

Numerical Modelling of Humidity and Temperature Conditions in Buildings with Different Boundary Structures

Ansis Ozoliņš¹, Andris Jakovičs², Jānis Ratnieks³, Staņislavs Gendelis⁴

Laboratory for mathematical modelling of environmental and technological processes,

*Faculty of physics and mathematics, University of Latvia
Zellu str. 8, Rīga, LV-1002, Latvia*

¹ansiso@inbox.lv

²andris.jakovics@lu.lv

³janis.ratnieks@fizmati.lv

⁴stanislavs.gendelis@lu.lv

Abstract

Human thermal comfort conditions in the room depend on such factors as temperature, airflow, humidity etc. This work is a preliminary study of humidity content in building constructions as well as airflow and temperature distributions in living environment, particularly the test houses built in Riga. The humidity and temperature is solved with WUFI software for stationary and transient cases by using six year period of Latvia's climate changes. The airflow and temperature distribution is computed using Ansys/CFX. The results show that the stationary solutions differ from transient and the latter must be used for reliable results. Also the more effective way of heating the room is considered in the paper.

Keywords – numerical modelling; CFD; humidity; thermal comfort; buildings.

1. Introduction

Nowadays passive house building is popular because of reduced energy for heating during the heating season. However the lack of ventilation can make inhabiting them unpleasant. Thermal comfort [1] consists of different parameters including various temperature differences, humidity, radiation, and airflow velocities, and still the passive house requirements should be met. In the European Regional Development Fund partly sponsored project the aim is to find out the best local materials that can meet the required standards and still keep the heating costs minimal. This is a new approach because usually only one of factors either energy or comfort is studied.

Furthermore, the Directive 2010/31/EU of the European Parliament aims at promoting the energy performance of buildings and building units [2]. By 31 December 2020, all new buildings are to become the “nearly zero energy consumption buildings” and the overall energy consumption in EU is to be decreased by 20%.

To achieve the goal, five test houses are built in Riga (hereafter called “test polygon”) in which the *in situ* monitoring will take place and mathematical models will be verified with. Similar studies have been carried out in [3]. Examples from the building stage for different types of test houses are shown in Fig. 1.

This is a preliminary study to show that it is important to make transient simulations for airflow, humidity and temperature as the stationary ones can give unreliable results. The third and fourth chapter deals with humidity and temperature profiles in constructions in stationary and transient cases respectively. Commercial software WUFI and programming environment MATLAB are used for calculations and 1D case is assumed. The fifth chapter deals with airflow and temperature distribution in the projected test houses, the Ansys/CFX software is used for these fields. In the sixth chapter results are discussed.

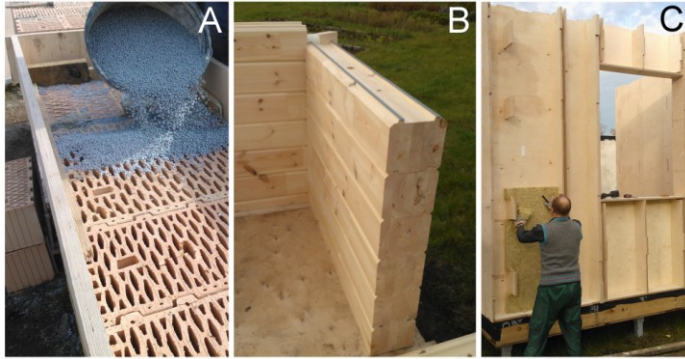


Fig. 1. Test houses: (A) Keraterm 44 with insulation filling, (B) wooden log with rock wool layer, (C) plywood with thick rock wool insulation layer.

2. The Mathematical Model for Heat and Moisture Transport in a Building Wall

2.1. The Mathematical Model for the Profiles of Temperature and Relative Humidity in a Building Wall

To model the heat and moisture transport in the multi-layer wall of a building, the following set of partial differential equations is used [4,5]:

$$\frac{\partial}{\partial x} \left(\lambda \frac{\partial T}{\partial x} \right) + h_v \frac{\partial}{\partial x} \left(\delta_p \frac{\partial (\phi P_{sat})}{\partial x} \right) = \rho (c + w c_w) \frac{\partial T}{\partial t}, \quad (1)$$

$$\frac{\partial}{\partial x} \left(D_\phi \frac{\partial \phi}{\partial x} \right) + \frac{\partial}{\partial x} \left(\delta_p \frac{\partial (\phi P_{sat})}{\partial x} \right) = \rho \frac{dw}{d\phi} \frac{\partial \phi}{\partial t}. \quad (2)$$

Descriptions of used symbols and quantities are mentioned in the nomenclature section.

