2. Heat engineering

2.1. Analytical part

On January 1, 2003 the Building standard LBN 002-01 “Thermal techniques of the envelope structures of buildings” entered into force [4]. It harmonizes the heat engineering requirements defined for envelope structures of buildings in Latvia with the requirements of EU. In the above building standard the main heat engineering index of buildings is the heat loss coefficient of the building calculation **(H_T, W/K) determining the losses of energy in Watts via the limiting structures of buildings if the temperature difference on their opposite surfaces is one degree.** The heat losses coefficient of the building calculation HT shall not exceed the standard heat loss coefficient (H_{TR}). For the purpose of calculation of H_T, first, it is necessary to calculate the heat resistance coefficients or thermal transmittance coefficients U of limiting structures.

The heat flow in the limiting structures of buildings usually is calculated for a stationary (not depending on weather) case. Coefficient of thermal transmittance U shows what amount of heat flows via an area of the structure equal to one square metre within a certain time unit if the temperature difference between the opposite surfaces of limiting structures is equal to one degree. In compliance to the standard LVS EN ISO 6946 [1] the heat transmission coefficient U for flat structures shall be calculated based upon the formulae containing also the heat insulation of the structure:

$$U = \frac{1}{R_i + R_e + \sum_{i=1}^{N} \frac{d_i}{\lambda_i}} \qquad (2.1)$$

where U – heat transmission coefficient, W/(m^2·K);

R_i – thermal resistance to convection heat transfer the structure – internal, m^2·K/W;

R_e – heat resistance to convection heat transfer the structure – external, m^2·K/W;

d_i – thickness of the n layer of the structure, m;

λ_i – the thermal conductivity of the n layer of the structure, W/(m·K);

N – number of layers in the structure.

The standard LVS EN ISO 6946 defines the following values for the heat transfer resistances R_i and R_e:

For the heat flow upwards R_i = 0.10 m^2·K/W;

For horizontal heat flow R_i =0.13 m^2·K/W;

For the heat flow downwards R_i =0,17 m^2·K/W;

R_e =0.04 m^2·K/W .

Then the heat losses via the area of 1 m^2 of the limiting structure of a building can be calculated based upon the following formula:

$$Q = U(T_i - T_e) \qquad (2.2)$$

where Q – heat losses, W/m^2;

T_i – internal temperature, °C;

T_e – average external temperature of the heating season as regulated by the Building Standard LBN 003-01 [5], °C.

The Building standard LBN 002-01 [4] stipulates certain requirements for the values of heat transmission coefficients of building envelopes. In compliance to [4] they shall comply with the standard U_{RN} values, however, when it is not possible, they shall not exceed the maximum values U_{RM}.

The standard U_{RN} and maximum U_{RM} values are calculated based upon the following methodology. Based upon the following formulae:

$$k = \frac{19}{T_i - T_e} \quad (2.3)$$

where T_i – temperature of the calculation of internal air, °C, [LBN 211-98];

T_e – average external temperature during the heating season, °C, [5],

the temperature factor k is calculated and then it is multiplied with the values of heat transmission coefficient provided in the Table 2.1.

Table 2.1.

Standard (U_{RN}) and maximum (U_{RM}) values of the heat transmission coefficients and values of the coefficient Ψ_R

Building element	U_{RN}, W/(m²·K)			U_{RM}, W/(m²·K)		
	Residential buildings	Public buildings	Industrial buildings	Residential buildings	Public buildings	Industrial buildings
Roofs and ceilings in contact with external air	0.20 k	0.25 k	0.35 k	0.25 k	0.35 k	0.50 k
Floors on the soil	0.25 k	0.35 k	0.50 k	0.35 k	0.50 k	0.70 k
Walls with the weight 100 kg/m² and above	0.30 k	0.40 k	0.50 k	0.40 k	0.50 k	0.60 k
Walls with the weight below100 kg/m²	0.25 k	0.35 k	0.45 k	0.30 k	0.40 k	0.50 k
Thermal bridges Ψ_R	0.20 k	0.25 k	0.35 k	0.25 k	0.35 k	0.50 k

2.2. Calculation of the heat conductivity of expanded polystyrene foam

The heat transmission coefficient U for flat structures is calculated based upon the formulae (2.1). For the purpose of calculating it the heat conductivity coefficients of the relevant building structure and the thickness of layers shall be known.

In the general case the heat conductivity of heat insulation materials depends on the temperature and humidity content in it. In the standard [6] this dependence has been expressed by the following relation:

$$\lambda = \lambda_{10} \cdot F_T \cdot F_m \quad (2.4)$$

where λ_{10} – insulation heat conductivity at 10 °C;

F_T – thermal correction multiplier of heat conductivity;

F_m – humidity correction multiplier of heat conductivity.

The above multipliers shall be calculated based upon the following formula:

$$F_T = e^{f_t \cdot (T_2 - T_1)} \quad (2.5a)$$

$$F_m = e^{f_\omega \cdot (\omega_2 - \omega_1)} \quad (2.5b)$$

where f_t , f_ω – temperature and humidity calculation coefficients, K^{-1}; m³/m³;

T_1, T_2, ω_1, ω_2 – temperature and humidity marginal values, °C; m³/m³.

For the temperature interval from 0 to +30 °C the temperature and humidity calculation coefficients expanded polystyrene foam are stipulated in the Standard [6]. If the temperature is outside the above interval direct measurements shall be performed for accurate determination of the heat conductivity of expanded polystyrene foam.

If in the formula (2.5a, 2.5b) the exponent indices are low (<1), an approximate relation can be obtained by arranging the equations (2.5a and 2.5b) in row and putting them in the formulae (2.4):

$$\lambda = \lambda_{10} + \Delta\lambda_T + \Delta\lambda_m \qquad (2.6)$$

where $\Delta\lambda_T$ – thermal correction of heat conductivity, $\Delta\lambda_T = \lambda_{10} \cdot f_t \cdot (T_2 - T_1)$, W/(m·K);

$\Delta\lambda_m$ – humidity correction of heat conductivity, $\Delta\lambda_m = \lambda_{10} \cdot f_\omega \cdot (\omega_2 - \omega_1)$, W/(m·K).

Heat conductivity coefficients for a dry expanded polystyrene foam layer at 10 °C can be calculated according to the European standard [2] in compliance to the following formula:

$$\lambda_{10} = 0.027174 + 5.1743 \cdot 10^{-5} \cdot \rho + 0.173606 \cdot \frac{1}{\rho} \qquad (2.7)$$

where ρ – density of expanded polystyrene foam, kg/m^3.

Heat conductivity of dry expanded polystyrene foam W/(m·K) calculated in compliance to the formula (2.7) taking into consideration the correction at small thickness levels of the layer, when $\lambda > 0.038$ W/(m·K) [2], has been summarised in the Table 2.2.

As it can be seen from the Table 2.2. heat conductivity of expanded polystyrene foam shall be corrected only in cases when $\rho < 25$ kg/m^3 and the thickness of layers is less than 0.10 m.

Table 2.2.

Heat conductivity of expanded polystyrene foam at 10 °C, W/(m·K)

Thickness, m	Mark of expanded polystyrene foam; density, kg/m³			
	EPS 60; 15	EPS 100; 20	EPS 150; 25	EPS 200; 30
0.05	0.0407	0.0373	0.0354	0.0345
0,10	0.0395	0.0369	0.0354	0.0345
0.15	0.0395	0.0369	0.0354	0.0345
0.20	0.0395	0.0369	0.0354	0.0345

As the heat conductivity of expanded polystyrene foam depends on temperature and humidity content it is necessary to calculate the corresponding corrections in the formula (2.6).

The value of the temperature correction calculation coefficient in compliance to [6] for thickness of insulation layers from 50 to 200 mm and λ_{10} values from 0.035 to 0.040 W/(m·K) varies from 0.0033 to 0.0036 K^{-1}. The average value **f_T=0.0035 K^{-1}** may be applied in calculations. It should be noted that this value in the standard [6] is guaranteed up to the temperature of 30 °C. If there are no experimental measurements the same value shall be applied in an approximate way.

The operating temperature of the heat insulation material can be assumed to equal to the average temperature of the relevant layer.

$$T = 0.5 \cdot (T_1 + T_2) \qquad (2.8)$$

where T_1, T_2 – temperature on the borders of the layer, °C.

For the calculation of the humidity correction of the heat transmission coefficient the humidity correction coefficient $f_\omega = 4\ m^3/m^3$ [6].

