Moisture Presence in Building Materials: Deterioration of Building Energy Properties

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Abstract

Energetic solution of thermal comfort in cities buildings plays a vital role at present and also for future. The problem of building energy saving is usually solved by means of the building insulation. However, a moisture presence in the building materials causes many risks. In this paper a linear system is formulated and its exact solution is determined. The system describes the wetting process in porous building material with phase transition. It consists of four equations. The first equation is a diffusion equation for air concentration w_a; the second equation is a diffusion equation for liquid moisture concentration w_l; the third one is a diffusion equation for saturated vapor concentration w_v; the second and the third equations are tied with the rate S of change of moisture concentration that arises in the pores due to the evaporation or condensation. The fourth equation is an algebraic one and describes three complementary parts of the masses in the pores volume. The system is solved by means of the variables separation method. The obtained analytical solutions are programmed and displayed in figures. An upper estimate of energetic loss is presented for the case of a moist building material.

Key words: management, environment, model, moisture, variable separation method

JEL Classification: C39, C69

1 Introduction

Urbanization is a strong and extensive driver that causes environmental pollution and climate change from local to global scale. Urban ecosystem modeling (UEM) is defined in an inter-disciplinary context to acquire a broad perception of urban ecological properties and their interactions with global change. (Chen, S., Chen, B., Fath, 2014). UEM plays one of the vital roles in smart cities' energetic solutions for the future. Climate changes are determined by anthropogenic activities and have a harmful effect on the environment. Through building design we can obtain mitigation and adaptation strategies in order to face climate changes and bring into being comfort management policies (Kadhim-Abid, 2014). This author proposes solution of changing climate conditions with the use of green roofs. At present, the energy saving management is closely related to the environmental management. MES (multi-energy systems) whereby electricity, heat, cooling, fuels, transport, and so on optimally interact with each other at various levels (for instance, within a district, city or region) representing an important opportunity to increase technical, economic and environmental performance relative to "classical" energy systems whose sectors are treated "separately" or "independently". It is not straightforward to identify performance metrics that are capable to properly capture costs and benefits that are relating to various types of MES according to different criteria (Mancarella, 2014). Energy providers will play a pivotal role over the coming decades in managing energy demand growth and reducing greenhouse gas (GHG) emissions (Heffner, du Pont, Rybka, Paton, Roy, and Limaye, 2013). The role of economic instruments (taxes, loans and grants, trading schemes and white certificates, public procurement and investment in R&D or infrastructure) is to kick-start the private financial markets, and to motivate private investors to fund energy efficiency measures. They should reinforce and promote energy performance regulations (Hilke, Ryan, 2012). The achievement of sustainable architectures, including control of energy relations between climate and built environment, in order to optimize energy consumption and reduce environmental impact, requires an integrated planning dealing with a multi-scale and integral view of building-plant system (Desideri, Proietti, Sdringola, Taticchi, Carbone, and Tonelli, 2010). The authors describe the design of a multifunctional complex, namely Solaria. Renewable power system solutions are widely investigated for residential applications. Grid-connected systems including energy storage elements are designed. Advanced research is actually focused on improving the reliability and energy density of renewable systems reducing the whole utility cost (Boscaino, Miceli, Capponi, Ricco Galluzzo, 2014). This author provides a detailed review of renewable energy system design issues and solutions. Sustainable technologies are important in the façade renewal of existing buildings in order to fit their energetic performance to different climatic inputs, following the new European Energy Standards for energy savings. The energy failure in existing buildings is mainly due to the poor insulating efficiency of the façades. Making use of hi-tech envelopes, not only the energetic balance, but also the architectural value of a building can be improved. (Brunoro, 2008). Buildings account for about 40% of the global energy consumption and contribute over 30% of the CO2 emissions. A large proportion of this energy is used for thermal comfort in buildings (Yang, Yan, Lam, 2014). This author reviews thermal comfort research work and discusses the implications for building energy efficiency. Judicious building design can significantly reduce energy required to heat, cool, and illuminate buildings. A novel approach to optimizing light and heat exchanges across the building envelope (i.e., exterior surfaces such as walls and windows) is proposed in (Futurell, Ozelkan, 2014). Marketing "building performance" alone or even "energy efficiency" to consumers may not be the best approach. Most successful contractors sit down and listen to homeowners talk about their house, and a typical driver has to do with comfort. Homeowners are not comfortable in some rooms, or they find they have odors, have seen mold or know they have a wet basement (Betz, 2012).

