The finite element analysis of water vapor diffusion in a brick with vertical holes

Madalina Calbureanu, Mihai Talu, Carlos Manuel Travieso-González,
Stefan Talu, Mihai Lungu, Raluca Malciu

Abstract— This paper presents a finite element analysis of water vapor diffusion in a brick with vertical holes. The isotherms, isodensity, isopressure and isohumidity surfaces considering the longitudinal and transverse direction diffusion of water vapor in a brick with vertical holes are determined. The numerical results obtained from this study are usually used in the engineering practice to optimal design the spatial structure of building walls. The results obtained from this analysis are compared with the experimental data taken from the literature, and a good agreement is observed.

Keywords— Brick wall, diffusion, finite element method (FEM), numerical simulation.

I. INTRODUCTION

BUILDING physics processes, the structural and material properties of wall structures and the geometry of external surfaces, play an important role in their future energy efficiency and maintenance, [1]–[8].

The water vapor diffusion through the building walls, is an important problem related to comfort and quality living conditions inside a building, [9]–[49].

The vapor quantity in the air at a given temperature determines the water vapor pressure.

The vapor diffusion in building structural components, is due to the pressure difference of water vapor between the inside air p_i and outside air p_e; in winter the $p_i > p_e$ and in summer the $p_i < p_e$

The diffusion process depends on the internal structure of building elements, the vapor pressure, the vapor permeability and the climate data.

In assessing the risk of condensation, there are two cases:
a) to risk assessment of condensation on the interior surface of element;
b) to risk assessment of condensation inside the building element.

In the first case (a) it must be evaluated the relation: $\theta_{si} > \tau_r$, where: θ_{si} – the interior surface temperature; τ_r - dew point temperature.

The dew point temperature depends on the temperature and humidity of the interior surface temperature.

In the second case (b) it must be evaluated:
- the temperature variation within the building element;
- the variation of vapor saturation pressure in the structure of building element, p_{vs};
- the variation of water vapor effective pressure, p_v;
- the variation of the relative air humidity in the structure element, φ.

The condition to avoid condensation inside the building element is to respect the relationship: $p_v < p_{vs}$.

Let's consider the study for a model of a 3D wall made by the brick blocks (Fig. 1).

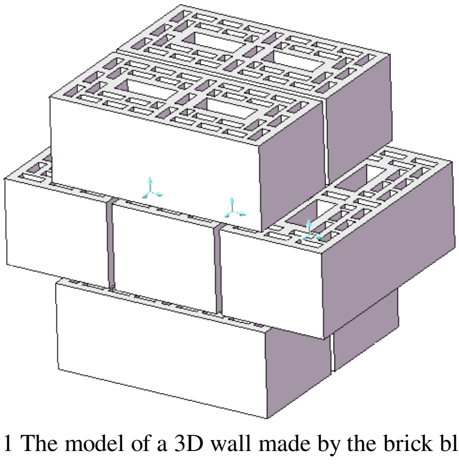

Fig. 1 The model of a 3D wall made by the brick blocks

Manuscript received May 10, 2010. This work was supported in part by the Romanian Ministry of Education, Research and Youth, through The National University Research Council, Grant PN–II–ID–PCE–2007–1, code ID_1107, 2007 - 2009.

Madalina Călbureanu is with the University of Craiova, Romania. He is now with the Department of Road Vehicles, Faculty of Mechanics, no. 165, Calea Bucuresti Street, Craiova, 200585 Romania (phone: +40-251-418-803; fax: +40-251-418-803; e-mail: madalina.calbureanu @gmail.com).

MihaiȚălu is with the University of Craiova, Romania. He is now with the Department of Applied Mechanics, Faculty of Mechanics, no. 165, Cl. Bucuresti St., Craiova, 200585 Romania (e-mail: mihai_talu@yahoo.com).

Carlos Manuel Travieso-Gonzalez is with the University of Las Palmas de Gran Canaria, Spain. He is now with the Technological Centre for Innovation in Communications (CeTIC), Higher Technical School of Telecommunications Engineering Campus Universitario de Tafira, s/n, Pabellon B - Despacho 111 35017 - Las Palmas de Gran Canaria, Spain (e-mail: ctravieso@dsc.ulpgc.es).

Stefan Țălu is with the Technical University of Cluj-Napoca, Romania. He is now with the Department of Descriptive Geometry and Engineering Graphics, Faculty of Mechanics, no. 103-105, B-dul Muncii Street, Cluj-Napoca, 400641 Romania (e-mail: stefan_ta@yahoo.com).