2.3. Forecast of condensate discharge

The Paragraph 25 of the Latvian Building Standard LBN 002-01 [4] stipulates the following: **«In a building element not consisting of a homogeneous material it shall be ensured that the total water vapour resistance air diffusion equivalent of the layers at the warm side of its heat insulation material s_d exceeds the total water vapour resistance air diffusion equivalent of the materials at the cold side of heat insulation s_d at least five times"».**

In the Paragraph 31 it is stipulated that: **«Deviations from the requirements of the Paragraph 25 of the present Building Standard shall be justified by a calculation that guarantees that the annual accumulation of condensate is not with positive balance and does not harm the structure. Formation of condensate in wooden building constructions shall not be permitted».**

The condensate calculation is based upon the solution of the diffusion equation. The humidity diffusion in general case is characterised by the non-stationary diffusion equation . The methodology of calculations is provided in the Standard LVS EN ISO 13788. Humidity diffusion flow is calculated based upon the following formulae:

$$g = \delta_0 \frac{p_i - p_e}{s_d} \tag{2.9}$$

where g – humidity diffusion flow, $kg/(m^2 \cdot s)$;

δ_0 – coefficient, $2 \cdot 10^{-10}\ kg/(m \cdot s \cdot Pa) = 2 \cdot 10^{-10}\ s$;

p_i – unsaturated vapour pressure inside the building, Pa;

p_e – unsaturated vapour pressure outside the building, Pa;

s_d – water vapour diffusion equivalent, m.

Water vapour diffusion equivalent for a multi layer building element is calculated according to the following formulae:

$$s_d = \sum_{j=1}^{N} d_j \mu_j \tag{2.10}$$

where d_j – thickness of the n-th layer of the building element, m;

μ_j – water vapour resistance factor of the n-th layer of the building element.

When the unsaturated water vapour pressure depending on the water vapour diffusion equivalent $p=f(s_d)$ is depicted graphically a straight line is obtained. When the dependence of the saturated water vapour pressure from the temperature corresponding to s_d is depicted in the same coordinate system it is possible to perform analysis of humidity discharge in the limiting structures of buildings. If both lines do not cross each other it means that no condensate is being discharged (Figure 2.1.). If both lines cross each other (Figure 2.2. ; interrupted and dot-line line) it means that there is discharge of condensate in the limiting structures of the building. As higher water vapour pressure than saturated vapour pressure is not possible there is a break in the curve of the unsaturated vapour (continuous line) at the surface where condensate is discharged (discharge of condensate on one border surface only).

Humidity diffusion flow is directed from the inside to the place of condensate formation. Its value can be calculated according to the following formulae:

$$g_i = \delta_0 \frac{p_i - p_c}{s_{d\ i}} \tag{2.11}$$

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[1]) An extended theory description in literature [9].

where g_i – moisture flow from inside the room to the place of condensate formation, kg/(m²·s);

p_i – unsaturated vapour pressure in a room, Pa;

p_c – saturated vapour pressure on the condensation surface, Pa;

$s_{d\,i}$ – water vapour diffusion equivalent (room : condensation surface), m.

Further the humidity diffusion flow follows from the place of condensate formation to outside. Its value can be calculated based upon the following formulae:

$$g_e = \delta_0 \frac{p_c - p_e}{s_{d\,e}} \tag{2.12}$$

where g_e – humidity flow from the place of condensate formation to outside, kg/(m²·s);

p_e – unsaturated vapour pressure outside, Pa;

p_c – saturated vapour pressure on the condensate formation surface, Pa;

$s_{d\,e}$ – water vapour diffusion equivalent (condensation surface : outside), m.

The speed of accumulation of the condensate g_c, kg/(m²·s) equals to:

$$g_c = g_i - g_e = \delta_0 \left(\frac{p_i - p_c}{s_{d\,i}} - \frac{p_c - p_e}{s_{d\,e}} \right) \tag{2.13}$$

The total amount of accumulated condensate M_a is calculated by multiplying the monthly condensate accumulation speed with the length of every month and summing the obtained amounts of condensate according to the Standard [3]:

$$M_a = g_c \cdot t_m \tag{2.14}$$

where M_a – monthly accumulated amount of condensate, kg/m²;

t_m – length of a month, s.

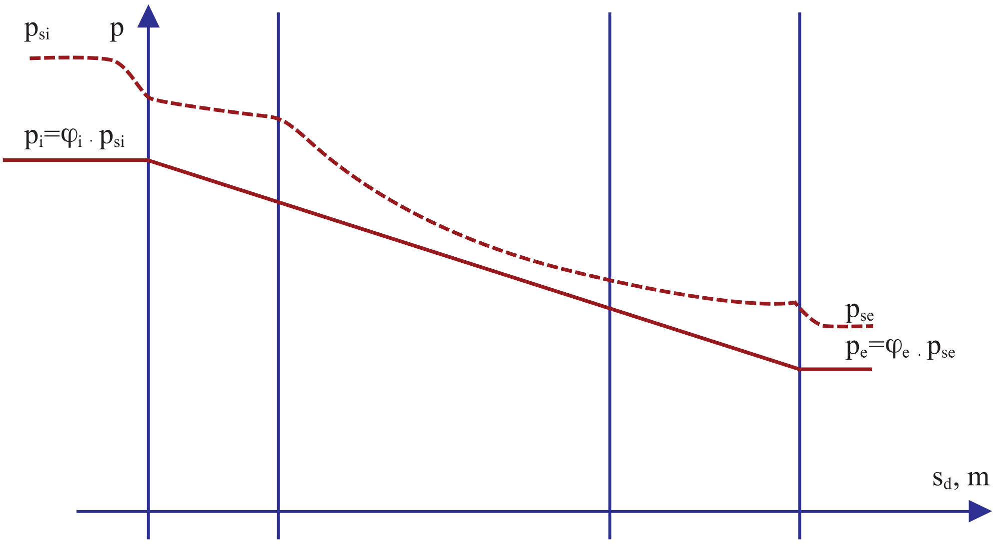

Figure 2.1. Schematic dependence of saturated (interrupted line) and unsaturated (continuous line) water vapour of the water vapour diffusion equivalent s_d (p_{si}, p_{se} – pressure of saturated water vapour inside and outside; p_i, p_e – pressure of unsaturated water vapour inside and outside; φ_i, φ_e – relative air humidity inside and outside)

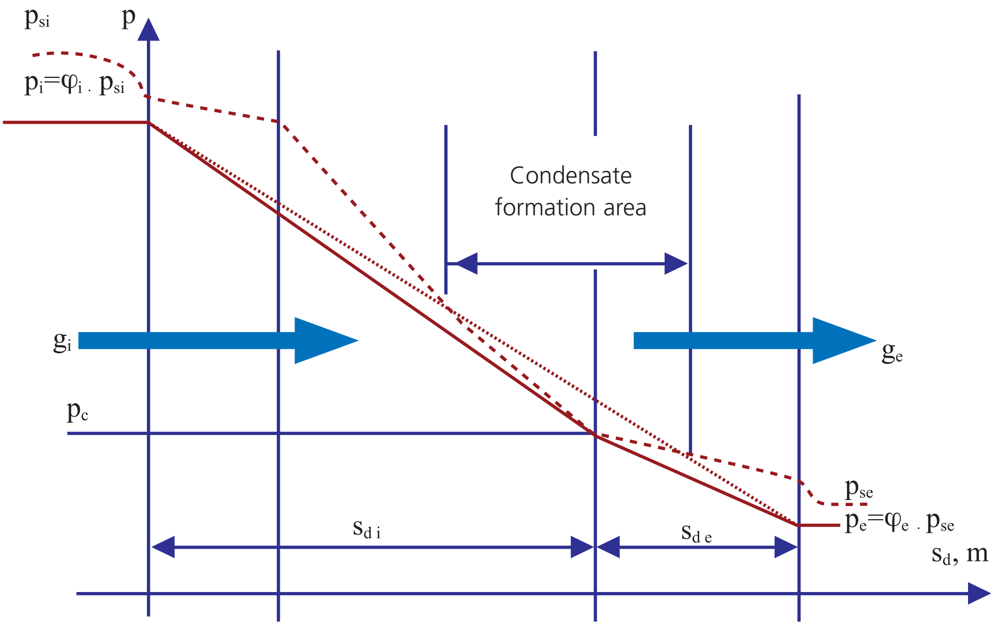

Figure 2.2. Schematic dependence of saturated (interrupted line) and unsaturated (continuous broken line) water vapour of the water vapour diffusion equivalent s_d. The dotted line shows how the condensate is formed (p_{si}, p_{se} – pressure of saturated water vapour inside and outside; p_i, p_e – pressure of unsaturated water vapour inside and outside; φ_i, φ_e – relative air humidity inside and outside; p_c – water condensate saturated vapour pressure; $s_{d\,i}$, $s_{d\,e}$ – corresponding water vapour diffusion equivalent between the place of formation of the condensate and inside or outside; g_i , g_e – water vapour diffusion flows)

