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HEAT AND MOISTURE TRANSPORT IN MULTI-LAYER WALLS: INTERACTION AND HEAT LOSS AT VARYING OUTDOOR TEMPERATURES

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The heat and moisture transport in multi-layer walls is analysed for five building units. Using the developed program, a typical of Latvian conditions temperature and relative humidity profiles in multi-layered constructions has been obtained and the indoor heat losses estimated. Consideration is also given to the risk of condensate formation and to the influence of moisture on the U-value. The created mathematical model allows forecasting the energy efficiency and sustainability of different technical solutions as refer to the heat and moisture transport in buildings.

Key words: *moisture, temperature, transport, multi-layer wall.*

1. INTRODUCTION

The Directive 2010/31/EU of the European Parliament aims at promoting the energy performance of buildings and building units [1]. 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%. In the climatic conditions of Latvia, the coefficient of heat transmission (hereinafter referred to as ‘U-value’) has to be relatively low. At the same time, a relatively small exploit-tation cost is recommended.

Therefore, the energy efficiency and the sustainability of technical solutions for the heat and moisture transport in buildings are to be ensured in two aspects:

- The building should have almost no heat loss (depending on U-value, thermal bridges and seals) due to seasonal factors – *e.g.* moisture, sun, wind.
- The mechanical properties of a building, its comfort conditions and the general visual view of rooms should not be deteriorated significantly.

The crucial factors that affect these two aspects are the outdoor temperature and the relative humidity variance within 24-h periodicity and seasonal cycle (i.e. taking into account that the climate in Latvia is humid, with 24-hourly fluctuations of the outdoor temperature).

Therefore, the main goals of this work were to estimate – based on the mathematical model and numerical analysis – the following:

- the moisture influence on U-value for different technical solutions of a construction;
- the risk of condensate formation;

- the influence of outdoor temperature variation on the 24-hourly indoor moisture and temperature.

2. THE MATHEMATICAL MODEL FOR HEAT AND MOISTURE TRANSPORT IN A BUILDING WALL

2.1. Mathematical model for the profiles of temperature and relative humidity in a building

To model the heat and moisture transport in the multi-layer wall of a building, the following set of partial differential equations is used [2, 3]:

$$\frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right)+h_v \frac{\partial}{\partial x}\left(\delta_p \frac{\partial(\varphi P_{sat})}{\partial x}\right)=\rho(c+wc_w)\frac{\partial T}{\partial t} \tag{1}$$

$$\frac{\partial}{\partial x}\left(D_\varphi \frac{\partial \varphi}{\partial x}\right)+\frac{\partial}{\partial x}\left(\delta_p \frac{\partial(\varphi P_{sat})}{\partial x}\right)=\rho \frac{dw}{d\varphi}\frac{\partial \varphi}{\partial t}, \tag{2}$$

where λ is the thermal conductivity of building material, W/(m·K);
T is the temperature, °C;
x is the wall thickness, m;
h_v = 2260000 J/kg is the heat of vaporisation;
δ_p is the water vapour permeability of building material, kg/(m·s·Pa);
φ is the relative humidity;
P_{sat} is the saturation vapour pressure, Pa;
ρ is the bulk density of dry building material, kg/m^3;
c is the specific heat capacity of dry building material, J/(kg·K);
w is the dry basis moisture content, kg/kg;
c_w = 4187 J/(kg·K) is the specific heat capacity of water;
D_φ is the liquid conduction coefficient, kg/(m·s).

Coefficient D_φ is important at a high relative humidity, allowing for determination of its maximum admissible value from the viewpoint of possible condensate formation. However, this coefficient is not characterised by the properties of material, and in simplified approximations it could be determined ambiguously. To obtain a relatively precise estimate of the liquid conduction coefficient special experiments are needed. For the purposes of the present work it is assumed that $D_\varphi = 0$.

The above equations are non-linear (due to variable properties of λ, δ_p and D_φ values), strongly coupled, and have time-variable boundary conditions.