Mihai Lungu is with the University of Craiova, Romania. He is now with the Department of Avionics, Faculty of Electrical Engineering, no. 107, Decebal Blv., Craiova, 200585 Romania (e-mail: mlungu@elth.ucv.ro).

Raluca Malciu is with the University of Craiova, Romania. He is now with the Faculty of Mechanics, no. 165, Calea Bucuresti Street, Craiova, 200585 Romania (e-mail: rmalciu@yahoo.com).

The study for this model was adopted in order to analyze the longitudinal (Fig. 2) and transverse (Fig. 3) diffusion of water vapor in the brick block.

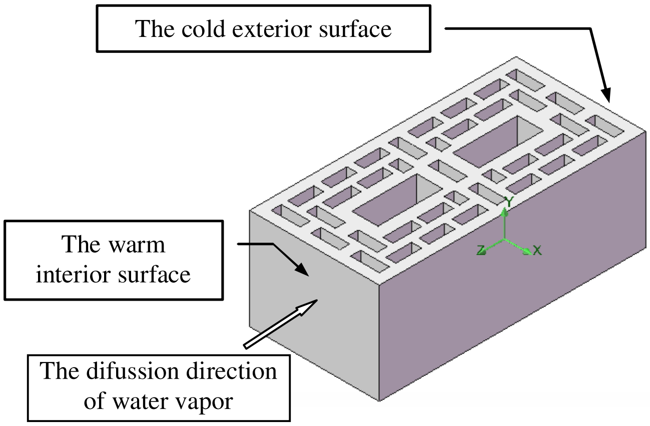

Fig. 2 The longitudinal diffusion of water vapor in the brick block

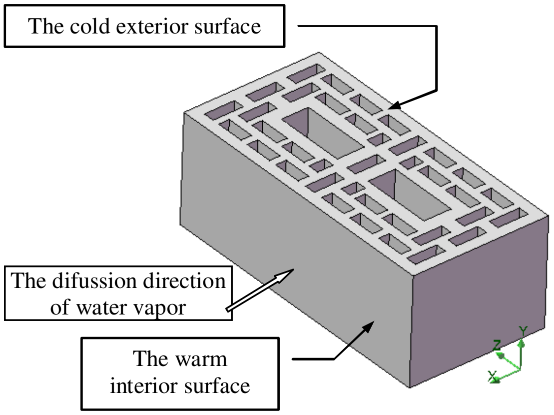

Fig. 3 The transverse diffusion of water vapor in the brick block

The brick blocks shown in isometrical representation (Fig. 2 and Fig. 3) are standardized building elements according STAS 5185/2-86.

This construction element by type 36.5 x 18 has the dimensions shown in Table I.

TABLE I
THE DIMENSIONS FOR CONSTRUCTION ELEMENT BY TYPE 36.5 X 18

Sizes [mm]	Nominal dimension [mm]	Limit deviation [mm]
Length (L)	365	+5 -7
Width (b)	180	+4 -5
Height (h)	138	+4 -4

II. MATHEMATICAL MODEL

Within each layer of a wall construction, moisture transfer is governed by dimensional conservation of mass equation [50]:

$$\frac{\partial}{\partial y}\left(D_{\gamma}(\gamma,T)\frac{\partial\gamma}{\partial y}\right)+\frac{\partial}{\partial y}\left(D_{T}(\gamma,T)\frac{\partial T}{\partial y}\right)=\frac{\partial\gamma}{\partial t}. \tag{1}$$

where: y (m) - distance from inside surface of wall; γ (kg/kg) - moisture content on dry basis; T (ºC) - temperature; D_γ (m^2/s) - diffusivity for moisture gradient; D_T (m^2/ºC·s) - diffusivity for temperature gradient; t (s) – time.

The selection of moisture content (γ) and temperature (T) as potentials has the advantage that the same mathematical formulation represents both diffusion transfer and capillary transfer. This formulation is equivalent to using water-vapor pressure as the moisture transfer potential in the diffusion regime and suction pressure in the capillary flow regime with a single required diffusivity.

Heat transfer is governed by the one-dimensional conservation of energy equation:

$$\frac{\partial}{\partial y}\left(k(\gamma,T)\frac{\partial T}{\partial y}\right)=\rho_{d}(C_{d}+\gamma C_{w})\frac{\partial T}{\partial t}. \tag{2}$$

where: k (W/m · ºC) - thermal conductivity of porous material; ρ (kg/m^3) - density of dry material; C_d (J/kg · ºC) - specific heat of dry material; C_w (J/kg · ºC) - specific heat of water;

Latent transport of heat is included at the boundaries of the layers. The other components of enthalpy transport by moisture movement are generally small and are therefore neglected in the analysis. In the term $\rho(C_d + \gamma C_w)$ the heat capacity of dry material is given by ρC_d and the heat capacity of the accumulate moisture is given by $\rho\gamma C_w$.

