$$

Temperature T and relative humidity φ are the dependent variables in equations (1) and (2), hence the spatial derivative of $\varphi Psat$ term must be expressed in terms of T and φ [1]:

$$\delta_p\frac{\partial\left(\varphi p_{sat}\right)}{\partial x} = \delta_p\varphi\frac{\partial p_{sat}}{\partial T}\frac{\partial T}{\partial x} + \delta_p p_{sat}\frac{\partial \varphi}{\partial x} \quad (3)$$

In (2), the first term on the right side of the equation is linked to Darcy's law and the second term is linked to Fick's law which describes vapor and liquid transport respectively. Equation (3) describes the vapor diffusion term linked to a vapor diffusion coefficient δp as a hygric property of material. In building physics, the term linked to gravity effects on Darcy's law is disregarded.

The pressure vapor saturation is calculated as a function of temperature by the following empirical expression [4]:

$$p_{sat} = 611 \cdot exp\left(\frac{a \cdot T}{T_0 + T}\right) \quad (4)$$

With:

$$\begin{array}{lll} a = 22.44 & T_0 = 272.44°C & T < 0°C \\ a = 17.08 & T_0 = 234.18°C & T \geq 0°C \end{array}$$

The enthalpy of a system is the sum of sensitive and latent enthalpies:

$$H = \rho_s c_{ps} T + w c_{pw} T + w h_v \quad (5)$$

Thus, the heat storage capacity *dH/dT* in (1) depends on the heat capacity of the solid media (dry material) and the heat capacity of the moisture stocked in its pores:

$$\frac{dH}{dT} = \rho_s \left(c_{ps} + \frac{1}{\rho_s} w c_{pw} \right) \tag{6}$$

Substituting equations (3) and (6) into (1) and (2) yields :

$$\rho_s \left(c_{ps} + \frac{1}{\rho_s} w c_{pw} \right) \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(\lambda \frac{\partial T}{\partial x} \right) + h_v \frac{\partial}{\partial x} \left(\delta_p \varphi \frac{\partial p_{sat}}{\partial T} \frac{\partial T}{\partial x} + \delta_p p_{sat} \frac{\partial \varphi}{\partial x} \right) \tag{7}$$

$$\xi \frac{\partial \varphi}{\partial t} = \frac{\partial}{\partial x} \left(D_\varphi \frac{\partial \varphi}{\partial x} + \delta_p p_{sat} \frac{\partial \varphi}{\partial x} + \delta_p \varphi \frac{\partial p_{sat}}{\partial T} \frac{\partial T}{\partial x} \right) \tag{8}$$

With:

$\xi = dw/d\varphi$, $D\varphi = Dw.\xi$ and $\delta p = \delta/\mu$

4. Study cases

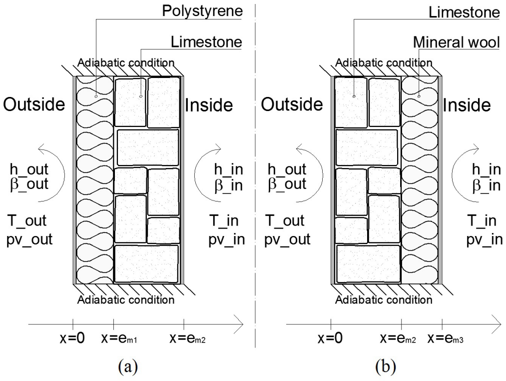


Figure 2. Case studies a) Case 1 outside polystyrene insulation, b) Case 2 inside mineral wool insulation

4.1. Description and hypotheses

In this paper, two cases are modeled. In case one, outside Polystyrene insulation and limestone are modeled, and in case two, inside mineral wool insulation and limestone are modeled (Figure 2). In both cases we assume that two layers are homogeneous with perfect contact between them, which means that contact resistance is neglected.

We have simplified two cases putting only two layers. In reality a renovated wall has multiples layers like mortar and plaster, that participate in heat and mass transfer process. Furthermore, old building walls built with limestone have small air cavities inside them.

As known, thermal conductivity *λi* is a material thermal property that change depending on the moisture content stocked in its pores. In this study we assume that has *λi* a constant value. In Table 1, some hygrothermal properties are shown.