The temperature dependence of the saturation vapour pressure is described as [3]

$$P_{sat} = 611\exp\left(\frac{17.08T}{234.18+T}\right), \qquad T \geq 0;$$

$$P_{sat} = 611\exp\left(\frac{22.44T}{272.44+T}\right), \qquad T < 0. \tag{3}$$

The water vapour permeability is [3]:

$$\delta_p = \frac{1}{\mu} \cdot 2 \cdot 10^{-7} \frac{(T + 273.15)^{0.81}}{p_L} , \tag{4}$$

where μ is the factor of water vapour diffusion resistance of a dry building material;

p_L is the ambient air pressure.

The boundary conditions for the indoor and outdoor surfaces are the following:

$$\alpha_{indoor}\left(T_{indoor} - T_{surf}\right) = -\lambda \frac{\partial T}{\partial x}; \qquad \alpha_{outdoor}\left(T_{surf} - T_{outdoor}\right) = -\lambda \frac{\partial T}{\partial x};$$

$$\beta_{indoor}\left(\varphi_{indoor} P_{sat,indoor} - \varphi_{surf} P_{sat,surf}\right) = -\delta_p \frac{\partial(\varphi P_{sat})}{\partial x}; \tag{5}$$

$$\beta_{outdoor}\left(\varphi_{outdoor} P_{sat,outdoor} - \varphi_{surf} P_{sat,surf}\right) = \delta_p \frac{\partial(\varphi P_{sat})}{\partial x},$$

where α is the total heat transfer coefficient, W/(m^2·K);

β is the coefficient of water vapour transfer, kg/(m^2·s·Pa);

$q = -\lambda \frac{\partial T}{\partial x}$ is the heat flux density corresponding to the interior/exterior wall surface.

The initial conditions are found from the time-invariable stationary equations:

$$\frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) + h_v \frac{\partial}{\partial x}\left(\delta_p \frac{\partial\left(\varphi P_{sat}\right)}{\partial x}\right) = 0; \tag{6}$$

$$\frac{\partial}{\partial x}\left(D_\varphi \frac{\partial \varphi}{\partial x}\right) + \frac{\partial}{\partial x}\left(\delta_p \frac{\partial\left(\varphi P_{sat}\right)}{\partial x}\right) = 0. \tag{7}$$

Here $\beta_{indoor} = 2.5 \cdot 10^{-8}$ kg/(m^2·s·Pa), $\beta_{outdoor} = 7.5 \cdot 10^{-8}$ kg/(m^2·s·Pa), $\alpha_{indoor} = 25$ W/(m^2·K), $\alpha_{outdoor} = 8$ W/(m^2·K) [3],

λ is a function of the temperature and moisture content (varies for different building materials),

w is a function of the relative humidity (also called the moisture storage function).

The w value could be approximated by the following relationship [3]:

$$w = w_f \frac{(b-1)\varphi}{b - \varphi}, \tag{8}$$

where w_f is the free water saturation,

b is the approximation factor (always greater than unity).

The b factor can be determined from the water content at 80% relative humidity by substituting the corresponding numerical values in Eq. (8).

The U-value is given by the inverse dependence $U = \frac{1}{R}$, where R is the thermal resistance of the wall:

$$R = \frac{1}{\alpha_{indoor}} + \frac{1}{\alpha_{outdoor}} + \sum_{i=1}^{f} \int_{y_{i-1}}^{y_i} \frac{1}{\lambda_i} dy \ . \quad (9)$$

Here f is the number of layers in the wall,

$y_i - y_{i-1}$ is the length of the i-th layer, and

λ_i is the thermal conductivity of the i-th layer.