Strong couplings exist between heat and moisture transfer in the preceding two governing equations. Both the diffusivity for the moisture gradient (D_γ) and the diffusivity for the temperature gradient (D_T) are strong functions of moisture content and temperature. The thermal conductivity (k) is a function of moisture content and temperature.

When the moisture content of a material is below fiber saturation, the diffusivity for the moisture gradient (D_γ) and the diffusivity for the temperature gradient (D_T) are determined with next relations:

$$D_{\gamma}=\frac{\mu(\phi)P_{vg}(T)}{\rho_{d}\dfrac{\partial f(\phi)}{\partial\phi}}\ ;\ D_{T}=\frac{\mu(\phi)\phi\dfrac{P_{vg}(T)}{\partial T}}{\rho_{d}}. \tag{3}$$

where: μ (kg/s·m·Pa) - water-vapor permeability; *Φ* - relative humidity; P_{vg} (Pa) - water-vapor saturation pressure; f (*Φ*) - sorption isotherm function.

The above equations may be derived by introducing the sorption isotherm fimction f (*Φ*) and applying the chain rule to Fick's steady-state diffusion equation with the gradient of the water-vapor pressure as the driving-force potential.

When the moisture content of a material is above fiber saturation, a liquid diffusivity (D_γ) is used in eqn. (1).

The diffusivity for the temperature gradient (D_T) is calculated using the second relation of eqn. (3).

The model also has a provision for including non-storage layers that may be sandwiched between two storage layers.

III. THE FINITE ELEMENT ANALYSIS

A. *Initial data*

The Finite Elements Analysis was performed using SolidWorks 3D Design and CosmosFlow 2010, [51]-[58].

The initial data are: pressure, temperature and humidity on the warm surface of water vapor (corresponding to the interior of room) and of the cold surface (from exterior that is in direct contact with external environment), that are shown in Table II.

TABLE II
THE INITIAL DATA

Surface	The pressure [N/mm^2]	The temperature [°K]	φ [%]
The cold surface	100100	255.2	80
The warm surface	101325	291.2	60

It is also considered the gravity effect of water vapor.

Tab. III presents the enviroment conditions such as the temperature for inside of the wall and in exterior and the convection coefficient.

TAB. III THE ENVIRONMENTAL CONDITIONS USED IN EXPERIMENTAL SOFT SIMULATION - TEMPERATURES AND CONVECTION COEFFICIENTS

Interior Temperature [^{0}C]	External Temperature [^{0}C]	Interior Convection Coefficient α_i [W/m^{2}K]	Exterior Convection Coefficient α_e[W/m^{2}K]
18	-18	7	17
18	-18	7	17

The graphical variations of water for: density, dynamic viscosity, thermal conductivity with temperature and the specific heat, are shown from Fig. 4 to Fig. 7.