Table 1. Material hygrothermal properties

Hygrothermal property	Units	Limestone	polystyrene insulation	Mineral wool
Bulk density ρ	[kg/m3]	2000	16	110
Thermal conductivity λ	[W/m.K]	2,3	0,036	0,043
Heat capacity c_p	[J/kgK]	840	1470	850
Water vapor resistance μ	[-]	50-40	73	3

4.2. Boundary conditions

The heat flux and mass flow exchanged between air and building element surfaces, are respectively described by the following relationship as a third kind boundary condition:

$$g_h = h_i \cdot (T_i - T) \tag{9}$$

$$g_m = \beta_i \cdot (p_{vi} - p_v) \tag{10}$$

Ti et *Pvi* are conditions from outside and inside air. This data is provided from measurements taken inside of an old renovated apartment in Paris during a summer day. External conditions have been taken from météo-Paris weather data website[10]. Indoor air temperature have been taken own project data (Figure 3). Heat transfer coefficient *hi* and mass transfer coefficient *βi* are taken as a constant value from [4]:

Indoor *h_in* = 17 [W/m^{2}K]

$\beta\_in = 75 * 10^{-9}$ [kg/m^{2}sPa]

Outdoor $h\_out = 17$ [W/m^{2}K]
$\beta\_out = 75 * 10^{-9}$ [kg/m^{2}sPa]

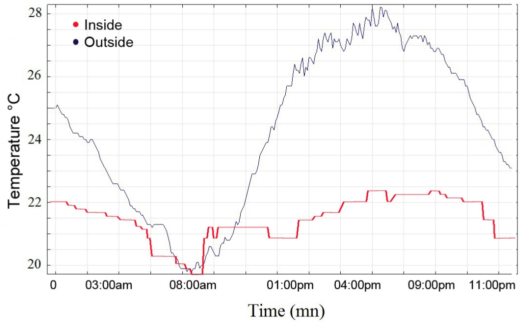


Figure 3 Indoor and external air temperature temperature in Paris during 25th July 2014

5. Use of COMSOL Multiphysics

COMSOL is a multiphysics commercial software, based on the finite element method (FEM) which allows coupling between different physics.

The solutions of equations (7) and (8) are solved simultaneously in COMSOL 4.4. multiphysics PDE's interface. These PDE's equations are describe and thereby coupled to be modeled. The generic form (11) offers the possibility to replace each term in the governing equation by coefficients, as shown below:

$$e_a \frac{\partial^2 u}{\partial t^2} + d_a \frac{\partial u}{\partial t} + \nabla \cdot (-c\nabla u - \alpha u + \gamma) + \beta \cdot \nabla u + au = f \quad (11)$$

With:

$$u = \{T, \varphi\}$$

$$d_a = \left\{ \frac{dH}{dT} = \rho_s \left(c_{ps} + \frac{1}{\rho_s} w c_{pw} \right), \frac{dw}{d\varphi} = \xi \right\}$$

$$c = \left\{ \lambda_s + h_v \delta_p \varphi \frac{dp_{sat}}{dT}, D_\varphi + \delta_p p_{sat} \right\}$$

$$\gamma = \left\{ h_v \delta_p p_{sat} \frac{\partial \varphi}{\partial x}, \delta_p \varphi \frac{\partial p_{sat}}{\partial T} \frac{\partial T}{\partial x} \right\}$$

$$e_a = \alpha = \beta = a = \{0, 0\}$$

The boundary conditions in COMSOL are expressed in the following manner:

$$\vec{n} \cdot (-c\nabla u - \alpha u + \gamma) + qu = g \quad (12)$$

g is the heat flux and mass flow exchange between air and walls surfaces, h_i and β_i from (9) and (10) respectively.

The spatial discretization, then the mesh of the model, is selected based on length scale governing physical phenomena modeled. In heat transfer and mass transport particularly, significant exchanges occurs on the surface or on the interfaces between materials. For this reason, we have chosen an extra-fine mesh along boundaries and fine mesh for the rest of the model. In this study, spatial discretization is build using triangular mesh.

6. Results

Modelling has been performed for one hot day during 25th July 2014 in Paris. Figure 3 and Figure 4 show temperature and relative humidity evolution at 6 different hours in this particular day, where outdoor temperature and relative humidity are important.

Figure 4 and Figure 6a show temperature evolution in materials. We observe that limestone damps down the daily temperature variation. This is explained by fact that limestone has a high heat capacity. Thus, an important a heat flow is required to cool down or heat up the material by one degree.