2.2. The integral model for estimation of the indoor temperature variance

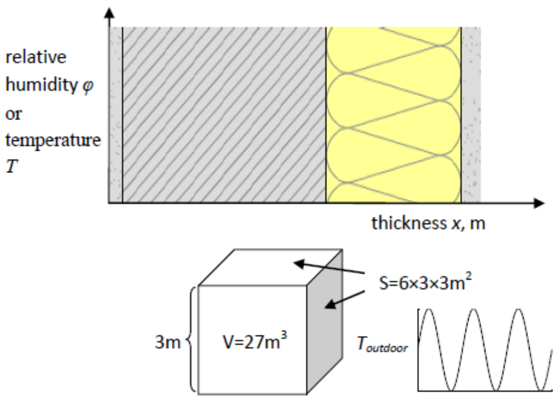

Fig. 1. The multi-layered wall and the integral mathematical model: graphical illustration.

In this model it is assumed that there are two components of the indoor heat: a constant and a variable (following the temperature variations outdoors). In Fig. 1 the multi-layered wall and the integral mathematical model are illustrated graphically, with V and S being the interior volume and surface area, respectively.

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

$$\Delta Q_1 = V c_{air} \rho_{air} \left(T_{indoor}(t + \Delta t) - T_{indoor}(t) \right), \quad (10)$$

and the variation dependent on the difference with the outdoor temperature is:

$$\Delta Q_2 = \left(q(t + \Delta t) - q_0 \right) S \Delta t \, , \quad (11)$$

where q_0 is the initial heat flux on the interior surface.

From this it can be inferred that

$$\Delta Q_1 + \Delta Q_2 = 0 \Rightarrow \lim_{\Delta t \to 0} \left(\frac{\Delta Q_1 + \Delta Q_2}{\Delta t} \right) = \frac{V c_{air} \rho_{air}}{S} \frac{dT_{indoor}}{dt} - \lambda \frac{\partial T}{\partial x} - q_0 = 0 \, . \quad (12)$$

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

$$\frac{Vc_{air}\rho_{air}}{S}\frac{dT_{indoor}}{dt} = \lambda\frac{\partial T}{\partial x} + q_0 . \tag{13}$$

If moisture is taken into account, it is assumed that the absolute humidity indoors is constant, while relative humidity φ_{indoor} and saturation vapour pressure $P_{sat,indoor}$ are changing with time.

For calculation of the temperature and relative humidity profiles in the construction, the mathematical model described in subsection 2.1 is used, with V and S taken 27 m^2 and 54 m^2, respectively. This volume ($V = 3\times3\times3$ m^2) is chosen to correspond to that used in experiments with similar constructions [4].

3. NUMERICAL MODEL

To obtain the temperature and relative humidity profiles in exterior walls, the finite difference method is used. For space the following grid is applied: $\Delta = \{0 = y_0 < y_1 < \cdots < y_n\}$, where $h_i = y_i - y_{i-1}$, $i = 1,\ldots n$. For the time a uniform grid with step Δt is used.

The central difference scheme is applied to the space calculations, while the backward difference scheme – to the time ones, according to Eqs. (1) and (2).

The equations below describe the heat and moisture transport in a multilayer wall on the discrete grid points

$$\begin{aligned}
&\lambda_{i-1/2}^{j-1}\frac{T_{i-1}^{j}-T_{i}^{j}}{h_{i-1}} + \lambda_{i+1/2}^{j-1}\frac{T_{i+1}^{j}-T_{i}^{j}}{h_{i}} + \\
&+ h_v\left(\delta_{i-1/2}^{j-1}\frac{\varphi_{i-1}^{j-1}P_{sat,i-1}^{j-1}-\varphi_{i}^{j-1}P_{sat,i}^{j-1}}{h_{i-1}} + \delta_{i+1/2}^{j-1}\frac{\varphi_{i+1}^{j-1}P_{sat,i+1}^{j-1}-\varphi_{i}^{j-1}P_{sat,i}^{j-1}}{h_{i}}\right) = \\
&= h_i\rho\left(c + w_i^{j-1}c_w\right)\frac{T_i^{j}-T_i^{j-1}}{\Delta t};
\end{aligned} \tag{14}$$