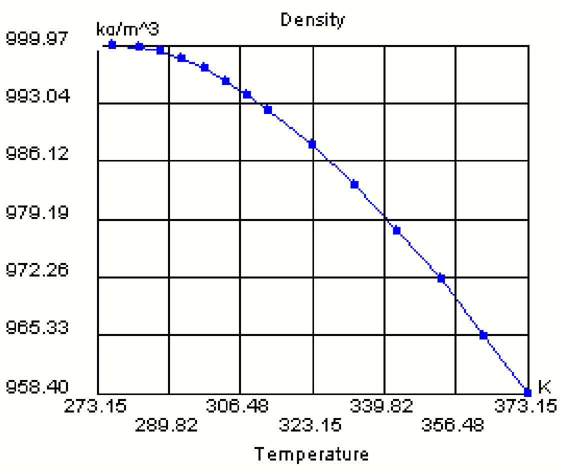

Fig. 4 The variation of density with temperature for water

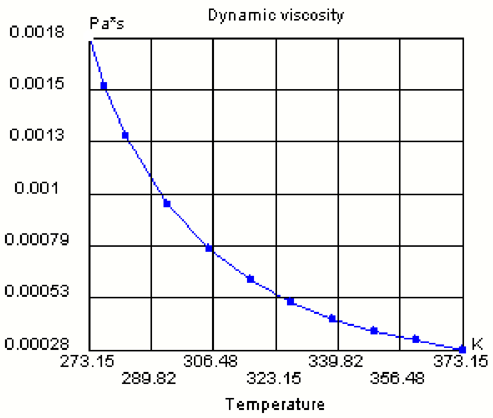

Fig. 5 The variation of dynamic viscosity with temperature for water

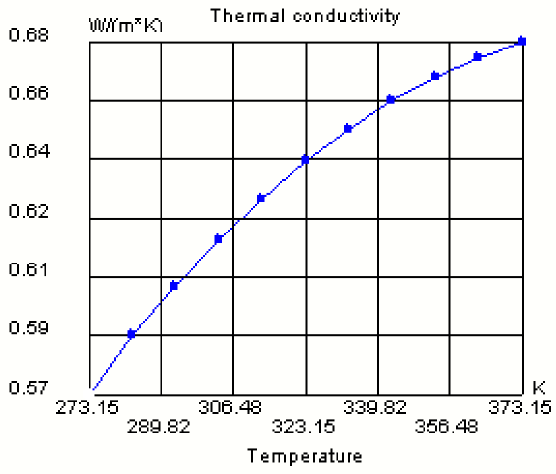

Fig. 6 The variation of thermal conductivity with temperature for water

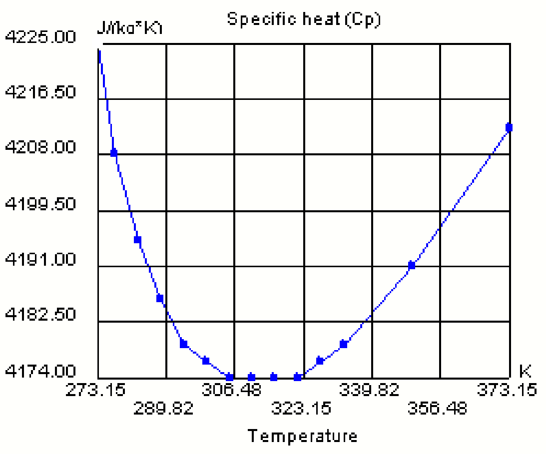

Fig. 7 The variation of the specific heat with temperature for water

B. The study of spatial field distribution when the diffusion direction is longitudinal

Analysis of water vapor diffusion in the longitudinal direction of the brick block is shown from Fig. 8 to Fig. 11.