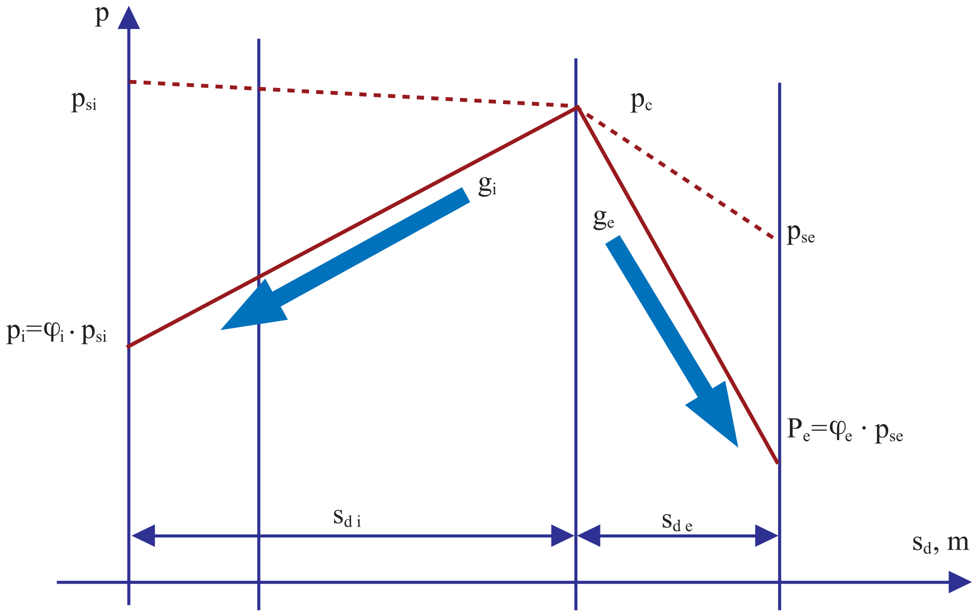

Figure 2.3. Schematic dependence of saturated (interrupted line) and unsaturated (continuous broken line) water vapour of the water vapour diffusion equivalent s_d (p_{si}, p_{se} – pressure of saturated water vapour inside and outside; p_i, p_e – pressure of unsaturated water vapour inside and outside; φ_i, φ_e – relative air humidity inside and outside; pc – water condensate saturated vapour pressure; $s_{d\,i}$, $s_{d\,e}$ – corresponding water vapour diffusion equivalent between the place of formation of the condensate and inside or outside; g_i , g_e – corresponding humidity flows from the place of condensate formation to the inside or outside)

2.3.1. Condensate drying in walls of buildings

The methodology of calculation of the condensate drying is defined by the Standard [3]. The humidity diffuses from the area of condensate formation to the internal (flow g_i) and external surface of the building wall (Figure 2.3.).

When the unsaturated water vapour pressure depending upon the water vapour diffusion equivalent $p=f(s_d)$ is depicted graphically a broken line is obtained (Figure 2.3.; continuous line). When also the dependence of saturated water vapour pressure upon sd is depicted in the same coordinates system (interrupted line) the analysis of the condensate drying in the building walls can be performed. From the surface on which humidity has accumulated during the discharge of condensate it moves to the surfaces of the building walls during the drying period. Humidity flows g_i and g_e are calculated according to the formula (2.11., 2.12.; g_i is taken with the positive sign in this case). In the total condensate amount (balance) the amount of drying humidity is summed with the negative sign. If the annual total condensate balance is not positive the condensate dries during the summer period.

2.3.2. Drying of roof structures

When the roof structures that do not have a ventilated air separation layer dry usually the situation forms when the condensate humidity first diffuses to another place in the structure where it condensates again. Only after the second (or more) condensation the drying process starts and it is depicted schematically in Figure 2.4.

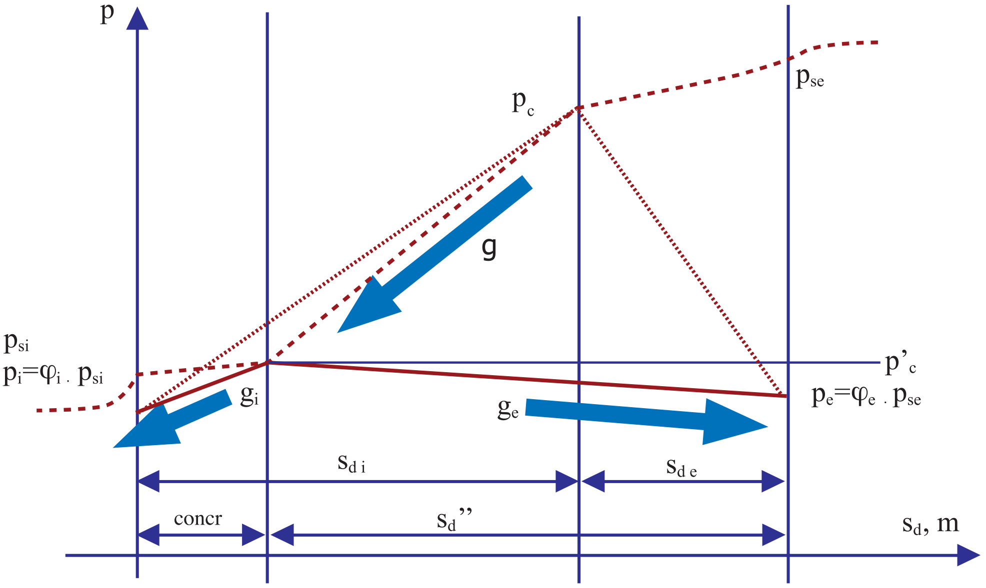

Figure 2.4. Schematic dependence of saturated (interrupted line) and unsaturated (continuous broken line) water vapour of the water vapour diffusion equivalent s_d (p_{si}, p_{se} – pressure of saturated water vapour inside and outside; p_i, p_e – pressure of unsaturated water vapour inside and outside; φ_i, φ_e – relative air humidity inside and outside; p_c, p'_c – the relevant pressure of the water saturated vapour of the condensate and new condensate; $s_{d\,i}$, $s_{d\,e}$ – corresponding water vapour diffusion equivalent between the place of formation of the condensate and the inside or outside; s_d' , s_d''– the corresponding water vapour diffusion equivalent between the place of formation of the new condensate and inside or outside; g – humidity flow to the new place of condensation; g_i, g_e – the corresponding humidity flows from the place of formation of the new condensate to the inside or outside)

Drying with supplementary condensation will form when the saturated vapour line (interrupted line) is below the unsaturated vapour line (dotted line). In this case the humidity will first diffuse to the new condensation surface (flow g), and only then it will escape the structure. Such a diffusion mechanism is referred to as the drying with an obstacle. Following the diffusion of humidity the drying process is much slower because the condensate saturated vapour pressure has got reduced from p_c to p'_c. In the direction of the flow to the external and internal side of the structure it can be calculated according to the formula (2.11, 2.12), by applying them to the new location of condensate in the building structure:

$$g_i = \delta_0 \frac{p_c' - p_i}{s_d'} \tag{2.15}$$

where g_i – humidity flow from the place of condensation to the inside of the room, kg/(m²·s);

p_i – unsaturated vapour pressure in the room, Pa;

p_c' – saturated vapour pressure on the condensation surface, Pa;

s_d' – water vapour diffusion equivalent (inside the room : condensation surface), m.

There is another humidity diffusion flow from the place of condensate formation to outside and it can be calculated according to the following formulae:

$$g_e = \delta_0 \frac{p_c' - p_e}{s_d''} \tag{2.16}$$

where g_e – humidity flow from the place of the condensate formation to outside, kg/(m²·s);

p_e – unsaturated vapour pressure outside, Pa;

p_c' – saturated vapour pressure on the condensation surface, Pa;

s_d'' – water vapour diffusion equivalent (condensation surface : outside), m.

The amount of condensate per month is calculated by multiplying the length of a month in seconds with the flow (2.15) and (2.16) sum. The total annual balance of condensate amounts to the sum of the amounts of condensate of all the 12 months where the dried condensate is included with the negative sign. If the annual balance of condensate is not positive the structure dries out during the summer period.

2.4. Calculation example of the system of stay-in-place forms «Dobeles panelis»

We will assume that there is a building structure of external wall made of the stay-in-place forms system «Dobeles panelis» and it consists of the following layers (counting from inside; Table 2.3.) and where the heat conductivity of heat insulation is according to the data in the Table 2.2.[2]. The values marked in the Table 2.3. will be varied further in the Tables 2.7. and 2.8.

Table 2.3.

Structure of an external wall of the stay-in-place forms system «Dobeles panelis»

No.	Layers	Thickness, m	Heat conductivity, W/(m·K)	Water vapour resistance factor
1.	Gypsum board	0.013	0.25	10
2.	Air separation layer[3]	0.002	0.036	1
3.	EPS 200	0.05	0.0345	60
4.	Reinforced concrete	0.15	2	100
5.	EPS 200	0.05	0.0345	60
6.	External finish	0.015	0.87	15

[2]) Possibly worst case has been selected for the analysis – the thinest external heat insulation layer (0.05 m).

[3]) According to the standard [1] non-ventilated or weakly ventilated air layers provide additional heat resistance.

The distribution of temperature in the above building structure under the climatic conditions in Riga in January when the inside temperature is 20 °C is shown in the Figure 2.5.

