Moisture regime of enclosing structures with different thickness of insulation layer

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Abstract. Construction industry has different problems including the moisture regime of enclosing structures. If we want to protect an enclosing structure from the negative impact of moisture, we need to evaluate a moisture balance transfer. We used well-known graphical method to calculate the maximum wetting plane positions in three enclosing structures, which are represented the composite insulating systems with external plaster layers, aerated concrete bases and mineral wool insulations. These researching encloses differ only by thicknesses of insulation layers. It was found that the maximum wetting plane is located between the insulation layer and the external plaster layer. Moreover, when the indoor climate parameters change, the position of the maximum wetting plane does not change. However, it is determined that with a significant increase in the thickness of the insulation, the second maximum wetting plane appears inside the aerated concrete layer. This phenomenon was called as «overheating effect». To assess the position of the second maximum wetting plane we developed the criterion “relative displacement coordinate of maximum wetting plane” and obtained the graphic dependence of the introduced criterion and the thickness of the insulation.

1. Introduction

Construction industry interacts with different direction of building problems: heat and mass transfer inside enclosing structures \cite{1-12} or in heating, ventilation and air conditioning systems \cite{13-16}, energy efficiency and energy saving \cite{17-25}. One of the crucial problems is evaluating the moisture balance transfer, which affords to control building in its life cycle.

In terms of physics, if you want to protect an inclosing structure from negative impact of moisture, two demands must be executed.

The first demand is the condition, which avoids the moisture accumulation in the building enclosing structure during a year of exploitation. Required vapor resistance for the first demand is described by formula:

\[ R_{\text{eq}}^{\text{crit}} = \frac{(e_{\text{in}} - E) \cdot R_{\text{m}}}{E - e_{\text{ext}}}. \]  (1)
where \( R_{n1}^{\alpha} \) – required vapor resistance for the first demand, which avoids the moisture accumulation in the building enclosing structure during a year of exploitation, \((m^2 \cdot s \cdot Pa)/kg\); \( e_{in} \) – partial pressure of inside air water vapor, \( Pa \); \( e_{eo} \) – partial pressure of inside air water vapor, \( Pa \); \( E \) – saturated water vapor pressure in the maximum wetting plane during a year of exploitation, \( Pa \); \( R_w \) – resistance to vapor permeation of the part of the enclosing structure located between the outer surface of the enclosing structure and the maximum wetting plane, \((m^2 \cdot s \cdot Pa)/kg\).

Saturated water vapor pressure in the maximum wetting plane during a year of exploitation can be obtained by formula:

\[
E = \frac{E_1 \cdot z_1 + E_2 \cdot z_2 + E_3 \cdot z_3}{12}. \tag{2}
\]

where \( E_i \) – saturated water vapor pressure in the maximum wetting plane during a winter period of exploitation, \( Pa \); \( E_2 \) – saturated water vapor pressure in the maximum wetting plane during a spring-autumn period of exploitation, \( Pa \); \( E_3 \) – saturated water vapor pressure in the maximum wetting plane during a summer period of exploitation, \( Pa \); \( z_1 \) – the duration of the winter period of exploitation, \( s \); \( z_2 \) – the duration of the spring-autumn period of exploitation, \( s \); \( z_3 \) – the duration of the summer period of exploitation, \( month \); 12 – the duration of the year period of exploitation, \( s \).

Saturated water vapor pressure can be described by analytical expression [26–28]:

\[
E_i = 1.84 \cdot 10^3 \cdot \exp(-5330/(273+t)). \tag{3}
\]

where \( t \) – temperature of air, \(^\circ C\).