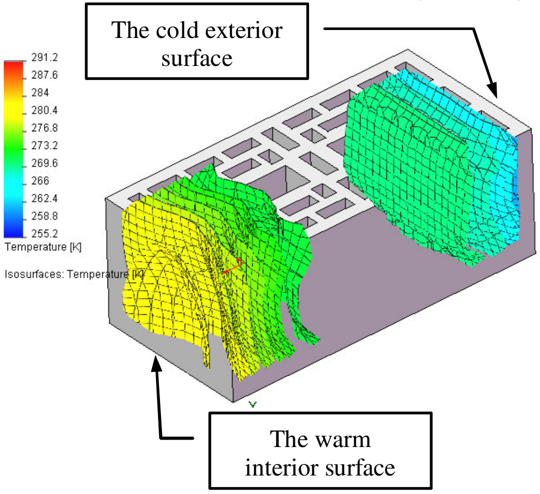

Fig. 8 The isotherms surfaces into the brick block

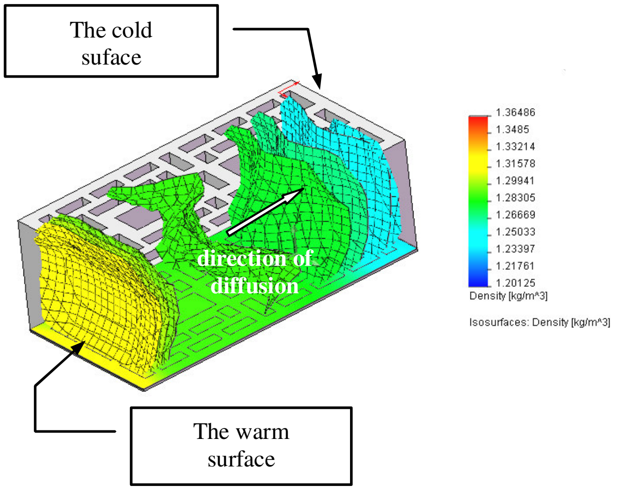

Fig. 9 The isodensity surfaces into the brick block

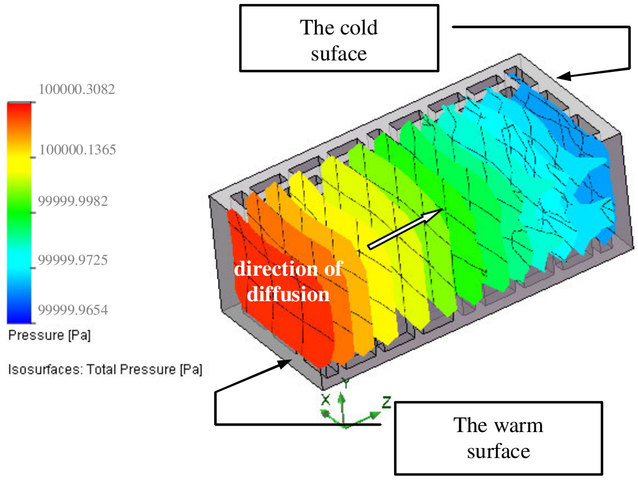

Fig. 10 The isopressure surfaces into the brick block

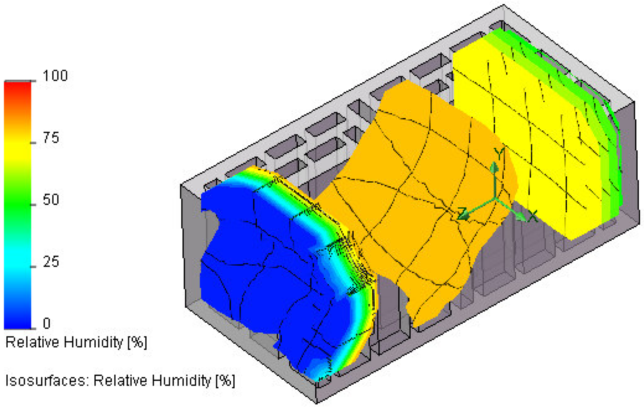

Fig. 11 The isohumidity surfaces into the brick block

A. The study of spatial field distribution when the diffusion direction is transverse

Analysis of water vapor diffusion in the transverse direction of the brick block is shown from Fig. 12 to Fig. 15