The boundary conditions for indoor and outdoor walls are following:

$$\begin{aligned} \alpha_{indoor}(T_{indoor} - T_{surf}) &= -\lambda \frac{\partial T}{\partial x}, \quad \alpha_{outdoor}(T_{surf} - T_{outdoor}) = -\lambda \frac{\partial T}{\partial x} \\ \beta_{indoor}(\varphi_{indoor} P_{sat,indoor} - \varphi_{surf} P_{sat,surf}) &= -\delta_p \frac{\partial(\varphi P_{sat})}{\partial x}, \\ \beta_{outdoor}(\varphi_{outdoor} P_{sat,outdoor} - \varphi_{surf} P_{sat,surf}) &= \delta_p \frac{\partial(\varphi P_{sat})}{\partial x} \end{aligned} \quad (3)$$

where α is total heat transfer coefficient, β is water vapour transfer coefficient.

2.2. The Integral Model for Estimation of the Indoor Temperature Variance

In this model [6] it is assumed that there are two components of the indoor heat: a constant and a variable (following the temperature variations outdoors). In Fig. 2 the multi-layered wall and the integral mathematical model are illustrated graphically, with V and S being the interior volume and surface area, respectively.

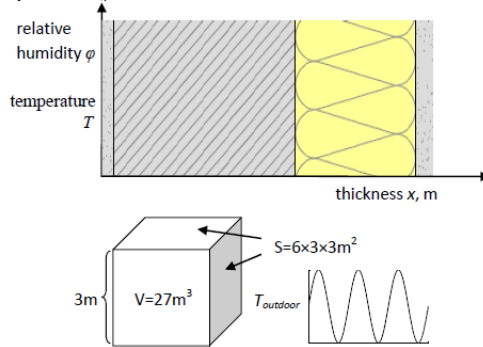


Fig. 2. The multi-layered wall and the integral mathematical model: graphical illustration.

The heat amount variation ΔQ indoors during time interval Δt is:

$$\Delta Q_1 = V c_{air} \rho_{air} (T_{indoor}(t + \Delta t) - T_{indoor}(t)) \quad (4)$$

and dependence on temperature difference is:

$$\Delta Q_2 = (q(t + \Delta t) - q_0) S \Delta t, \quad (5)$$

where q_0 is the initial heat flux on the interior surface. From this it can be inferred that

$$\Delta Q_1 + \Delta Q_2 = 0 \Rightarrow \lim_{\Delta t \rightarrow 0} \left(\frac{\Delta Q_1 + \Delta Q_2}{\Delta t} \right) = \frac{V c_{air} \rho_{air}}{S} \frac{dT_{indoor}}{dt} - \lambda \frac{\partial T}{\partial x} - q_0 = 0. \quad (6)$$

Finally, the boundary condition for the interior surface is the following:

$$\frac{V c_{air} \rho_{air}}{S} \frac{dT_{indoor}}{dt} = \lambda \frac{\partial T}{\partial x} + q_0. \quad (7)$$

It is assumed that the indoor absolute humidity is constant, while relative humidity φ_{indoor} and saturation vapour pressure $P_{sat,indoor}$ are time-dependent.

For calculation of the temperature and relative humidity profiles in the construction, the mathematical model described in subsection 2.1 is used, with volume of 27 m³ and inner surface area of 54 m², respectively. This volume (3×3×3 m³) is chosen to correspond to that is used in test polygon.

3. Relative Humidity and Temperature Profiles in a Building Wall: the Stationary Case

The results for humidity and temperature distributions in stationary case are shown on Fig. 3. It is assumed that the indoor temperature and relative humidity are +20°C and 50%, respectively, and the outdoor relative humidity and temperature are 85% and 0°C, that are typical for Latvian climatic conditions for a heating season [7].