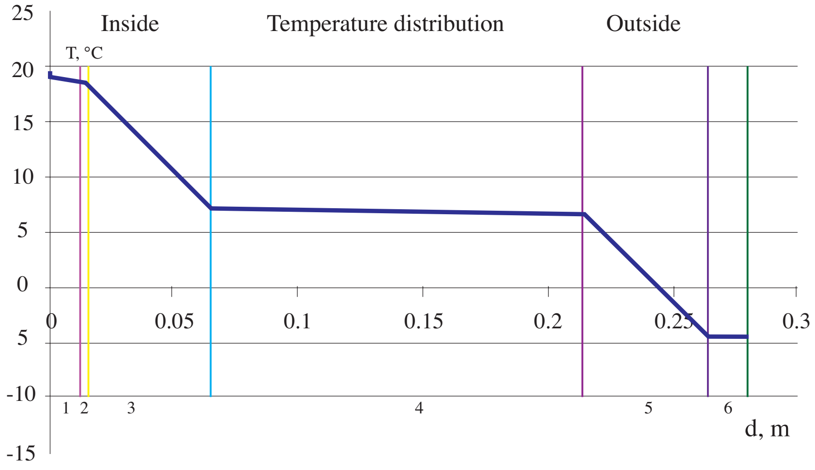

Figure 2.5. Distribution of temperature in the building structure under climatic conditions in Riga in January per layers according to the Table 2.3. when counting from inside. The inside temperature is 20 °C; numeration of the layers (1 – 6) corresponds to the Table 2.3.

As it can be seen from the Figure 2.5 the average operating temperature of the internal expanded polystyrene foam layer of the structure (3) amounts to 12.7 °C. Consequently this causes the increase of the heat conductivity of the layer (3) (see the explanation at the formula 2.6.):

$\Delta\lambda_T = \lambda_{10} \cdot f_t \cdot (T_2 - T_1) = 0.0345+0.0035 \cdot (12.7 - 10) = 0.000326$ W/(m·K).

The operating temperature of the layer (5) amounts to 1.2 °C, which consequently produces negative increase of the heat conductivity: –0.0010 W/(m·K).

The heat transmission coefficient U of this structure has been calculated according to the formula (2.1) and the heat conductivity of the layers (3) and (5) of 10 °C, is 0.306 W/(m^2·K). When it is recalculated considering the temperature corrections of the calculated heat conductivity 0.303 W/(m^2·K), the correction of the heat transmission coefficient is negative: –0.003 W/(m^2·K).

To be able to forecast the condensate formation risk in the limiting structure of the building in accordance with the standard [3] it is necessary to know the humidity conditions of the building maintenance. The Standard [3] provides for five humidity classes of the building maintenance and their short description is provided in the Table 2.4.

Table 2.4.

Humidity classes of the building maintenance according to the standard [3]

Humidity classes of the building maintenance	Description
1.	Warehouse premises (low level of humidity)
2.	Offices, shops
3.	Buildings with low level of population. One storied residential houses
4.	Dwellings with high occupancy. Multi storied residential houses, sports halls, kitchens, canteens
5.	Humid special purpose buildings: washhouses, breweries, swimming places, etc.

The calculation of the condensate formation of the structure in the Table 2.3. under the climatic conditions of Riga in January for the buildings of the 4th humidity maintenance class is shown in the Figure 2.6.

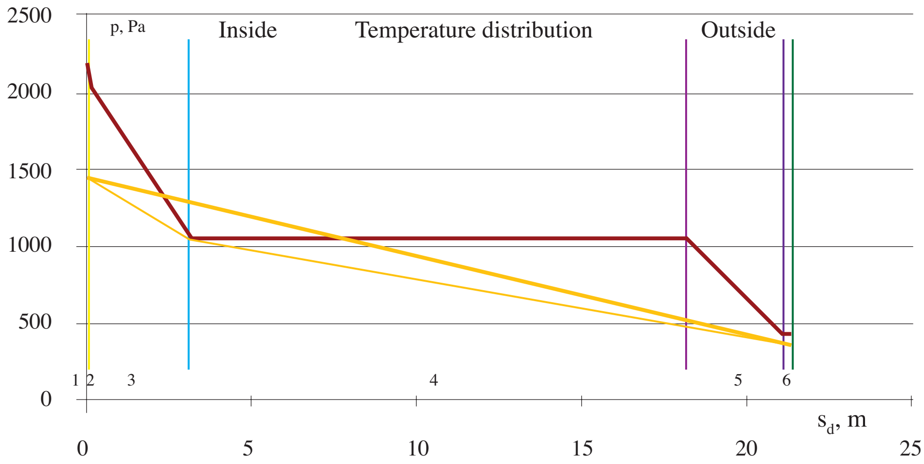

Figure 2.6. Distribution of humidity in the building structure under the climatic conditions of Riga in January per layers according to the Table 2.3. counting from inside. The internal temperature is 20 °C; numeration of layers (1–6) complies to the Table 2.3. (yellow broken line – unsaturated vapour pressure; red line – saturated vapour pressure)

As it can be seen in the Figure 2.6. in the structure condensate gets formed and its absolute amount calculated in accordance with the standard [3] is 0.217 kg/m^2. During the summer period the condensate dries out. Thus the layer (3) is subject to humidity impact during winter period. We will calculate the humidity correction of the heat conductivity of this layer (see the explanation at the formula 2.6.):

$\Delta\lambda_m = \lambda_{10} \cdot f_\omega \cdot (\omega_2 - \omega_1) = 0.0345 \cdot 4 \cdot 0.217 \cdot 10^{-3} / 0.05 = 0.0006$ W/(m·K).

In this case humidity U must be recalculated m^3/m^3 (the volume of one square meter of the layer (3) is 0.05 m^3; the condensate takes 0.217·10^{-3} m^3). When the heat transmission coefficient U is recalculated taking into consideration the humidity correction of heat conductivity we obtain 0.3062 W/(m^2·K). The correction is positive: 0.0002 W/(m^2·K).

As it can be seen the temperature and humidity corrections of heat transmission coefficient are with opposite signs and their absolute values are quite low: –0.003 and 0.0002 W/(m^2·K). Therefore these corrections can be disregarded in the further calculation of the system «Dobeles panelis».

If the thickness of the external heat insulation layer is increased to 0.1m the absolute amount of condensate that is discharged in the buildings of the 4th maintenance humidity class in the layer (3) decreases to 0.002 kg/m^2. Therefore it is not recommended to use the structure with the external heat insulation layer of 0.05 m. The condensate does not form at all in the buildings of the 3rd maintenance humidity class.

The Figures 2.7. and 2.8. show the distribution of the temperature and water vapour in the limiting structures of the buildings of the 4th and 3rd maintenance humidity class in the Table 2.3. when the external heat insulation layer (5) is 0.1 m. Meteorological conditions correspond to the climatic conditions in Riga in January [5].

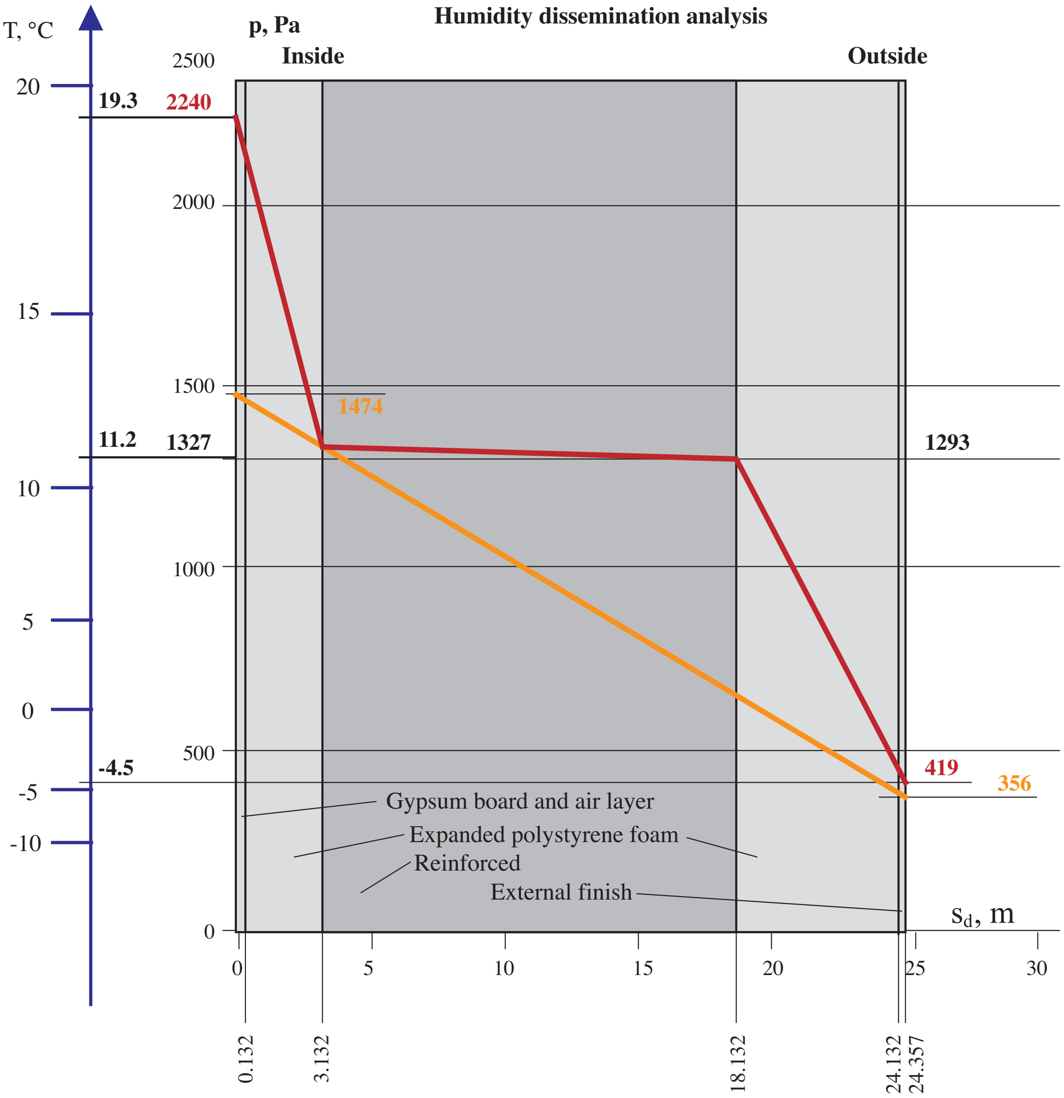

Figure 2.7. Distribution of the temperature and water vapour pressure in the envelope structure (Table 2.3.; thickness of the external expanded polystyrene foam layer (5) is 0.1 m) for the buildings of the 4th maintenance humidity class (yellow line – distribution of unsaturated water vapour pressure; red line – saturated water vapour and simultaneous temperature distribution)