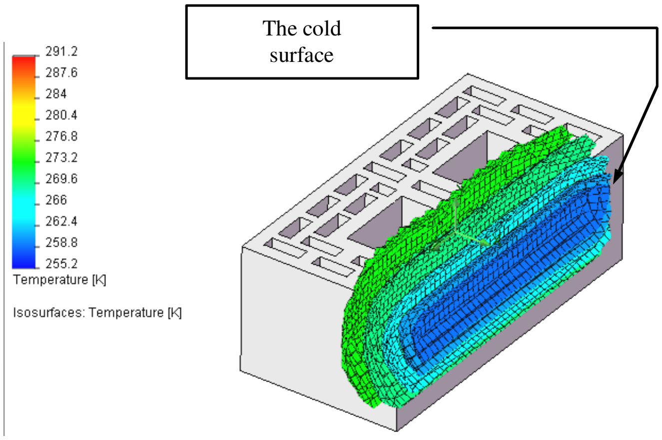

Fig. 12 The isotherms surfaces into the brick block

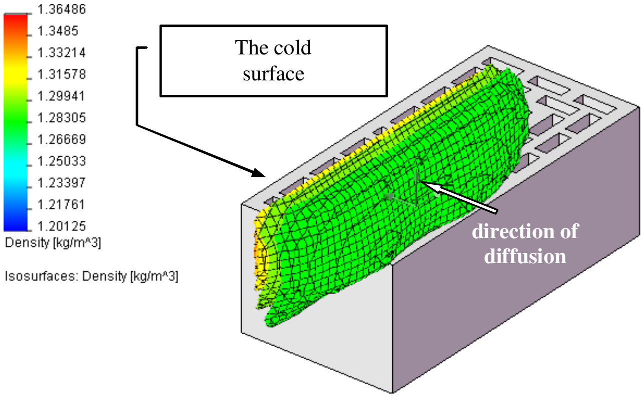

Fig. 13 The isodensity surfaces into the brick block

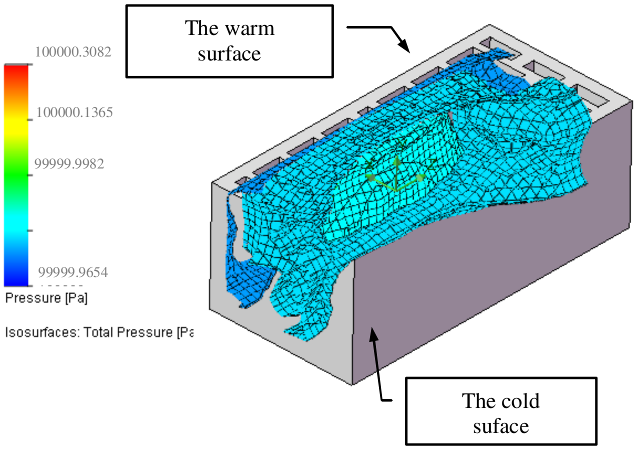

Fig. 14 The isopressure surfaces into the brick block

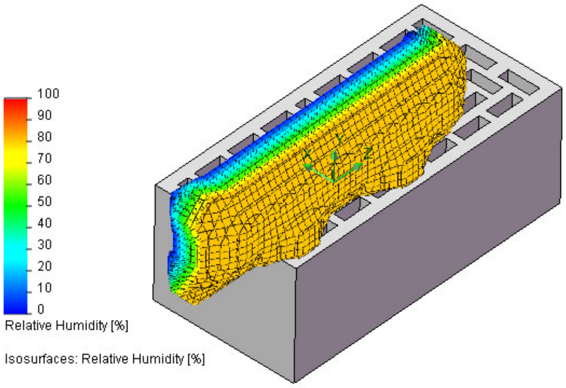

Fig. 15 The isohumidity surfaces into the brick block

IV. CONCLUSION

The condensed water, which accumulates inside the building walls causes various problems. The phenomenon of the internal condensation process in porous material is complex, because of non-linearity of moisture transfer equation and coefficient dependency greatly on potentials.

The finite element analysis is very useful in the prediction of thermodynamic processes (dynamical interactions between heat and mass flows in material's porous structure) and provides a powerful tool for good design practice in building engineering.

The results are presented in terms of spatial field distribution of isotherms, isodensity, isopressure and isohumidity surfaces considering the longitudinal and transverse direction diffusion of water vapor in a brick with vertical holes, showing the importance of the approach presented model 3D simulations.

The dew-point, the temperature at which water vapor condenses, is located inside the brick layer, which leads to the possibility that condensation will collect in the walls, possibly freezing and causing damage.

The dew-point in brick cladding is typically in the interior of the cladding, increasing the chance that moisture will condense within the wall, possibly freezing and causing damage.

The results will be used to predict the performance and stability of such construction systems depending on the degree of exposure to changeable parameters of the local climate.

REFERENCES

[1] H. M. Kunzel, *Simultaneous heat and moisture transport in building components: one- and two-dimensional calculation using simple parameters*, Fraunhofer-Informationszentrum Raum and Bau, IRB Verlag, Stuttgart, Germany, 1995.

[2] Ch. Hall, W. D. Hoff, *Water Transport in Brick, Stone and Concrete*. London and New York: Spon Press, 2002.

[3] P. Mukhopadhyaya, M. K. Kumaran, *Heat-air-moisture transport: measurements on building materials.* West Conshohocken, PA, USA: ASTM International, 2007.

[4] H. Hens, *Building physics - heat, air and moisture: fundamentals and engineering methods with examples and exercises*, Berlin: Ernst & Sohn, 2007.

[5] F.P. Incoperra, D.P. De Witt, *Fundamentals of Heat and Mass Transfer*, Third Edition, New York, John Wiley & Sons, 2001.

[6] A. F. Mills, *Basic Head Mass Transfer*, New Jersey, USA, Prentince Hall, 1999.

[7] M. Moran, H. Shapiro, *Fundamentals of engineering thermodynamics*, New York: John Wiley Sons, 2000.

[8] M. Călbureanu, M. Georgescu, R. Malciu, *Thermal isolation in buildings*, Craiova, Romania, Publishing house Universitaria, 2010.

[9] H. Hens, “Proposal for a new annex. whole building heat, air and moisture response (moist-eng)”, Katholieke Universiteit Leuven, Belgium, 2003.

[10] ASHRAE. “Handbook of Applications“, Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., USA, 2002.

[11] J. R. Philip, D. De Vries, “Moisture movement in porous material under temperature gradients”, *Transactions of the American Geophysical Union*, vol. 38, no. 2, pp. 222-232, 1957.

[12] M. Mitzuhata, "Numeric Analysis of Movements of Internal Condensation Front", *Journal of Architecture, Planning and Environmental Engineering (Transactions of AIJ)*, no. 300, pp. 95-104, 1980.

[13] T. Ikeda, "Studies of Simultaneous Heat and Moisture Transfer in Porous Materials under Conditions of Condensation", *Journal of Architecture, Planning and Environmental Engineering (Transactions of AIJ*, no. 355, pp. 1-10, 1985.

[14] K. K. Hansen, H. B. Lund, “Cup method for determination of water vapor transmission properties of building materials. sources of uncertainty in the method,” in Proceedings of the 2nd Symposium, Building Physics in the Nordic Countries, Trondheim, pp. 291-298, 1990.

[15] E. J. Garboczi, “Permeability, diffusivity, and microstructural parameters: a critical review”, *Cem Concr Res*, vol. 20, pp. 591–601, 1990.