The layers of the wall on Fig. 3 are listed in the direction from outdoors to indoors. The temperature and relative humidity profiles for test house of filled ceramic blocks are not smooth curves (Fig. 3, black curves) due to different properties of blocks and insulation filling (Fig. 1A). The main factor is the thermal conductivity, which is almost 10 times less for insulation filling.

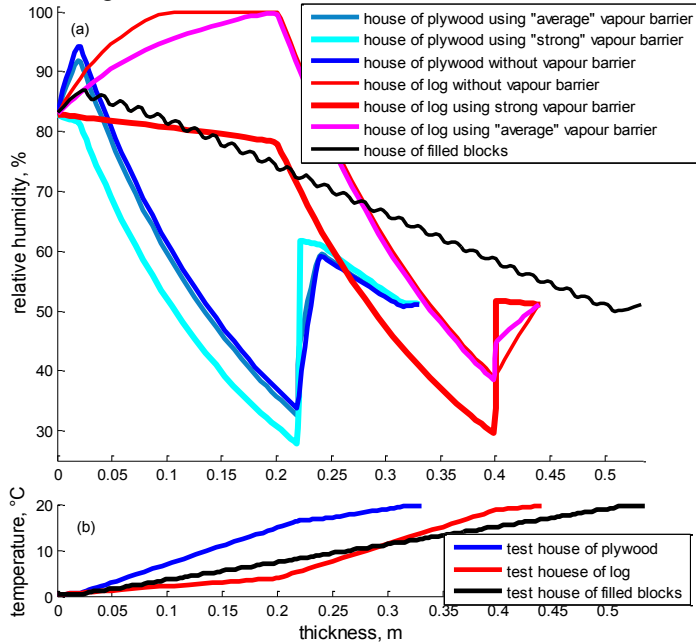


Fig. 3. (a) Relative humidity profiles in 3 different building walls; (b) The temperature profiles in 3 different building walls.

4. Relative Humidity and Temperature Profiles in a Building Wall: the Transient case

4.1. Relative humidity variation at annual cycle

Annual cycle is taken to analyse the risks of condensate formation and the risks of mould in multi-layered walls in long term. Outdoor data is taken from observation stations [8]. Data is taken by the time step one hour as average from the last 6 years. The results are calculated using: “strong” vapour barrier with water vapour diffusion resistance factor $\mu=100000$, „average” vapour barrier with $\mu=8000$ and without vapour barrier. It is expected, that „average” vapour barrier is used in the test polygon.

Results at transient case (Figs. 4, 5) are different from stationary case (Fig. 3a), because the risk of condensate formation in real climatic conditions is not as high as in the stationary case. Vapour barrier helps to decrease the risks of condensation, especially for the wooden log construction (Fig. 4a).

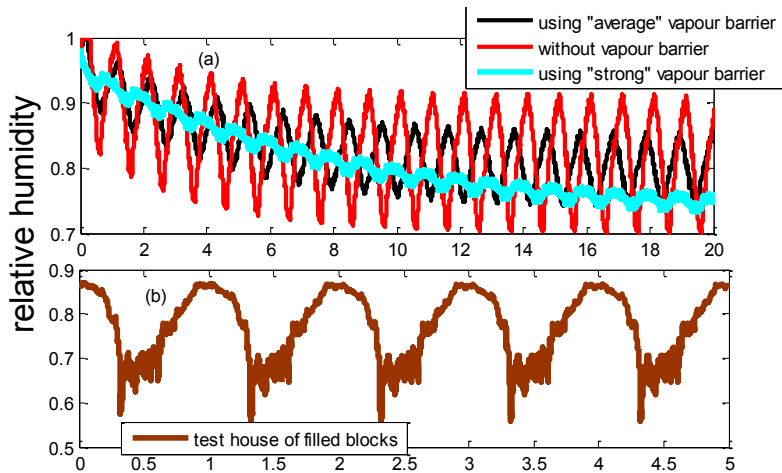


Fig. 4. Relative humidity on the interlayer adjacent to the outer layer of a construction wall.
(a) Test house of log; (b) Test house of filled blocks.