Metrics are essential methodological tools for analyzing the financial position of the subject in each of the domains of management (Jenčová, 2011). The energy saving management and closely related the environmental management play a vital role in thermal insulation of buildings. One of the main risks in this area is the presence of moisture in the porous building material used. Damage to building envelope is mostly caused by moisture. Building envelope failures can be attributed to this aspect of moisture accumulation. Severe condensation in wall cavities has resulted in splintered masonry, the formation of a crusty deposit, and corrosion of masonry ties and precast wall anchors. (Leong, 1990). The problems that influence enclosure functionality the most - moisture intrusion, air infiltration, and faulty or missing insulation - are often the hardest to identify because they can't be readily seen. There are several telltale signs that your envelope isn't getting the job done. Early indications of problems include thermal discomfort, a moldy scent, or the presence of moisture. Energy consultants, structural engineers, and building science experts can do an investigation and make the real diagnosis. Materials can't be looked at independently. It should be recognized how the insulation interacts with the water and air control layers, the vapor permeability of all materials, and their locations relative to each other. Then take into consideration both the exterior and interior environments. (Curtland, 2013). In addition, work (Kong, Zhang, 2013) states that some parameters as apparent density, specific heat, average thermal diffusivity, heat storage coefficient and thermal inertia index, which were always considered as constants for a fixed building envelope are also changed with the heat and mass transfer of building envelope.

In our work we focus on moisture. One of key information for determining real diagnosis is knowing the characteristics of transfer of moisture and air through the external wall, which consists of porous material. We are especially focusing on complicated problem of exact formulation of moisture and air transfer through porous material in the form of mathematical functions, which are a result of analytical solution of formulated problem (task) of linear system of differential equations with special conditions. Main outcome of this article is an analytical expression of functions from exact found solution and graphical representation of behavior of these functions.

In the past, several authors have studied the problem of moisture transfer in porous media. (Let us mention at least the following works of Lykov, 1954, 1971, de Vries 1957, 1958, Glasser, 1958, Vasilieva, 1966,, Reeves and Celia, 1996, Reshetin and Orlov, 1998, Korjenic, Teblick and Bednar, 2010, 2011, Litavcová, Pavluš, and Seman, 2011-2014, and many others). In some of these works the moisture is viewed as a set of water molecules regardless of their phase state. The reason is that even new experimental methods for moisture detection like neutron radiography method (Reeves, Celia, 1996). or magnetic resonance method (Valckenborg, Pel, Hazreti, Kopinga, Marchand, 2001) cannot distinguish between different phases. In reality, different phases of water in the pores of material are present and should be considered.

The present work provides moisture transfer model, in which the moisture is subdivided into a liquid component (water) and saturated vapor (water vapor). Moreover, dry air is considered in the pores, as well. Air presence was not considered in the previous studies (Litavcová, Pavluš, and Seman, 2011-2014). This subdivision has a practical significance in the fact that during the wetting of a dry sample (sample contains a dry air in the pores at the beginning) an evaporation occurs in the pores of the material as well as diffusion of vapor within material pores to the material surface where the vapor evaporates to the outer space. Furthermore, the model describes not only the evaporation of water into the vapor but also, in general, the condensation of the saturated vapor to water in the pores of material. Next, we suppose a macroscopic isothermal process of wetting when wetting rates are rather low for imparting too large temperature gradients within the material.

In this work we formulate a problem of wetting of a dry sample and looking for the exact solution using the method of separation of variables and the method of constant variation. The received formulas of exact solution are programmed and displayed in the corresponding figures which allow us to conclude a correctness of the proposed model.

2 Model

Let us consider a dry sample consisting of a solid phase while in the pores of the material some air, saturated vapor and no liquid are present. Let us introduce the function of the concentration of air $w_a(x,t)$, liquid $w_l(x,t)$, the function of the concentration of saturated vapor $w_v(x,t)$, and the source function $S(x,t)$ characterizing the rate of a phase transition which takes positive values if the liquid is evaporating and negative values if saturated vapor is condensed into liquid, while x is independent spatial variable and t is independent time variable. Let us denote Π the constant pores volume, ϱ_i and D_i the density and the diffusion coefficients for the air ($i = a$), liquid phase ($i = l$), and for the saturated vapor phase ($i = v$). We shall assume that all these coefficients are positive and that $\varrho_l > \varrho_v$.
Then we can describe the model of wetting of a dry sample by the following system of four equations

$$\frac{\partial w_a}{\partial t} = \frac{\partial}{\partial x}\left(D_a \frac{\partial w_a}{\partial x}\right),\ 0 < x < 1,\ t > 0, \tag{1}$$

$$\frac{\partial w_l}{\partial t} = \frac{\partial}{\partial x}\left(D_l \frac{\partial w_l}{\partial x}\right) - S,\ 0 < x < 1,\ t > 0, \tag{2}$$

$$\frac{\partial w_v}{\partial t} = \frac{\partial}{\partial x}\left(D_v \frac{\partial w_v}{\partial x}\right) + S,\ 0 < x < 1,\ t > 0, \tag{3}$$