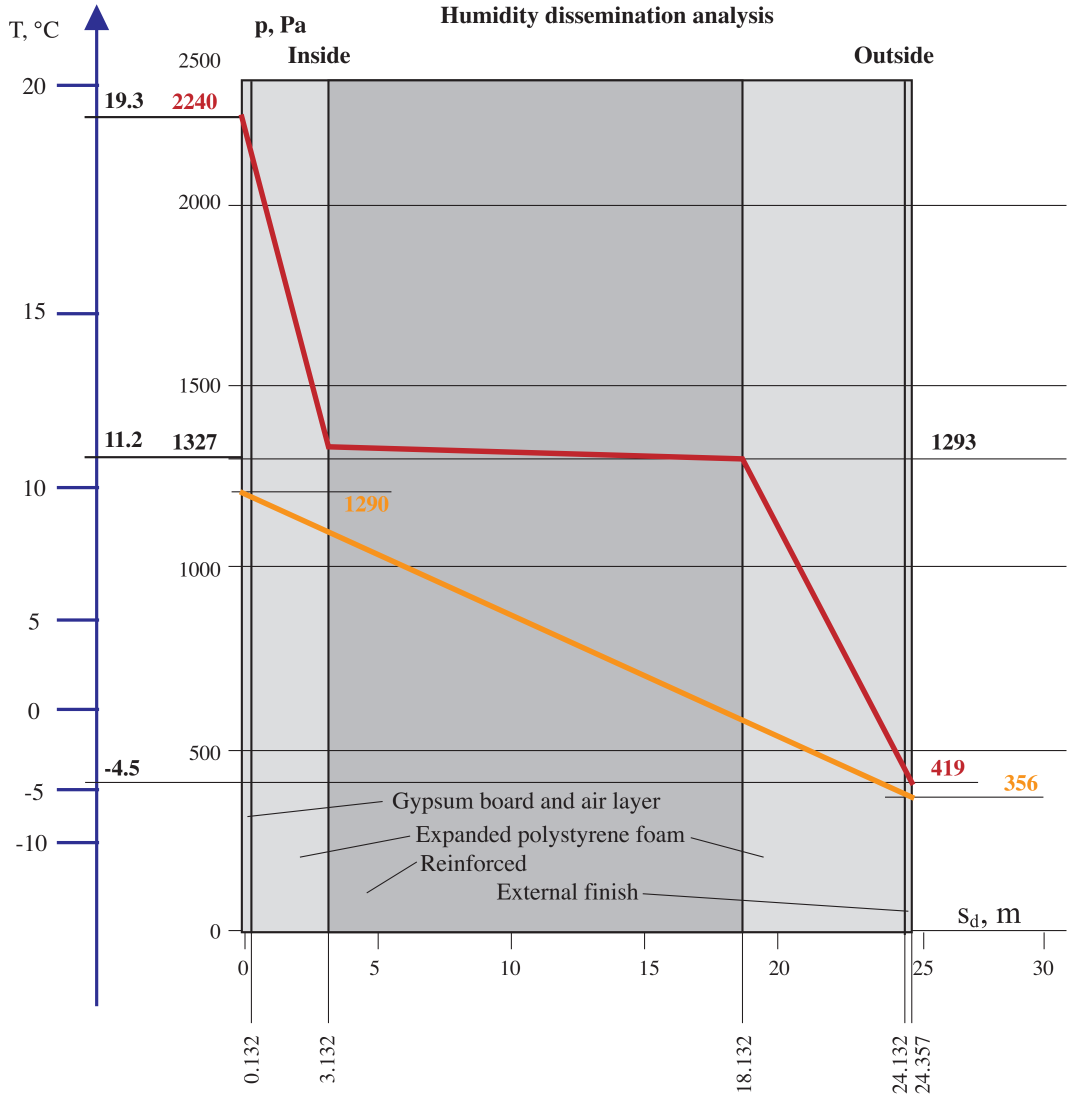

Figure 2.8. Temperature and water vapour pressure distribution in the limiting structure (Table 2.3.; thickness of the external expanded polystyrene foam layer (5) is 0.1 m) for the buildings of the 3rd maintenance humidity class (yellow line – distribution of unsaturated water vapour pressure; red line – saturated water vapour and simultaneous temperature distribution)

2.5. Influence of the fastening screws

2.5.1. Correction of the heat transmission of the fastening screws

Passing through fastening screws of the structure (steel λ=50 W/(m·K); diameter 5.2 mm) cause additional increase of the heat permeability coefficient of the structure and it depends on the number of screws per unit of area. In the Table 2.5. the increase of the heat permeability coefficient is shown, it has been calculated for one screw per 1 m^2 depending on its length.

Table 2.5.

Corrections of the coefficient U for a single fastening screw per 1 m^2

Length of screw, m	0.25	0.30	0.35	0.40	0.45	0.50	0.55
ΔU_S, W/(m^2·K)	0.0042	0.0035	0.0030	0.0027	0.0024	0.0021	0.0019

In this case the total increase of the heat transmission coefficient of the structure (corrections) caused by the screws can be calculated according to the following formulae:

$$\Delta U_{ks} = \frac{N}{A} \Delta U_s \qquad (2.17)$$

where N – number of screws in the area A;

A – area, m^2 (if the distance between screws is 0.2 m, then N/A=25);

ΔU_S – correction of heat transmission coefficient of one screw (Table 2.5.), W/(m^2·K).

Considering the corrections of screws the heat transmission coefficient in the wall structures of the system «Dobeles panelis» can be calculated according to the following formulae:

$$U = U_{10} + \Delta U_{ks} \qquad (2.18)$$

where U_{10} – heat transmission coefficient of the panel at 10 °C, calculated according to the formulae (2.1);

ΔU_{KS} – screw correction of the heat transmission coefficient (2.17), W/(m^2·K).

2.5.2. Influence of the fastening screws upon the temperature of the internal wall

One of the topical questions could be as follows: «Does an area of lower temperature get formed inside the building structure nearby the ends of the fastening screws during winter period forming a zone of risk of formation of mould or can even discharge of condensate take place there?»

The answer to this question can be provided only by the calculation of the coldness bridges which were performed (Figure 2.9.), however, they have not been included here due to their amount and level of complexity. The calculations are based upon the assumed system «Dobeles panelis» with the following thickness of layers: EPS 100 inside, 0.05 m (Figure 2.9.; left side); reinforced concrete, 0.15 m; EPS 100 outside, 0.05 m. External temperature: –25, internal temperature +20 °C. The lines 1 and 3 provide the temperature on the surface of the joining screw: 3 – without taking into account the interaction between the screw and its surrounding environment, 1 – taking into account the above interaction, 2 – temperature of the surrounding environment of the screw. As it can be seen the initial difference of the screw and surrounding environment is levelled out quite soon (charts 1 and 2 merge) if the diameter of the screw is small (the assumed value in the calculations is 5.2 mm). In case of large diameter of the screw the situation will change. It means that a local decrease of the temperature of internal wall surface nearby the end of the screw cannot be expected (coordinate d=0; Figure 2.9.). Still these screws act as coldness bridges and they cause even decrease of temperature on the internal wall. When it is assumed for the calculation purpose that there are 25 screws per 1 m2 in the structure the corresponding temperature decrease is approximately 0.5 °C (from 18.5 °C which could be forecasted if this coldness bridge did not operate, to 18 °C).