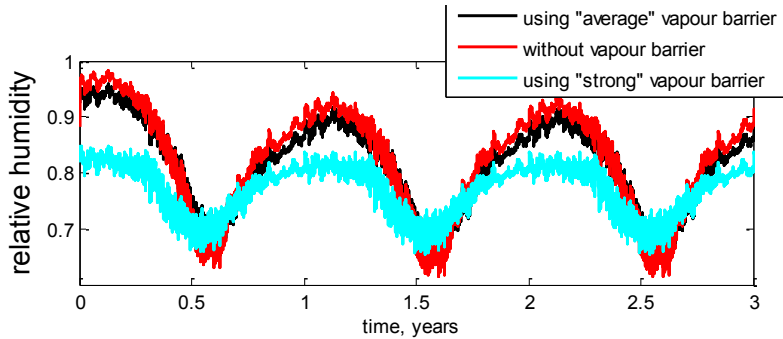


Fig. 5. Relative humidity on the interlayer adjacent to the outer layer of a construction wall. Test house of plywood.

4.2. Results for the non-stationary Case taking into account the Indoor Temperature Variations

In the work it was assumed that the outdoor temperature is changing between -4.1°C and $+2.9^{\circ}\text{C}$ as a sinusoidal function within a 24-h periodicity and that the indoor temperature is changing in compliance with the integral model described in subsection 2.2. Outdoor temperature behaviour is chosen according to Latvian climatic conditions in March [7].

The temperature on the inner surface is changing significantly for plywood construction (Fig. 6b), rather insignificant temperature amplitude on the inner surface is observed (Fig. 6c,d), because thermal inertia for the latter is significantly lower than in the constructions containing only the insulation material, plywood and fibrolite. However, for Latvian climatic conditions heat losses are low also for plywood house that is inspected on the test polygon (Fig. 1C).

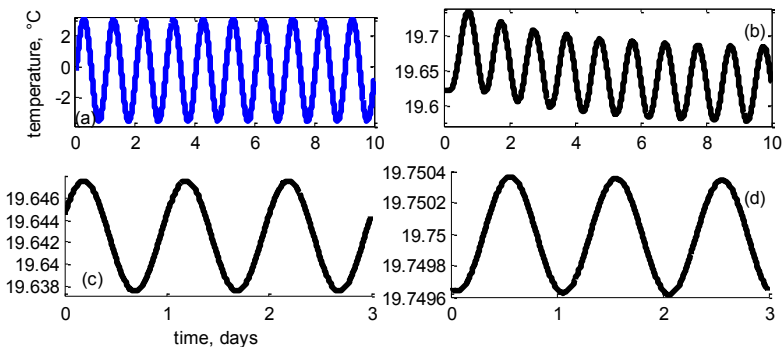


Fig. 6. Temperature on the outer surface of the wall (a), on the inner surface for plywood test house (b), log test house (c) and filled blocks test house (d).

5. Airflow and Temperature Distribution Analysis.

Airflow velocity and temperature distribution is variables that are needed to find out thermal comfort in living rooms. Also the WUFI model can use the temperature distribution in the room to calculate the humidity in the building construction. To find out temperature and velocity distribution a computational fluid dynamic (CFD) approach is being used. Ansys/CFX pre/post processor and solver are used and Reynolds Averaged Navier-Stokes (RANS) as well as continuity equations are solved. As the flow is turbulent, the shear stress transport (SST) turbulence model is used because it provide realistic values both for the near wall region and the rest of computational domain. The equations are not given here but are provided in reference [9,10].

The simplified model includes an air domain without any walls. The walls are introduced as an additional heat resistance in boundary condition by defining the heat transfer coefficient and outside temperature of 0°C (as in WUFI model). The thermal transmittance for all constructions are projected $U_c=0.16 \text{ W}/(\text{m}^2\cdot\text{K})$ and the total value used in model is introduced as:

$$U = \frac{1}{R_c + R_{out}}, \quad (8)$$

where R_c – thermal resistance of a building construction ($=1/U_c$) and R_{out} – outer surface thermal resistance ($=0.04 \text{ K}\cdot\text{m}^2/\text{W}$).