[16] I. N. Nassar, R. Horton, A. M. Globus, “Simultaneous transfer of heat, water, and solute in porous media: II. Experiment and analysis”, *Soil Sci Soc Am J*, vol. 56, pp. 1357–1365, 1992.

[17] C. R. Pederson, "Prediction of Moisture Transfer in Building Constructions", *Building and Environment*, vol. 27, no. 3, pp. 387-397, 1992.

[18] R. El Diasty, P. Fazio, I. Budaiwi, “Dynamic modeling of moisture absorption and desorption in buildings”, *Building and Environment*, vol. 28, pp. 21-32, 1993.

[19] R. J. Liesen, “Development of a response factor approach for modeling the energy effects of combined heat and mass transfer with vapor adsorption in building elements“, Ph.D. thesis, Mechanical Engineering Department, University of Illinois, Chicago, Il, USA, 1994.

[20] L. Pel, “Moisture Transport in Porous building Materials”, Ph. D. Thesis, Eindhoven University of Technology, The Netherlands, 1995.

[21] W. Liu, S. Peng, K. Mizukami, “A general mathematical modelling for heat and mass transfer in unsaturated porous media: an application to free

evaporative cooling", *Heat and Mass Transfer*, vol 31, no. 1, pp. 49-55, 1995.

[22] M. A. Wilson, W.D. Hoff, C. Hall, "Water Movement in Porous Materials - XIII. Absorption into a Two-layer Composite", *Building and Environment*, vol. 30, no. 2, pp. 209-220, 1995.

[23] N. Mendes, "Models for prediction of heat and moisture transfer through porous building elements", Ph.D. Thesis, Federal University of Santa Catarina - UFSC, Florianópolis - SC, Brazil, 1997.

[24] J. C. Lackey, R. G. Marchand,, M. K. Kumaran, "A logical extension of the astm standard e 96 to determine the dependence of water vapor transmission on relative humidity," Insulation Materials: Testing And Applications: Third Volume, ASTM STP 1320, R. S. Graves and R. R. Zarr, Eds, ASTM International, West Conshohocken, PA, pp. 456-470, 1997.

[25] M. K. Kumaran, "An alternative procedure for the analysis of data from the cup method measurements for determination of water vapor transmission properties", *Journal of Testing and Evaluation*, vol. 26, pp. 575-581, 1998.

[26] H. Brocken, "Moisture transport in brick masonry", Ph.D. thesis, Technische Universiteit Eindhoven, The Netherlands, December 1998.

[27] M. K Kumaran,. "Moisture Diffusivity of Building Materials from Water Absorption Measurements", *Journal of Thermal Envelope and Building Science*, Vol. 22, pp. 349-355, 1999.

[28] Q. Pei, Z. Pei., "An experimental study on isothermal moisture absorption and desorption process of some common-used building materials", *Journal Of Hunan University (Natural Sciences Edition)*, vol. 26, no. 4, pp. 96-99, 1999.

[29] S. L. Sinha, "Numerical simulation of twodimensional room air flow with and without buoyancy", *Energy and Buildings*, vol 32, pp. 121-129, 2000.

[30] G. H. Galbraith, C. Ji, R. Mclean, P. Baker, "The influence of space discretization on the accurancy of numerical simulation of heat and moisture transport in porous building materials", *Journal of Thermal Envelope and Building Science*, vol. 5, no. 2, pp. 143–160, 2001.

[31] J. Wang, C.E. Hagentoft, "A numerical method for calculating combined heat, air and moisture transport in building envelope components", *Nordic Journal of Building Physics*, vol. 2, pp. 1–17, 2001.

[32] E.F. Sowell, P. Haves, "Efficient solution strategies for building energy simulation", *Energy and Buildings*, vol. 33, pp. 309-317, 2001.

[33] N. Mendes, P. C. Philippi, R. Lamberts, "A new mathematical method to solve highly coupled equations of heat and mass transfer in porous media", *International Journal of Heat and Mass Transfer*, Vol. 45, pp. 509-518, 2002.

[34] M. P. Deru, A. T. Kirkpatrick, "Ground-coupled heat and moisture transfer from building. Part 2. Aplication*", Journal of Solar Energy Engineering*, vol. 124, pp. 17–21, 2002.

[35] M. K. Kumaran, J. C. Lackey, N. Normandin, D. van Reenen, F. Tariku, "A thermal and moisture transport property database for common building and insulating materials". ASHRAE website, Research Project Report 1018-RP, p. 229, 2002.