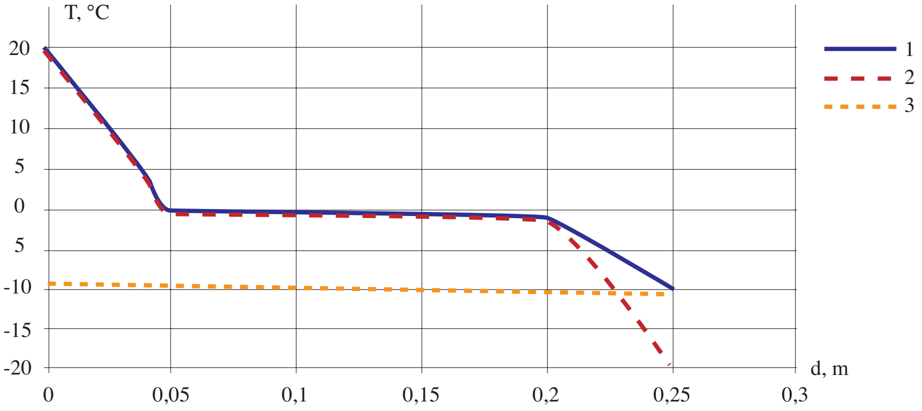

Figure 2.9. Temperature of the pass-through screw of the system «Dobeles panelis» and its surrounding environment: 1 – environment temperature; 2 – temperature of the screw surface taking into account the interaction between the screw and the environment; 3 – temperature of the screw surface not taking into account the above interaction

2.6. Heat transmission of the external wall structures of the system «Dobeles panelis»

The Tables 2.7 and 2.8. provide the values of the heat transmission coefficient U of the system «Dobeles panelis», $W/(m^2 \cdot K)$ and maximum condensate amount during the winter period kg/m^2 for the buildings of the 3rd and 4th maintenance humidity class (Table 2.4.), it has been calculated in compliance to the standard [3] (3rd class – Dwellings with low occupancy. One storied residential houses; 4th class – buildings with high population level; Multi-storeyed residential houses, sports halls, kitchens, canteens. etc.) under the climatic conditions of Riga [5], taking into account correction for 25 fastening screws per 1 m^2 depending upon the thickness of the external expanded polystyrene foam (1st vertical column) and the reinforced concrete. In all the cases shown in the Tables 2.7. and 2.8. the parameters of the other layers of the panels of external walls of the system «Dobeles panelis» comply with the Table 2.3. The varied parameters are marked in the Table 2.3. The condensate dries out during the summer period.

Colouring the U values in the Tables 2.7. and 2.8. complies with the requirements in the Table 1 (temperature factor k=1) and are shown in the Table 2.6.

Table 2.6.

Colours of U values in the Tables 2.7. and 2.8.

⬜	> 0.60 $W/(m^2 \cdot K)$ – not compliant to the standards	U_{RN}–U_{RM} U_{RN} – standard value; U_{RM} – maximum value
🟦	0.50–0.60 $W/(m^2 \cdot K)$ – industrial buildings	
🟩	0.40–0.50 $W/(m^2 \cdot K)$ – public buildings	
🟨	0.30–0.40 $W/(m^2 \cdot K)$ – residential buildings	
🟥	Condensate is discharged in the structure and it dries out during the summer period	

Table 2.7.

Values of the heat transmission coefficient of the external walls of the system «Dobeles panelis» U, W/(m^2·K) and maximum amount of condensate during winter period kg/m^2 depending upon the thickness of the external heat insulation and reinforced concrete layers

External insulation, EPS 200					Condensate, kg/m^2							
U, W/(m^2·K)					3rd humidity class				4th humidity class			
EPS 200	Thickness of reinforced concrete, m				Thickness of reinforced concrete, m				Thickness of reinforced concrete, m			
d, m	0.15	0.20	0.25	0.30	0.15	0.20	0.25	0.30	0.15	0.20	0.25	0.30
0.05	0.41	0.39	0.38	0.37	0.01	0.02	0.03	0.03	0.23	0.25	0.26	0.26
0.10	0.30	0.29	0.28	0.27	None	None	None	None	0.00	0.01	0.02	0.03
0.15	0.24	0.23	0.22	0.21	None	None	None	None	None	None	None	None
0.20	0.20	0.19	0.18	0.18	None	None	None	None	None	None	None	None

When the stay-in-place forms of external walls of the system «Dobeles panelis» are manufactured of expanded polystyrene foam with graphite supplements – Neopor EPS 200 with the density 25–30 kg/m^3 and heat conductivity of approximately 0.03 W/(m·K), the analogous to the Table 2.7. is the Table 2.8.

Table 2.8.

Values of the heat permeability coefficient of the external walls of the system «Dobeles panelis» with expanded polystyrene foam «Neopor EPS 200» U, W/(m^2·K) and maximum amount of condensate during winter period kg/m^2 depending upon the thickness of the external heat insulation and reinforced concrete layers

External insulation, Neopor EPS 200					Condensate, kg/m^2							
U, W/(m^2·K)					3rd humidity class				4rd humidity class			
Neopor EPS 200 d, m	Thickness of reinforced concrete, m				Thickness of reinforced concrete, m				Thickness of reinforced concrete, m			
	0.15	0.20	0.25	0.30	0.15	0.20	0.25	0.30	0.15	0.20	0.25	0.30
0.05	0.38	0.36	0.34	0.33	0.02	0.02	0.03	0.04	0.24	0.25	0.25	0.26
0.10	0.27	0.26	0.25	0.24	None	None	None	None	0.00	0.01	0.02	0.03
0.15	0.22	0.21	0.20	0.19	None	None	None	None	None	None	None	None
0.20	0.18	0.17	0.17	0.16	None	None	None	None	None	None	None	None

2.7. Calculation of roof structure

Roof construction of the system «Dobeles panelis» is showed in a schematic way in the Figure 2.10. The structure is not homogenous and it contains three types of space with different heat conductivity coefficients: reinforced concrete, expanded polystyrene foam and unventilated air inserts. The thickness of the expanded polystyrene foam heat insulation of the prefabricated roof panels of the system «Dobeles panelis» under the reinforced concrete beams is fixed at the level of 0.04 m.

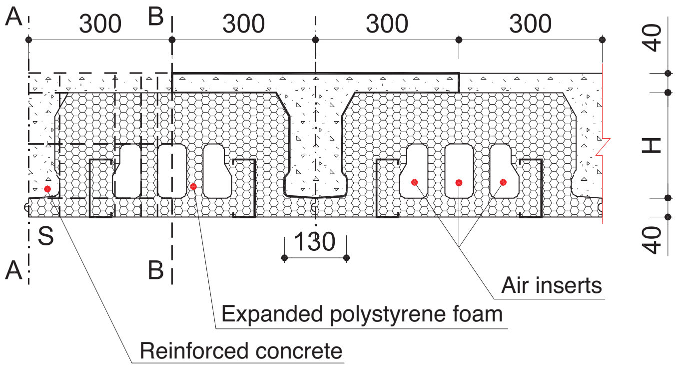

Figure 2. 10. Roof structure of the system «Dobeles panelis»

Calculation of the heat transmission coefficient U of such a structure is quite complicated. Based upon the standard [1] the heat transmission coefficient of unhomogenious building structures shall be calculated by splitting the structure in layers (perpendicular to the direction of the heat flow) and sections (parallel to the direction of the heat flow) in such a manner that every individual part of the structure is homogeneous. Then based upon the standard [1] the upper (R_T') and lower (R_T'') heat resistance margin of the building structure shall be calculated and their arithmetic mean is the value of the heat transmission coefficient we were looking for. For example in the structure shown in the Figure 2.10. the cuts shall be made first (dotted – lined lines) along the symmetry slabs of the panel (AA, BB etc.), and then the part of the panel in between two cuts, for example, AA and BB, has to split in 4 layers and 5 sections (totally 20 homogeneous areas; shown with interrupted lines in the Figure 2.10.). One can understand that the final calculation would have quite a big error.

As the structure will have only 40 mm heat insulation layer under the bearing cross-beam obviously that this joint is the most critical surface (point S; Figure 2.10.). Therefore we will perform as correct as possible analysis of this joint, solving the stationary heat conductivity equation for this area of the structure. Air inserts do not play essential role in this case – they are placed relatively far away and therefore we will not include them in the review. The analysed section of the building structure is shown in the Figure 2.11.

The following heat parameters were assumed for the calculation purposes:

1)heat conductivity coefficient of expanded polystyrene foam – 0.036 W/(m^2·K);

2) heat conductivity coefficient of reinforced concrete – 2 W/(m^2·K) [4];

3)) resistance of the heat transition of the external surface – 0.04 m^2 K/W;

4) resistance of the heat transition of the internal surface – 0.10 m^2 K/W;

5) external air temperature – -4.7 °C (the average temperature in January in Riga [5]);

6) internal air temperature – +20 °C.

Mathematically the structure was calculated by means of a square grid a section of which is shown in the Figure 2.11. 16 points of split were selected along the X axis direction and 23 points were selected along the y axis direction. The step of the grid is 0.01 m. Thus 16×23=368 junctions are formed. The problem solution leads to a system of linear algebra equations containing a number of equations equal to the junctions of the grid. When the system of 368 algebra equations is solved we obtain the temperature in 368 junctions. Based upon the calculated temperatures the isotherms group can be constructed and this has been shown in the Figure 2.12.