$$\begin{aligned}
&D_{i-1/2}^{j-1}\frac{\varphi_{i-1}^{j}-\varphi_{i}^{j}}{h_{i-1}} + D_{i+1/2}^{j-1}\frac{\varphi_{i+1}^{j}-\varphi_{i}^{j}}{h_{i}} + \delta_{i-1/2}^{j}\frac{\varphi_{i-1}^{j}P_{sat,i-1}^{j}-\varphi_{i}^{j}P_{sat,i}^{j}}{h_{i-1}} \\
&+ \delta_{i+1/2}^{j}\frac{\varphi_{i+1}^{j}P_{sat,i+1}^{j}-\varphi_{i}^{j}P_{sat,i}^{j}}{h_{i}} = h_i\rho\left(\frac{dw}{d\varphi}\right)_i^{j-1}\frac{\varphi_i^{j}-\varphi_i^{j-1}}{\Delta t}.
\end{aligned} \tag{15}$$

For example, T_i^j means the temperature in space y_i and time t_i.

The first step is to calculate the initial conditions. These are obtained by equating the right sides of Eqs. (14) and (15) to zero. Since these equations are strongly coupled, an approximate initial condition is found iteratively.

The second step is to obtain a non-stationary time-dependent solution. Initially, the temperature values are found on the grid points. The φ, w, λ, P_{sat} values are taken from the previous time step; then the relative humidity is found. Finally, the next time step is reached, for which the numerical calculation is done.

The numerical model is implemented in the MATLAB programming environment.

4. DESCRIPTION OF SOME TYPICAL CONSTRUCTIONS OF THE WALL

Five examples of multi-layer wall (with inclusion of mineral wool insulation) are analysed.

Table 1

Multi-layer walls

No.	1st layer	2nd layer	3rd layer	4th layer	5th layer
1.	Gypsum board, *d* = 0.015 m	Mineral wool, *d* = 0.235 m	Medium density fibreboard, *d* = 0.02 m		
2.	Gypsum board, *d* = 0.015 m	Vapour barrier, *d* = 0.00025 m	Mineral wool, *d* = 0.235 m	Medium density fibreboard, *d* = 0.02 m	
3.	Lime plaster, *d* = 0.02 m	*Aeroc classic 300*, *d* = 0.3 m	Mineral wool, *d* = 0.109 m	Lime plaster, *d* = 0.02 m	
4.	Lime plaster, *d* = 0.02m	Mineral wool, *d* = 0.109 m	*Aeroc classic 300*, *d* = 0.3 m	Lime plaster, *d* = 0.02 m	
5.	Lime plaster, *d* = 0.02 m	Vapour barrier, *d* = 0.00025 m	Mineral wool, *d* = 0.109 m	*Aeroc classic 300*, *d* = 0.3 m	Lime plaster. *d* =0.02 m

The layers of the wall are listed in the direction from indoors to outdoors, with *d* being the layer thickness (see Table 1).

In [4] similar constructions are studied. Constructions No. 1 and No. 3 are considered basic. Construction No. 1 is a "light" one, consisting of insulation material and plaster – both from inside and outside. In the case No. 1 there is a high risk of condensate formation, therefore a vapour barrier is added (construction No. 2) to analyse how much this solution would help to improve the properties of construction No. 1. Construction No. 3 is a typical one, with the insulation material after concrete and with plaster outside and inside. Construction No. 4 is an inverse construction, where the insulation material is transposed with concrete. This last construction can be used since insulation material is easier to insert inside. The vapour barrier is added (construction No. 5) to compare how much it helps in this case.

The summary of the main properties of the materials used is given in Table 2.

Table 2

Material properties

Material	λ_d	c	ρ	μ	b	w_{sat}
Gypsum board	0.24	1050	850	8	1.012	0.4706
Mineral wool *Paroc extra plus*	0.034	830	40	1	1.3	0.035
Mineral wool board	0.037–0.04	830	160	1	1.3	1.875
Medium density fibreboard	0.14	1700	790	23	1.037	0.9
Lime plaster	0.708	840	1600	15	1.011	0.2256
Aerated concrete *Aeroc classic 300*	0.1	850	425	4		
Vapour barrier	0.15	1700	290	8000	1.029	2.1724

In Table 2, λ_d is the thermal conductivity of a dry building material, and b is the coefficient used for water content w approximation in Eq. (8). The data are mainly taken from [5]. The λ value for *Paroc extra pluss* equals 0.036, with a modified coefficient taken from [7].The moisture storage function for *Paroc mineral wool* is borrowed from [8]. A different approximation for water content is used in [9] for *Aeroc classic300* blocks.