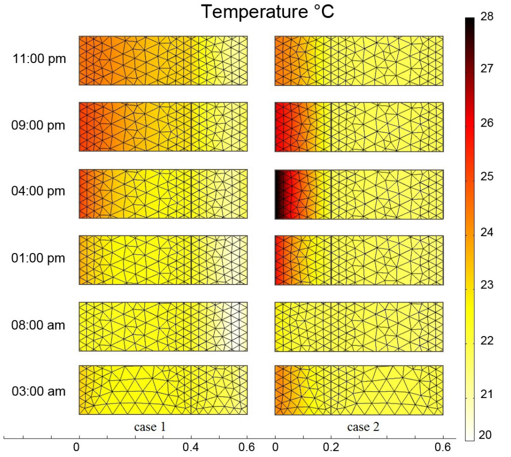


Figure 4. 2D modelling. Temperature Dependent variable evolution

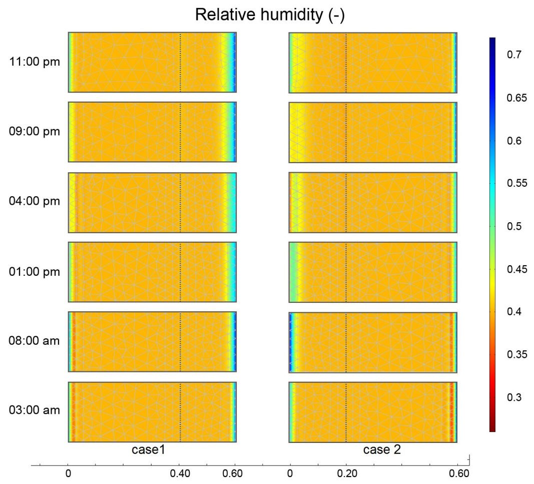
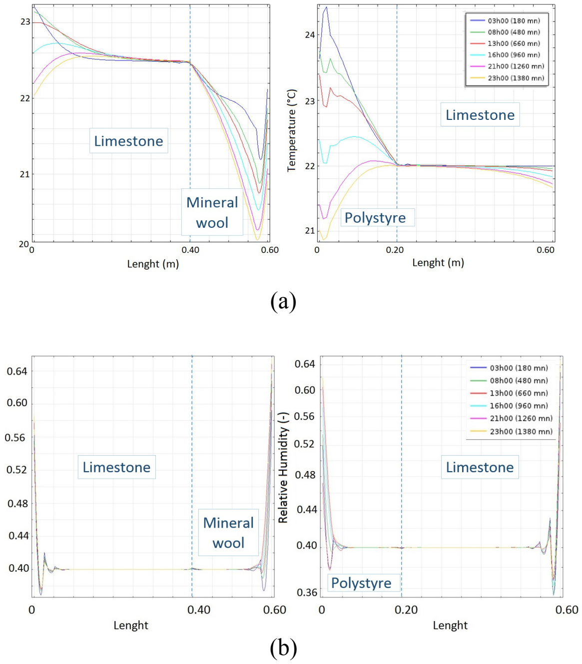


Figure 5. 2D modelling. Relative humidity Dependent variable evolution

In mass transfer (Figure 5 et Figure 6b) the modelling duration seems to be too short to assess moisture effect at the interfaces of two materials. Moisture transport for this period of time remains a surface phenomenon: changes are observed in thin layer 5 centimeters depth. Thus, it could be interesting to model mass transfer over a long period with more important external variations.



(a)

(b)

Figure 6. Temperature (a) and relative humidity (b) evolution at *0,50 meters from the ground*

7. Conclusions

This paper describes the process to model heat and moisture transfer in a multilayered wall using the COMSOL PDE module. In this interface, the mathematical model can be easily integrated by predefined coefficients that allow coupling between governing equations.

In mass transfer phenomena, more studies in time are required, because with one day data is difficult to evaluate moisture effect in interfaces between materials. Moreover, initial conditions are primary information on modeling, they could affect moisture and heat transfer results. Thus, it is important to build scenarios with different possible initial conditions over the same internal and external air conditions.

This study is a part of a project that aims to assess the impact of refurbishment measures in old buildings in Paris. One of the purposes is to interact between different scales in simulations, from the building component to a whole building. Thus, results obtained from modelling in COMSOL will be used in a simulation software that allows hygrothermal and dynamic building simulation during one year. Results will be also compared with literature and discuss.

8. References

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10. Nomenclature

c_{ps}	Heat capacity at constant pressure of solid media [J/kgK]
c_{pw}	Heat capacity at constant pressure of vapor water [J/kgK]
H	Enthalpy [J/m^3]
hi	Convective and radiative transfer coefficient [W/m^{2}K]
h_in	Inside convective and radiative transfer coefficient [W/m^{2}K]
h_out	Inside convective and radiative transfer coefficient [W/m^{2}K]
h_v	Evaporation enthalpy of water [J/kg]
D_φ	Liquid conduction coefficient [kg/ms]
D_w	Liquid transport coefficient [m^2/s]
g	Heat flux and mass flow from COMSOL boundary conditions
g_h	Heat flux [W/m^2]
g_m	Moisture flow [kg/m^{2}s]
p_{sat}	Water vapor saturation pressure [Pa]
p_v	Water vapor pressure [Pa]
T	Temperature [K]
w	Moisture content [kg/m^3]

Greek Symbols

β	Water vapor transfer coefficient [kg/m^{2}sPa]
δ_p	Water vapor permeability of material [kg/msPa]
δ	Water vapor permeability of stagnant air [kg/msPa]
φ	Relative humidity
λ	Heat conductivity of material [W/mK]
ξ	Moisture storage capacity [kg/m^3]
ρ_s	Bulk density of the dry material[kg/m^3]
μ	Water vapor diffusion resistance factor of building material [-]