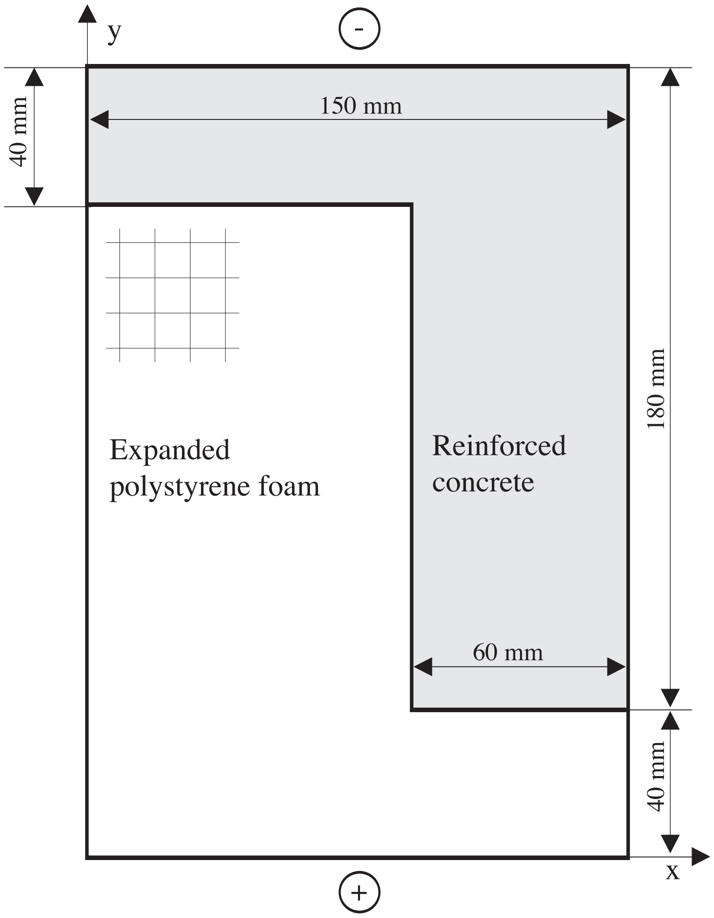

Figure 2.11. Calculation scheme of the roof structures

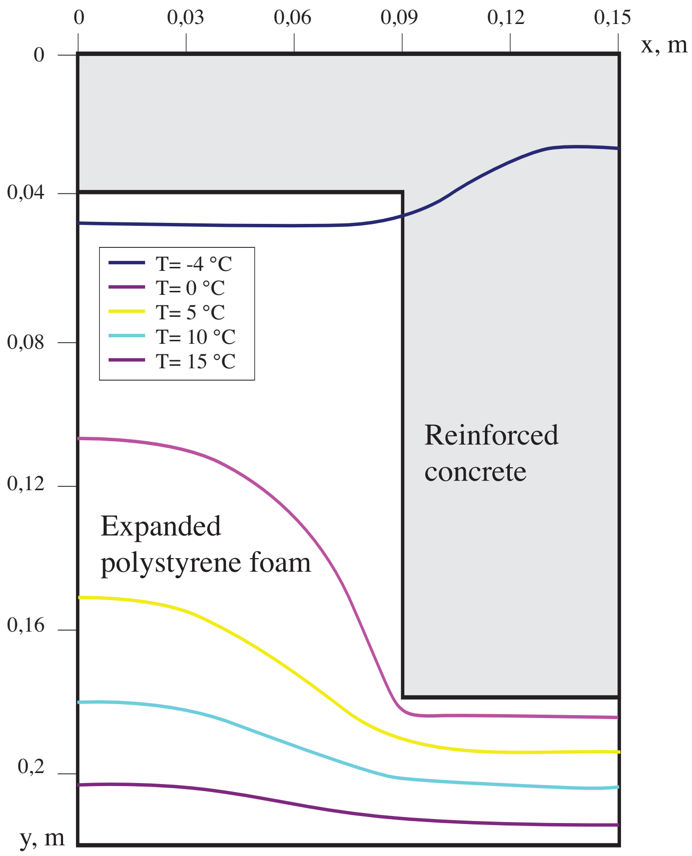

Figure 2.12. Isotherm group of the roof structure elements

As it can be seen from the isotherm group, the isotherm of 15 °C approaches the internal surface nearby the reinforced concrete cross-beam. It certifies that the surface temperature lowers under the reinforced concrete cross-beam. The temperature of the internal and external surface of the panel depending upon the coordinate x, if the external air temperature is –4.7 °C (average January temperature in Riga [5]) is shown in the Figure 2.13.

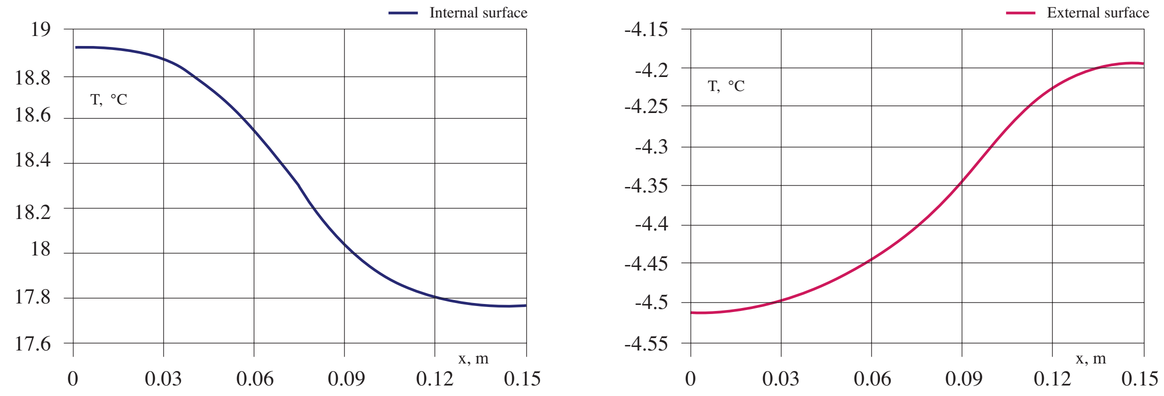

Figure 2.13. Changes of the temperature of the internal and external surface of the structure

As it can be seen the temperature below the internal surface of the cross-beam is 17.8 °C, which is by 1.1 °C lower than further away from it. In this temperature the relative air humidity in the room is 0.66 (4th humidity class) and it increases up to 0.79 on the surface below the cross-beam and this is close to the mould risk margin which is 0.8 [3]. However, in the buildings of the 3rd class of maintenance humidity the relative air humidity in the room increases from 0.53 to 0.61 on the surface below the cross-beam. If the external air temperature in December or January remains at the level of –20 °C for a sufficiently long period of time which is to some extent possible under the climatic conditions of Latvia the relative air humidity on the surface below the cross-beam increases to 0.88 (4th humidity class) or 0.77 (3rd humidity class). In compliance to the standard [3] when the relative air humidity remains above 0.8 for a sufficiently long time there is a risk of mould formation. When the layer of expanded polystyrene foam insulation nearby the cross beam is increased up to 0.06 m the maximum relative air humidity on the surface below the cross-beam in December – January decreases down to **0.82–0.80** (4th humidity class) or 0.67 (3rd humidity class). It means that in the buildings with the 4th maintenance humidity class the total heat insulation layer in the roof structure nearby the cross-beam shall be at least 0.06 m. As the heat insulation layer of pre-manufactured roof panels, shown in the Figure 2.10, is 0.04 m thick additional heat insulation measures shall be implemented to increase the total layer of the heat insulation to at least 0.06 m. Additional heat insulation layer can be placed both below or above the panel. These additional measures will reduce the risk of mould formation in the risk areas under the bearing reinforced concrete cross-beams.

The value of the heat transmission coefficient of the structure seen in the Figure 2.11. has been obtained from the data of the numeric solution and amounts to 0.58 W/(m^2·K), however, when it is calculated according to the standard [1], by splitting the building element in 3 layers and 2 sections we obtain the value of 0.52 W/(m^2·K). When the heat resistance of the building element is calculated according to the following formula:

$$R_T = \frac{R_T' + 2R_T''}{3} \tag{2.19}$$

which was applied prior to the approval [7] of the standard [1] and applying the upper R_T' and lower R_T'' value of the heat resistance we obtain the figure of 0.57 W/(m^2·K), which is much closer to the accurate calculation. Generally it should be concluded that when calculating the values of the heat transmission of such inhomogeneous building structures by applying the method provided for in the standard [1] an error of 15-20% can be expected.

The amount of the discharged condensate when calculated under the cross-beam with the method of grid and the standard calculation for homogeneous layers based upon the meteorology data in Riga for January equals to 0.19 kg/m^2 and 0.18 kg/m^2, which do not differ considerably. Therefore it can be expected that the condensate amount calculation will produce a considerably smaller error than the calculation of the heat transmission coefficient.

Still the condensate does not dry out in summer. It means that the roof structure can be operated only when the inside of the structure is covered by a vapour insulation layer the water vapour resistance diffusion equivalent of which $s_d > 75$ m, an analogous water vapour resistant painting or plastering with corresponding supplements resistant against water vapour.