For all the test houses the geometry is the same and therefore this model can save valuable time because one model with less degree of freedom is solved for instead of five larger models [3, 11].

For aerodynamics no slip boundary conditions are implemented that do not allow the air movement at wall surface.

The planned air exchange in the room is 0.6 h^{-1} for every test house; therefore the inlet speed was calculated to be 9.3 cm/s . The inlet was 45° with respect to the wall. The calculations were carried out for this setup and also for 40 cm/s because the real working conditions can also be of that magnitude if non – continuous. The inflow temperature is held constant at 25°C . The outlet is modelled as an opening that allows the flow in both directions.

The Boussinesque approximation is used in this model to take into account convective heat transfer. The density is kept constant, but the volume force that has density is described as function of temperature.

This approach is not perfect as it does not take into account corner effects however it can be a good first approximation about airflow and temperature distribution in a building. Furthermore, this also gives insight to the heating efficiency.

The mesh for analyses in question was 13 million nodes. The maximum mesh size was 2.7cm and at the inlet and outlet it was made smaller as the velocities there were higher.

The Ansys/CFX computations showed reasonable flow speeds for both cases as expected (Fig. 7). The temperature distribution (Fig. 8) shows symmetric values on both sides of symmetry axes. This solution behaviour shows that it is correct. The convergence criterion 10^{-3} was reached.

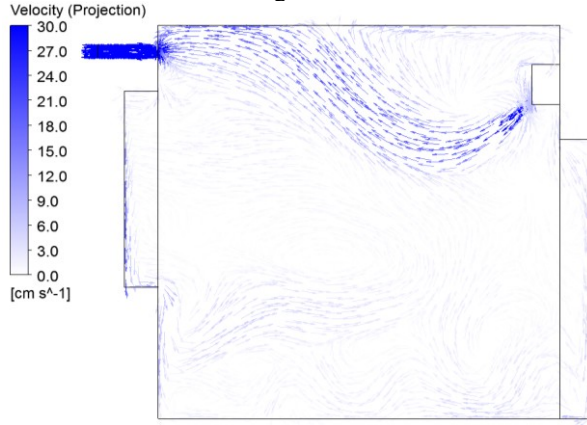


Fig. 7. Velocity component on symmetry plane with 40 cm/s inlet speed.

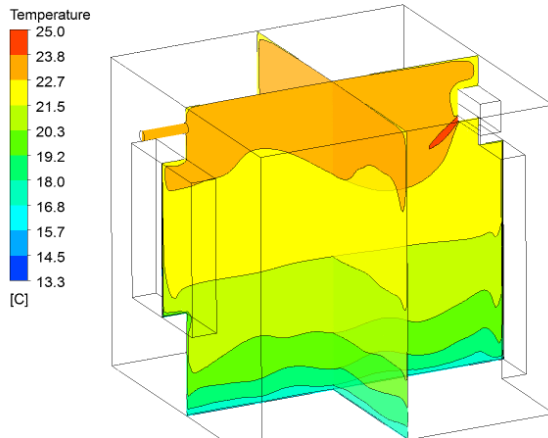


Fig. 8. Isothermal contours for 40 cm/s inlet speed.

6. Results and Discussion

The WUFI analysis clearly show that thermal insulation is time dependent as the stationary solution does not represent real values. Plenty of experiments have been carried out to verify the WUFI model. These experiments have been carried out in Germany and therefore cross validation for different climate and buildings is an interesting aspect.

The airflow analyses are only qualitative as the heat transmission is not taken into account and the corner effects are neglected. The heat conduction in constructions influence the temperature distribution across the wall and therefore the air flows will change. Also the thermal radiation is not taken into account that should be included in analysis. To compensate for this the wall should be included in model and the difference evaluated.

The greatest problem with a stationary model is that the airflows cannot be modelled correctly as the inflow will be periodical, not continuous. Also the flow angle with respect to wall normal direction should be increased for the hot air to travel larger distance before going to outlet, thus making temperature stratification less noticeable.

The time dependent airflow simulations are not possible for such long periods of time as years because the airflow must be resolved by mesh and the CFL number requirements increase the time step required. Taking into account above mentioned, different patterns should be modelled and their behaviour implemented in more robust model that can predict the thermal behaviour of different constructions by making various assumptions.