[36] X. Lu, "Modelling of heat and moisture transfer in buildings Ⅰ Model program", *Energy and Buildings*, vol. 34, no. 10, pp. 1033-1043, 2002.

[37] X. Lu, "Modelling of heat and moisture transfer in buildings II. Applications to indoor thermal and moisture control", *Energy and Buildings*, vol. 34, no. 10, pp. 1045-1054, 2002.

[38] N. Mendes, F. C. Winkelmann, R. Lamberts, P. C. Philippi, "Moisture Effects on Conduction Loads". *Energy and Buildings*, vol. 35, no. 7, pp. 631-644, 2003.

[39] M. K. Kumaran, P. Mukhopadhyaya, S. M. Cornick, M. A. Lacasse, W. Maref, M. Rousseau, M. Nofal, J. D. Quirt , W. A. Dalgliesh, "An integrated methodology to develop moisture management strategies for exterior wall systems", presented at the 9th Conference on Building Science and Technology, Vancouver, Canada, 2003, pp. 45-61.

[40] K. C. Mendonça, "Predicting temperature and moisture distributions in conditioned spaces using the zonal approach", Ph. D. Dissertation, University of La Rochelle, France, 2004.

[41] C. Rode, N. Mendes, K. Grau, "Evaluation of Moisture Buffer Effects by Performing Whole-Building Simulation", *ASHRAE Transactions*, USA, vol. 110, no. 2, pp. 783–794, 2004.

[42] G. H. Santos, N. Mendes, "Analysis of numerical methods and simulation time step effects on the prediction of building thermal performance", *Applied Thermal Engineering*, vol. 24, pp. 1129–1142, 2004.

[43] N. Mendes, P. C. Philippi, "Multitridiagonal matrix algorithm for coupled heat transfer in porous media: stability analysis and computational performance", *Journal of Porous Media*, vol. 7, no. 3, pp. 193-211, 2004.

[44] R. Becker, D. Shamir, O. Adan, H. Brocken, K. Kumaran, R. Djebbar, R., "Assessment method of numerical prediction models for combined heat, air and moisture transfer in building components: benchmarks for one-dimensional cases", *Journal of Thermal Envelope and Building Science*, vol. 27, no. 4, pp. 327-352, 2004.

[45] E. Djunaedy, "External coupling between building energy simulation and computational fluid dynamics", PhD thesis, Technische Universiteit Eindhoven, The Netherlands 2005.

[46] A. Neale, "A study in computational fluid dynamics for the determination of convective heat and vapour transfer coefficients", M.A.Sc. Thesis, Concordia University, Montreal, Canada, 2006.

[47] Janssen, H., Blocken, B., Carmeliet, J., "Conservative modelling of the moisture and heat transfer in building components under atmospheric excitation", *International Journal of Heat and Mass Transfer*, vol. 50, pp. 1128-1140, 2007.

[48] X. D. Chen, S. X. Q. Lin, G. Chen, "On the ratio of heat to mass transfer coefficient for water evaporation and its impact upon drying modeling", *International Journal of Heat and Mass Transfer*, vol. 45, pp. 4369-4372, 2002.

[49] A. J. J. van der Zanden, A. Aghaei, "Determination of the diffusion coefficient of water in brick with a simple mass distribution Technique", *Drying Technology*, vol. 27, pp. 393–402, March 2009.

[50] D. M. Burch, C. A. Saunders, "A computer analysis of wall constructions in the moisture control handbook", Building and Fire Research Laboratory National Institute of Standards and Technology Gaithersburg, MD 20899, USA, May 1995.

[51] J. L. Ferzieger, M. Peric, *Computational Methods for Fluid Dynamics*, Heidelberg: Springer-Verlag, Germany, 1996, pp. 86-123.

[52] Ş. Ţălu, *Computer assisted graphical representations*, Cluj-Napoca, Romania, Publishing house Osama, 2001.

[53] Ş. Ţălu, *Computer assisted technical graphics*, Cluj-Napoca, Romania, Publishing house Victor Melenti, 2001.

[54] T. Niţulescu, Ş. Ţălu, *Applications of descriptive geometry and computer aided design in engineering graphics*, Cluj-Napoca, Romania, Publishing house Risoprint, 2001.

[55] A. F. Gligore, Ş. Ţălu, D. Noveanu, *Representation and visualization of geometric shapes in industrial drawing*, Cluj-Napoca, Romania, Publishing house U. T. Pres, 2006.

[56] Ş. Ţălu, C. Racocea, *Axonometric representations with applications in technique*, Cluj-Napoca, Romania, Publishing house MEGA, 2007.

[57] **** User guide SolidWorks 2010 software.

[58] **** User guide CosmosWorks 2010 software.