5. RESULTS AND DISCUSSION

5.1. Relative humidity and temperature profiles in a building wall: the stationary case

The results were obtained under the assumption that the relative indoor temperature and humidity are +20°C and 50%, respectively, and the outdoor relative humidity is 80%. The temperature outdoors was taken +5°C or –5°C.

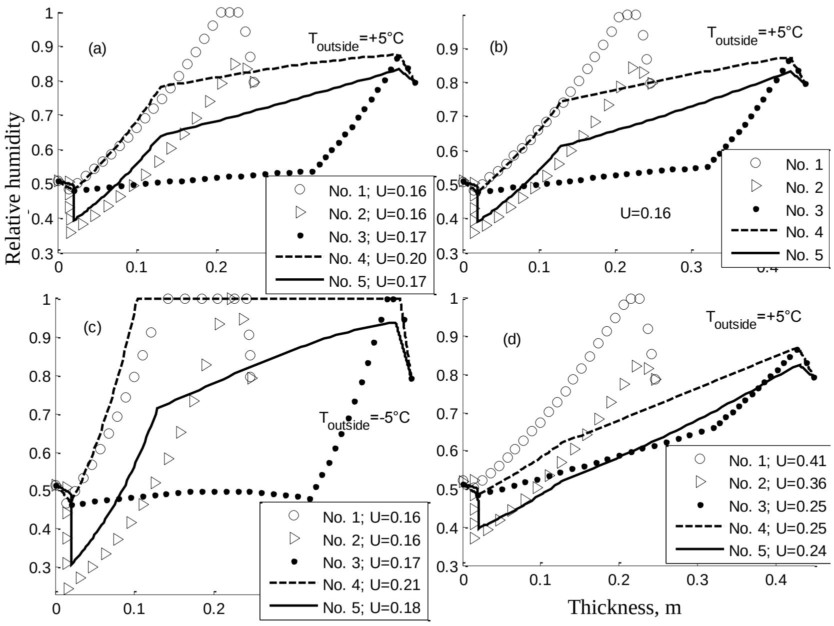

Fig. 2. Relative humidity in five different building walls. The moisture influence on thermal conductivity is: taken into account (*a*), (*c*); not taken into account (*b*). Insulation used (see Table 2): *Paroc extra plus* mineral wool (*a*), (*b*), (*c*); mineral wool board (*d*) .

With mineral wool board used (Fig. 2*d*) the *U*-value has been estimated to be from 0.164–0.177 for a dry building wall in our example, because the thermal conductivity is also influenced by temperature.

A condensate emerges in the case of „light" construction without vapour barrier (No. 1) in the given air conditions outdoors and indoors, while the relative humidity is decreasing to 84.9% due to the vapour barrier incorporated into construction No. 2 (see Fig. 2*a,c*); therefore, the vapour barrier effectively neutralises the risks of condensation in this construction. The *U*-value did not change because the free water saturation w_f is relatively low for mineral wool (see Table 2); therefore, the thermal conductivity did not change significantly due to moisture.

The application of mineral wool board (with parameters given in Table 2) can be problematic, especially in the cases of constructions No. 1 and No. 2 (see Fig. 2*d*). The *U*-values are increasing up to 0.36 and 0.41, because the thermal conductivity of a moist material is increasing over $\lambda = 0.1$. This evidences that the U-value can increase 2–2.5 times against the initially projected due to the ineffective insulation material. Therefore, in the present work the mineral wool board with mentioned properties will not be analysed further.