To analyse the risks of condensate for building wall, transient case, when temperature and humidity is changing at annual cycle is reliable than the stationary case. Stationary case is only an orientated for analysing the risks of condensate formation.

The construction with filled blocks is effective in several aspects: thermal inertia is relatively low, the risks of condensate are low and heat losses are insignificantly for such construction.

The effective vapour barrier is important for decreasing the risks of condensate for some constructions.

7. Conclusions

Many simplifications to mathematical models can be made that can change its validity, therefore an experiment is needed for verification and it is a great opportunity to carry out one in the Latvia where have been none so far.

Stationary analysis can only give preliminary insight of construction effectiveness regarding vapour content, but is not giving correct values, therefore the need for time dependent analysis is crucial that the future work will concentrate on.

Important aspects are rain and radiation factor, which will be included in future simulations and test polygons by removing the humidity barrier for some time.

Nomenclature

- c specific heat capacity of dry material (J/(kg·K))
- c_w specific heat capacity of water (=4187 J/(kg·K))
- D_ϕ diffusion coefficient of liquid phase (kg/(m·s))

h_v	latent heat of vaporization of water (=2.26 MJ/kg)
P_{sat}	saturation vapour pressure (Pa)
q	heat flux (W/m ²)
Q	heat amount (J)
$\bar{R}$	thermal resistance (K·m ² /W)
t	time (s)
T	temperature (K)
U	thermal transmittance (W/(m ² ·K))
w	dry basis moisture content (kg/kg)
x	thickness (m)
α	total heat transfer coefficient (W/(m ² ·K))
β	water vapour transfer coefficient (kg/(m ² ·s·Pa))
δ_p	water vapour permeability (kg/(m·s·Pa))
λ	thermal conductivity (W/(m·K))
μ	water vapour diffusion resistance factor (-)
ρ	bulk density of dry material (kg/m ³)
φ	relative humidity (%)

Acknowledgment

This work has been supported by the European Regional Development Fund in Latvia, project Nr. 2011/0003/2DP/2.1.1.1.0/10/APIA/VIAA/041.

References

- [1] ISO 7730, Moderate thermal environments – determination of the PMV and PPD indices and specification of the conditions for thermal comfort. International Organisation for Standardisation, Geneva, 1994.
- [2] European Parliament and the council. The Directive 2010/31/EU on the energy performance of buildings (EPBD). Official Journal of the European Communities 153 (2010) 13-35.
- [3] J. Vinha. Hygrothermal performance of timber-framed external walls in Finnish climatic conditions: A method for determining the sufficient water vapour resistance of the interior lining of a wall. Phd thesis, University of Tampere, Tampere, 2007.
- [4] J.M.P.Q. Delgado, E. Barreira, N.M.M. Ramos, V.P. de Freitas. Hygrothermal Numerical Simulation Tools Applied to Building Physics. Springer, Berlin, 2013.
- [5] Z. Zhong. Combined heat and moisture transport modelling for residential buildings. Phd thesis, Purdue University, Indiana, 2008.
- [6] A. Ozolinsh, A. Jakovich. Heat and moisture transport in multi-layer walls: interaction and heat loss at varying outdoor temperatures, Latvian Journal of Physics and Technical Sciences, 6 (2012) 32-43.
- [7] The Cabinet of Ministers of the Republic of Latvia. Regulations regarding the Latvian Building Code LBN 003-01 “Construction Climatology”, Riga, 2003.
- [8] Latvian Environment, geology and meteorology centre. Relative, humidity and temperature database. Accessed January, 2013. www.meteo.lv/meteorologija-datu-meklesana/ ?Nid=461
- [9] ANSYS CFX-Solver theory guide, ANSYS Ltd., 2011.
- [10] H.K. Versteeg, W. Malalasekera. An introduction to computational fluid dynamics: The finite volume method, 2nd Edition. Prentice Hall, New York, 2007.
- [11] S. Gendelis. Complex analysis of thermophysical processes in buildings. Phd thesis, University of Latvia, Riga, 2012.