The heat transmission values of the roof structure are provided in the Table 2.10. They have been calculated in compliance with the standard [1] methodology for inhomogeneous structures depending upon the thickness of the structure H (Figure 2.14.) containing also an expanded polystyrene foam layer of 0.04 m plus the variable thickness of the reinforced cross-beam from 0.14 to 0.28 m. In the calculation of the value U of the structure also the reinforced concrete layer outside with the thickness of 0.04 m has been considered, although it has not been included in the thickness H in the Table 2.10. The colouring of the U values of the table complies with the requirements of the Table 2.1 (temperature factor k=1) and it is shown in the Table 2.9.

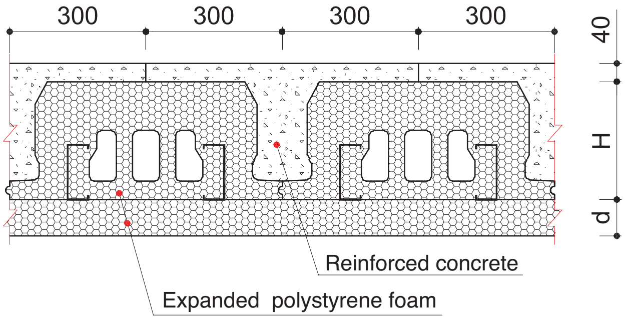

Figure 2.14. Roof panel with added heat insulation layer

Table 2.9.

Colours of U values of the roof structures

⬜	> 0.50 W/(m^2·K) – not compliant to the standards	U_{RN}–U_{RM} U_{RN} – standard value; U_{RM} – standard value
🟦	0.35–0.50 W/(m^2·K) – industrial buildings	
🟩	0.25–0.35 W/(m^2·K) – public buildings	
🟨	0.20–0.25 W/(m^2·K) – residential buildings	

Table 2.10.

Values of the heat transmission coefficient of roof structures with expanded polystyrene foam EPS 150 of the system «Dobeles panelis» U, W/(m²·K) depending upon the total thickness of the structure and additional heat insulation

H, cm d, cm	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
0	0.47	0.45	0.44	0.42	0.41	0.40	0.39	0.38	0.37	0.36	0.35	0.35	0.34	0.33	0.33
1	0.41	0.39	0.38	0.37	0.36	0.35	0.34	0.33	0.32	0.32	0.31	0.30	0.30	0.29	0.29
2	0.36	0.35	0.34	0.33	0.32	0.31	0.30	0.30	0.29	0.28	0.28	0.27	0.27	0.26	0.26
3	0.32	0.31	0.30	0.30	0.29	0.28	0.28	0.27	0.26	0.26	0.25	0.25	0.24	0.24	0.24
4	0.29	0.29	0.28	0.27	0.26	0.26	0.25	0.25	0.24	0.24	0.23	0.23	0.22	0.22	0.22
5	0.27	0.26	0.26	0.25	0.24	0.24	0.23	0.23	0.22	0.22	0.22	0.21	0.21	0.21	0.20
6	0.25	0.24	0.24	0.23	0.23	0.22	0.22	0.21	0.21	0.20	0.20	0.20	0.19	0.19	0.19
7	0.23	0.23	0.22	0.22	0.21	0.21	0.20	0.20	0.20	0.19	0.19	0.19	0.18	0.18	0.18
8	0.22	0.21	0.21	0.20	0.20	0.19	0.19	0.19	0.18	0.18	0.18	0.18	0.17	0.17	0.17

As it can be seen from the Tables 2.10. and 2.1. for the purpose of obtaining sufficient heat insulation of a roof structure additional heat insulation layer is required and in the Figure 2.14 and the Table 2.10 it has been marked with the letter «d».

For example, if the internal temperature of a residential house is 20 °C the temperature factor k, which is calculated according to the formula (2.3), amounts to 0.95 (For Riga T_e=0 °C [5]). When the standard value of the heat transmission coefficient is calculated (Table 2.1), $U_{RN}=0.25 \cdot k=0.25 \cdot 0.95=0.2375 \approx 0.24$ W/(m²·K). We will assume that the roof structure consists of the roof panels of the system «Dobeles panelis» with the thickness of H=24 cm (Figure 2.14.). As it can be seen in the Table 2.10. additional 5 cm thick heat insulation layer is required for achieving the standard heat transmission coefficient.

It is understandable that when additional heat insulation of roof is arranged in compliance to the Table 2.10 also the risk of mould formation in the residential houses under the reinforced concrete cross-beams (figure 2.10.) will be eliminated.

Concerning the public and industrial buildings, in particular, if the internal temperature in the industrial buildings is lower (along with the decrease of T_i in the formula 2.3 the requirements for the heat transmission coefficient decrease, Table 2.1.), it can turn out that additional heat insulation in compliance to the Table 2.10 is not required, still the risk of mould formation can remain. This is determined by several variable factors at the same time: heat transmission coefficient, internal temperature and relative air humidity which can vary on quite a wide scale under different conditions of the building maintenance. Therefore the risk of mould formation on the internal surface of the roof panel shall be analysed during the design stage when the exact heat engineering parameters of the building are known. If there is a risk of mould formation it can be eliminated by performing additional heat insulation measures exceeding the requirements of the Table 2.10.

At the conclusion we will still review the issue on the weight of a roof structure. Low weight of the structure leads to the situation that during the summer time when there is direct sun radiation upon the roof structure the heat gets into the rooms of the upper floor relatively faster and the temperature may raise there disturbing the pleasant climate for people. The solution to the task on the penetration of the temperature fluctuations cycle (annual, daily) into the material is known [8]. The temperature delay (deviation) term via a certain layer of materials can be calculated according to the following formula:

$$\tau = d\sqrt{\frac{t_{dien}}{4\pi a}} = 82.92 \cdot \frac{d}{\sqrt{a}} \quad (s) = \frac{82.92}{3600} \cdot \frac{d}{\sqrt{a}} = 0.023 \cdot \frac{d}{\sqrt{a}} \quad (h) \tag{2.20}$$

where d – thickness of the layer, m;

t_{dien} – length of the day (24 hours), s;

a – temperature conductivity coefficient of the material, m^2/s.

The temperature conductivity coefficient is calculated according to the following formula:

$$a = \frac{\lambda}{c\rho} \tag{2.21}$$

where λ – heat conductivity of the material, W/(m·K) [EPS ~ 0.035 W/(m·K)];

c – thermal capacity of the material, J/(kg·K) [EPS ~ 1450 J/(kg·K)] [4];

ρ – density of the material, kg/m^3 (EPS ~ 30 kg/m^3).

Based upon these figures we obtain $a=8 \cdot 10^{-7}$ m^2/s, and in case of the smallest thickness of the expanded polystyrene foam (0.14 m) τ=3.6 h. When the time deviation of 4 cm thick concrete layer outside the structure $\tau_{concrete}$=0.92 h, which is also found based upon the formula (2.20), is added to this time we obtain 4.5 h. This time can turn out to be insufficient in certain cases.

If additional heat insulation of the roof panel has been performed in compliance to the data of the Table 2.10, for example, to achieve the standard heat transmission coefficient value U_{RN} the time deviation reaches 9–11.5 h, and this will ensure pleasant climate in the premises of the upper floor and it will be possible to avoid overheating in summer.

In case additional heat insulation is not fit the following measures upon the customer's choice would be recommended for the purpose of avoiding temperature fluctuations in the rooms of the upper floor of the buildings:

- Application of as thick as possible layer of expanded polystyrene foam in the panel (it would also improve the heat insulation features of the panel);
- Construction of the roof structure of massive parts, for example, tiles;
- Construction of the roof structure with ventilated room of attic;
- Placement of metal foil above the panel for the purpose of reflecting the radiation;

Still one should understand that only application of the metal foil without implementation of other above listed measures cannot produce complete expected result, as this will impact only one mechanism of heat transmission – radiation, however, it will not have considerable impact upon the heat conductivity.

Sources

1. Standard LVS EN ISO 6946:2000. Building components and building elements . Thermal resistance and heat transmission. Calculation method.
2. Standard EN 13163. Wärmedämmstofe für Gebäude – Werkmäßig hergestellte produkte aus expandiertem Polystyrol (EPS) – Spezifikation.
3. Standard: LVS EN ISO 13788. Hygrothermal perfomance of buildings components and building elements – Estimation of internal surface temperature to avoid critical surface humidity and assessment of the risk of interstitial condensation.
4. Latvian Building Standard LBN 002-01 «Heat engineering of Building Envelopes ». Approved by the Regulations of the Cabinet of Ministers No. 495 dd. November 27, 2001.
5. Latvian Building Standard LBN 003-01 «Building climate». Approved by the Regulations of the Cabinet of Ministers No. 376 dd. August 23, 2001.
6. Standard LVS EN ISO 10456. Building materials and products . Procedures of determining the declared and designed thermal values.
7. O. Belindževa-Korkla. Heat calculations of the limiting structures. Methodological recommendations for the application of LBN 002-01. – Rīga, RTU publishing house, 2002. – 166 pp.
8. E. Riekstiņš. Mathematic methods of physics. – Rīga, Zvaigzne, 1969. – 629 pp.
9. U. Iljins, J. Skujāns, S. Štrausa, A. Vulāns. Tenapors. Methodological guidelines for designers and builders. – Dobele, Jelgava, 2002. – 99 pp.