At using *Paroc extra plus* mineral wool, the relative humidity profile did not change significantly, regardless of the moisture taken (Fig. 2*a*, 2*c*) or not taken (Fig. 2*b*) into account, whereas U-values slightly change for constructions No. 3, No. 4 and No. 5. This can be explained with thermal conductivity changing at using *Aeroc classic 300* blocks. The vapour barrier for construction No. 5 is effective because the *U*-value is decreasing from 0.21 to 0.18 and from 0.20 to 0.17. The relative humidity is decreasing about 3% in the interlayer adjacent to the external layer.

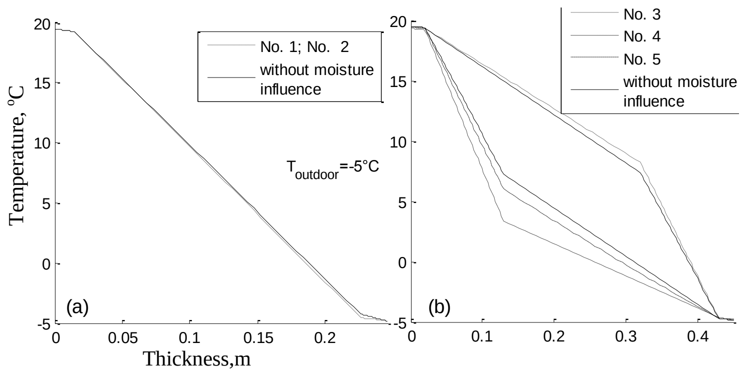

Fig. 3. The temperature profile in a building wall (the moisture influence on thermal conductivity taken into account). Solid line is the temperature curve (the moisture influence not taken into account).

The temperature profile shown in Fig. 3 is similar for „light" constructions No. 1, No. 2 (Fig. 3*a*), since the vapour barrier in these cases does not change the temperature profile in a building wall. This profile is quite different for construction No. 3 and for inverse constructions No. 4 and No. 5. This is because the temperature changes are more significant in the mineral wool than in the aerated concrete. A difference is seen in the cases with the presence and the absence of a vapour barrier. For constructions No. 3, No. 4 and No. 5 such a difference arises due to slight changes in *U*-values depending on whether or not the moisture influence is taken into account. If the insulation material is placed before the aerated concrete, this latter is exposed to a risk of freezing in winter, which can cause erosion (see Fig. 3*b*, No. 3 and No. 5). This risk could be reduced with the help of a vapour barrier (see Fig. 3*b*, No. 5). It can also be seen that in the temperature profile a slight non-linearity arises, which is caused by moisture.

5.2. Non-stationary case. Relative humidity variation in time

It is assumed that the temperature outdoors is changing periodically between the values –5 °C and +5 °C as a sinusoidal function within a 24-h periodicity (Fig. 4, dashed line).

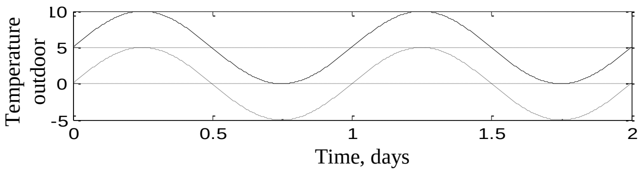

Fig. 4. Variations in the outdoor temperature.

In our examples the interlayer adjacent to the external layer of the construction is studied as that with the highest relative humidity.

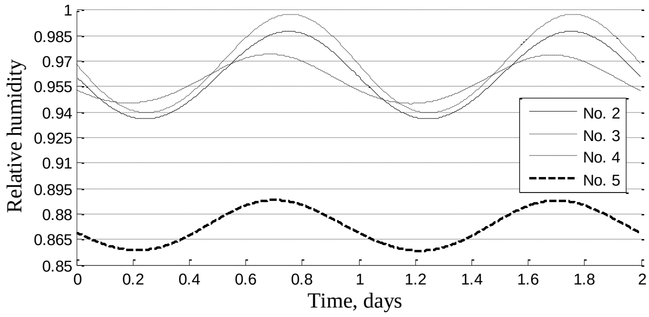

Fig. 5. Relative humidity on the interlayer adjacent to the outer layer of a construction wall.