$$\Pi = \frac{w_a}{\varrho_a} + \frac{w_l}{\varrho_l} + \frac{w_v}{\varrho_v},\ 0 \le x \le 1,\ t \ge 0, \tag{4}$$

with initial conditions for $t = 0$

$$w_a(x,0) = \Pi\varrho_a,\ w_l(x,0) = 0,\ S(x,0) = 0,\ 0 \le x \le 1, \tag{5}$$

boundary conditions for $x = 0$

$$-D_a \frac{\partial w_a}{\partial x}(0,t) = 0,\ -D_l \frac{\partial w_l}{\partial x}(0,t) = 0,\ t > 0 \tag{6}$$

and boundary conditions for $x = 1$

$$w_a(1,t) = \Pi\varrho_a e^{-\alpha_a t},\ w_l(1,t) = \Pi\varrho_l(1 - e^{-\alpha_l t}),\ t > 0. \tag{7}$$

We shall assume that ϱ_a, ϱ_l, ϱ_v, D_a, D_l, D_v, Π, α_a, α_l are positive constants and $\alpha_l \le \alpha_a$. From this using the boundary condition (7) and the equation (4) we shall easily get that

$$w_v(1,t) \ge 0,\ t > 0. \tag{8}$$

Detailed exact solution of the shown system of differential equations for basal expression of transfer of moisture through porous material under specific given conditions we have obtained using the elimination method, and the variables separation method, and it is shown in Appendix. Analytical expression of the function $w_a(x,t)$ is there referred in formula (9), the function $w_l(x,t)$ is referred in the formula (11), the function $w_v(x,t)$ is referred in formula (13) and the function $S(x,t)$ is referred in formula (14).

3 Conclusions

Relations (9-19) we used to calculate the curves of the functions w_a, w_l, w_v, S at the time moments 0, 0.02, 0.05, 0.3, 0.65, 1 corresponding to the state of the sample at 0, 0.4, 1, 6, 13 and 20 days from the beginning of the wetting process. We have made calculations for the following parameter values: $\Pi = 0.72$, $\alpha_a = 50, \alpha_l = 0.1$, $\varrho_a = 0.0016, \varrho_l = 1.39, \varrho_v = 0.000036$, $D_a = 0.2$, $D_l = 1$, and $D_v = 0.5$. In doing so, we approximately replaced $\sum_{k=1}^{\infty}$ by $\sum_{k=1}^{N}$ with a sufficiently large N. We have used $N = 10000$. The results are shown graphically in the following Figure.