Figure 5 shows that at the outdoor temperature between –5 °C and +5 °C the relative humidity is not changing considerably compared with the stationary case when this temperature is fixed at –5 °C or + 5°C (Fig. 2*a,c*).

5.3. 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 0 °C and +10 °C (Fig. 4, solid line), and that the indoor temperature is changing in compliance with the integral model (see subsection 2.2). Both the cases are compared taking and not taking into account the moisture influence in the construction, with the heat fluxes (Fig. 6) and temperatures (Fig. 7) analysed.

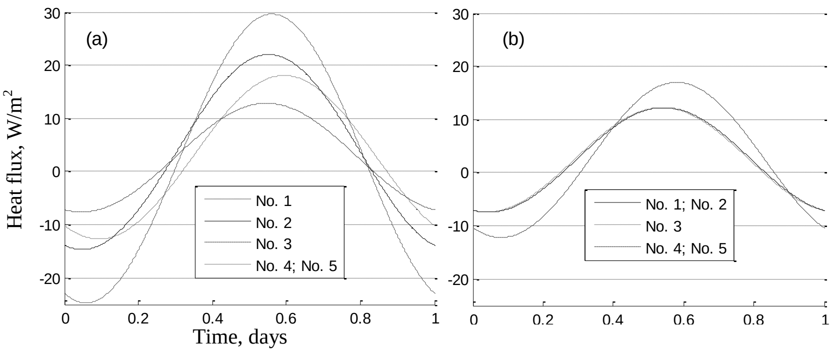

Fig. 6. Heat fluxes on the outer surface of construction: (*a*) the moisture influence is taken into account; (*b*) the moisture influence is neglected.

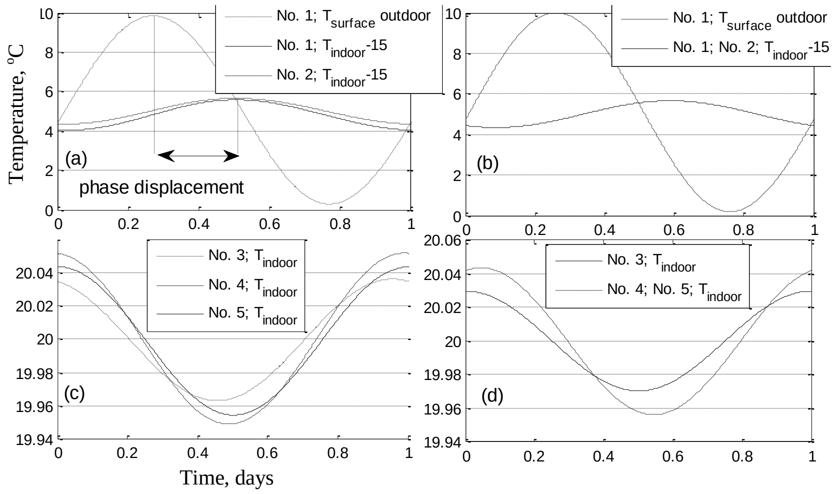

Fig. 7. Temperature behaviour indoors and on the outside surface of the wall:
(*a*), (*c*) the moisture influence is taken into account; (*b*), (*d*) the moisture influence is neglected.

The most important results for the five constructions are summarised in Table 3.

Table 3

Results for the five constructions under consideration

No	Indoor temperature, °C		Heat flux on the outside surface, W/m^2		Temperature amplitude fraction on outside and inside surfaces		Temperature phase displacement, h	
	wet	dry	wet	dry	wet	dry	wet	dry
1	1.55	1.32	53.86	19.70	6.16	7.43	5.64	7.85
2	1.32	1.32	36.69	19.70	7.42	7.43	5.83	7.85
3	0.07	0.06	20.47	19.64	133	162	16.65	17.7
4	0.10	0.09	30.77	29.84	90.4	107	17.35	18.7
5	0.09	0.09	30.09	29.84	104	107	17.66	18.7

In Table 3 the following parameters are used: the temperature amplitude (i.e. the difference between the maximum and minimum temperatures); the temperature amplitude fraction (the ratio of the temperature amplitudes on the outside and inside surfaces); the phase displacement (the difference between the time of reaching the maximum temperature on the outside surface and indoors). Columns: left (wet) – the moisture influence is taken into account; right (dry) –. the moisture influence is neglected.

Moisture does not affect the variation of heat fluxes (Fig. 6) in the case of constructions No. 3, No. 4 and No. 5, where the aerated concrete is incorporated, while its influence is stronger in constructions No. 1 and No. 2. The heat flux amplitude (Table 4) is markedly different for constructions No. 1 and No. 2, depending on whether the moisture is taken into account or not. The heat flux amplitude can increase up to 2.7 times for the „light" construction due to the moisture effect.

The indoor temperature is changing significantly for „light" constructions No. 1 and No. 2 (Fig. 7*a,b*), whereas in constructions No. 3, No. 4 and No. 5 (with aerated concrete) rather insignificant indoor temperature amplitude is observed (Fig. 7*c,d*), because thermal inertia for the latter is much lower than in the constructions containing only the insulation material and plasters. The temperature amplitude of the construction with mineral wool only (No. 1) noticeably differs from that of construction No. 2 with a vapour barrier, which is helpful in this case.

The phase displacement is relatively small for constructions No. 1 and No. 2, and the difference in the cases when a vapour barrier is present or absent is only minor. The phase displacement is much larger for constructions with aerated concrete (No. 3, No. 4 and No. 5), since the thermal inertia of these constructions is relatively low.

6. CONCLUSIONS

Different solutions of building wall constructions require specific suitable materials. For example, the *U*-value can increase more than twice as compared with the initially projected (see Fig. 2*d*).

As convincingly demonstrated in the present work, the vapour barrier can effectively prevent the risk of condensate formation in a wall. Such a barrier also helps to decrease *U*-value of the construction by reducing the relative humidity therein.

In the work it is shown that the heat losses are low and stable for the constructions consisting of aerated concrete with a properly selected insulation material.

To develop the model, the capillary pressure should be taken into account. Further experiments are required to determine the liquid conduction coefficient, as the available data are ambiguous. The next step would be comparison of the results obtained in experiments on similar constructions with theoretically calculated. Such experiments are planned to be carried out in a testing polygon [4].

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SILTUMA UN MITRUMA PĀRNESE CAUR DAUDZSLĀŅAINĀM BŪVKONSTRUKCIJĀM: ĀRA TEMPERATŪRAS IZMAIŅU IETEKME UZ SILTUMA ZUDUMIEM IEKŠTELPĀ

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K o p s a v i l k u m s

Darbā aprakstīts matemātiskais modelis mitruma un temperatūras sadalījuma noteikšanai daudzslāņainās būvkonstrukcijās, ievērojot procesu savstarpējo mij-iedarbību. Darbā apskatītas 5 raksturīgas būvkonstrukcijas, kurās siltuma izolāciju nodrošina akmens vate. Izmantojot izstrādāto programmu, iegūts reālistisks novērtējums mitruma un temperatūras sadalījumam būvkonstrukcijās Latvijas klimatiskajos apstākļos, kā arī novērtēta mitruma ietekme uz konstrukcijas siltuma caurlaidību *U*. Parādīts, ka daļā konstruktīvo risinājumu šī ietekme ir ļoti būtiska, un ir sagaidāma kondensāta rašanās konstrukcijā, kā arī parādīts, ka temperatūras svārstības telpā, āra temperatūrai mainoties diennakts ciklā, efektīvi slāpē būv-konstrukciju masivitāte. Izmantojot darbā aprakstītā modeļa pieņēmumus un pie-ejamos būvmateriālu raksturlielumus, var prognozēt dažādu konstruktīvo risinā-jumu energoefektivitāti un ilgtspēju.

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