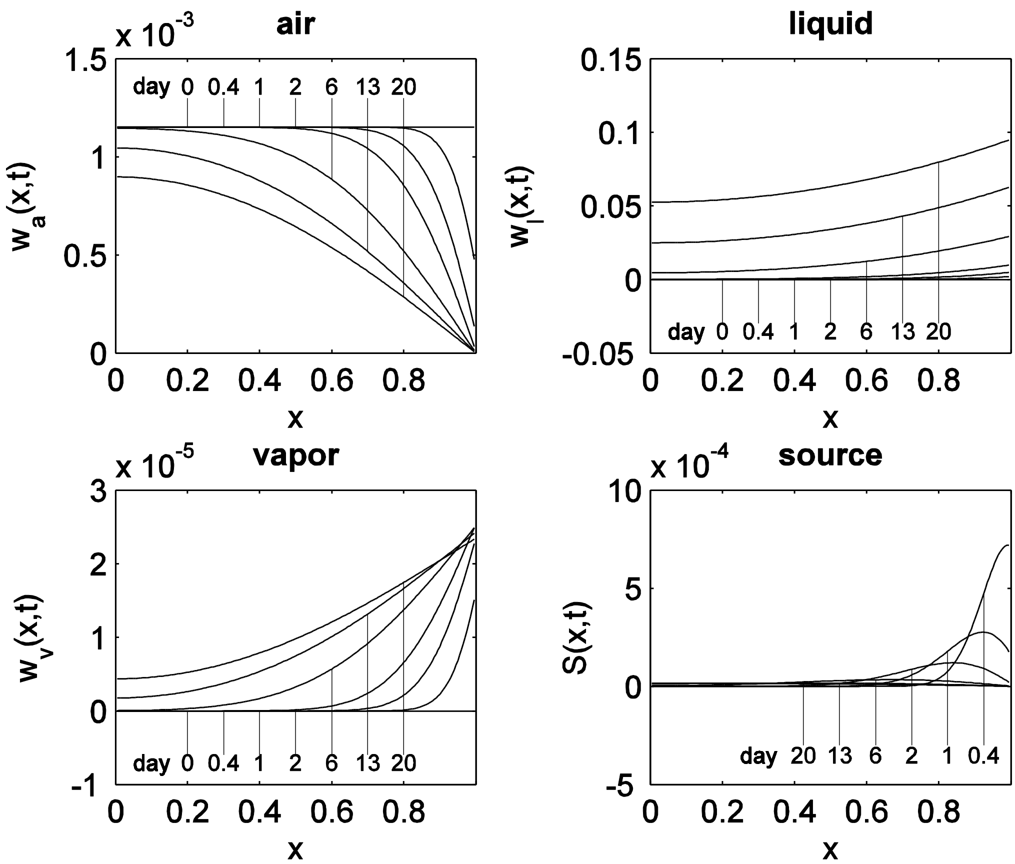

Fig. Graphs of the air, liquid and saturated vapor concentrations w_a, w_l, w_v , and the source S.

We can see that the profiles of liquid concentration w_l and vapor concentration w_v are successively increasing while the profiles of dry air are successively decreasing. The profiles of the source function S at the beginning of the process are rapidly increasing and after they are slowly decreasing. The obtained exact solution adequately reflects the wetting process with phase transition. Found exact solution brings knowledge about the process of wetting of buildings materials. This, in turn, allows a more precise formulation of the recalculation of the thickness of the insulating material for the optimal management of the cost of its acquisition.

Primary asset of this article consists of exact formulation of behavior of functions, which describe behavior of moisture in porous materials. That is a finding, which has a potential to significantly contribute to optimization of thermal insulation technology. The purpose is an elimination of errors, which are result of incorrect thermal insulation of buildings, which we are often witnessing in practice. It is an information, which can be used in smart cities energetic solutions for the future.

4 Appendix – solution

$$w_a(x,t) = \Pi\varrho_a \left\{ e^{-\alpha_a t} + 2\alpha_a \sum_{k=1}^{\infty} \frac{2(-1)^{k-1}}{(2k-1)\pi(\alpha_a + D_a\lambda_k)} \left(e^{D_a\lambda_k t} - e^{-\alpha_a t}\right) \cos\frac{(2k-1)\pi x}{2} \right\}, \quad (9)$$

$$\frac{\partial^2 w_a(x,t)}{\partial x^2} = 2\alpha_a \Pi\varrho_a \sum_{k=1}^{\infty} \frac{2(-1)^{k-1}\lambda_k}{(2k-1)\pi(\alpha_a + D_a\lambda_k)} \left(e^{D_a\lambda_k t} - e^{-\alpha_a t}\right) \cos\frac{(2k-1)\pi x}{2}, \quad (10)$$

$$w_l(x,t) = \Pi\varrho_l(1 - e^{-\alpha_l t}) + \sum_{k=1}^{\infty} Z_k(t)X_k(x), \quad (11)$$

$$\frac{\partial^2 w_l(x,t)}{\partial x^2} = \sum_{k=1}^{\infty} \lambda_k Z_k(t)X_k(x), \quad (12)$$

$$w_v(x,t) = \varrho_v \left(\Pi - \frac{w_a(x,t)}{\varrho_a} - \frac{w_l(x,t)}{\varrho_l} \right), \ 0 \le x \le 1, \ t \ge 0, \quad (13)$$

$$S(x,t) = -\frac{\varrho_l\varrho_v}{\varrho_l - \varrho_v} \left[\frac{1}{\varrho_a}(D_a - D_v)\frac{\partial^2 w_a}{\partial x^2} + \frac{1}{\varrho_l}(D_l - D_v)\frac{\partial^2 w_l}{\partial x^2} \right], \ 0 < x < 1, \ t > 0, \quad (14)$$

where

$$\lambda_k = -\left[\frac{(2k-1)\pi}{2}\right]^2, \ X_k(x) = \cos\sqrt{|\lambda_k|} = \cos\frac{(2k-1)\pi x}{2}, \ k = 1,2,3,\cdots \quad (15)$$

$$Z_k(t) = g_k e^{-\alpha_l t} + h_k e^{D_a\lambda_k t} + z_k e^{-\alpha_a t} - (g_k + h_k + z_k)e^{D\lambda_k t}, \ t \ge 0, \quad (16)$$

$$g_k = \Pi\varrho_l\alpha_l \frac{4(-1)^{k-1}}{(2k-1)\pi(\alpha_l + D\lambda_k)}, \quad (17)$$

$$h_k = \bar{D}\Pi\varrho_a\alpha_a \frac{4(-1)^{k-1}}{(2k-1)\pi(\alpha_a + D_a\lambda_k)(D_a - D)}, \quad (18)$$

$$z_k = \bar{D}\Pi\varrho_a\alpha_a \frac{4(-1)^{k-1}\lambda_k}{(2k-1)\pi(\alpha_a + D_a\lambda_k)(\alpha_a + D\lambda_k)}, \ k = 1,2,\cdots. \quad (19)$$

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