The second demand is the condition, which limits the moisture in the building enclosing structure during a period with negative average monthly outdoor temperatures. Required vapor resistance for second demand is described by formula:

\[
R_{n2}^{\alpha} = \frac{0.024 \cdot z_0 \cdot (e_{in} - E_0)}{\rho_w \cdot \delta_w \cdot \Delta w + \eta}. \tag{4}
\]

where \( R_{n2}^{\alpha} \) – required vapor resistance for the second demand, which limits the moisture in the building enclosing structure during a period with negative average monthly outdoor temperatures, \((m^2 \cdot s \cdot Pa)/kg\); \( z_0 \) – the duration of the moisture accumulation period, \( s \); \( E_0 \) – saturated water vapor pressure in the maximum wetting plane, which determined under average outdoor temperature during the moisture accumulation period, \( Pa \); \( \rho_w \) – the material density of the wetted layer, \( kg/m^3 \); \( \delta_w \) – thickness of the wetted layer of the building enclosing structure, \( m \); \( \Delta w \) – maximum permissible moisture increment in the material of the wetted layer, \( kg/kg \) (1 kg/kg = 100 % by weight); \( \eta \) – coefficient.
Required vapor resistance is the maximum of resistance values which are determined by formulas (1) and (4):

\[ R_{\text{req}} = \max(R_{\text{req}1}; R_{\text{req}2}) \]  

(5)

The main idea of the moisture balance transfer is the following: if vapor resistance of the building enclosing structure in the range from the inner surface to the maximum wetting plane more than required vapor resistance, we can construct this building without any problems of the moisture transfer. In the opposite case, we cannot construct this building.

However, we need to find the exact position of maximum wetting plane before calculation of the moisture balance transfer, so we need to obtain the maximum wetting complex:

\[ f_i(t_{\text{m.m.}}) = \frac{5330 \cdot (t_{\text{in}} - t_{\text{ext.neg}})}{R_i \cdot (e_{\text{in}} - e_{\text{ext.neg}}) \cdot \lambda_i} \]  

(6)

where \( f_i \) – function that corresponds to the temperature of the layer \( i \) in the maximum moisture zone «maximum wetting complex», (°C)/Pa; \( r_{i,v} \) – vapor permeability total resistance of enclosing structure, (m²·s·Pa)/kg; \( t_{\text{in}} \) – inside air average temperature, °C; \( t_{\text{ext.neg}} \) – outdoor air average temperature in the period of monthly average temperature below zero, °C; \( R_i \) – heat transfer total resistance of enclosing structure, (m²·°C)/W; \( e_{\text{ext.neg}} \) – partial pressure of outdoor air water vapor in the period of monthly average temperature below zero, Pa; \( \mu_i \) – vapor permeability coefficient of \( i \)-th layer material, kg/(m·s·Pa); \( \lambda_i \) – thermal conductivity coefficient of \( i \)-th layer material, W/(m²·°C); \( t_{\text{m.m.}} \) – maximum wetting temperature, °C.

2. Problem
It is possible to obtain the position of the maximum wetting plane according to the described method. However, it is interesting to research the position of maximum wetting plane in some enclosing structures with aerated concrete base and mineral wool insulation.

3. Materials and methods
Determination of the maximum wetting plane position is obtained by graphical method which was developed and described in the researches [29, 30].

Criterion \( \Delta \) is proposed to assess the maximum wetting plane position and it obtains the coordinate of maximum wetting plane relating joint of layers, which is between insulation and exterior stucco [29, 30]:

\[ \Delta = \frac{\delta_i}{\delta_{\text{in}}} \]  

(7)

where \( \Delta \) – relative displacement coordinate of the maximum wetting plane; \( \delta_i \) – coordinate of maximum wetting plane, m; \( \delta_{\text{in}} \) – insulation thickness, m.
4. Results and discussion

4.1. Calculation for the maximum wetting plane position in the enclosing structures with aerated concrete base and mineral wool insulation with various insulations thickness

To obtain the maximum wetting plane position we consider one type of inclosing structure: the enclosing structures with aerated concrete base and mineral wool insulation, but we increase insulation thickness in each next calculation.

The wall structures and physical properties of the layers are presented in table 1.

Table 1. Characteristics of the enclosing structures, consisting of aerated concrete block base and insulation of mineral wool plates.

| Wall structure                        | Layer thickness, $\text{m}$ | Density, $\text{kg/m}^3$ | Thermal conductivity coefficient, $W/(\text{m} \cdot ^\circ\text{C})$ | Vapor permeability coefficient, $\text{kg/(m} \cdot \text{s} \cdot \text{Pa})$ |
|---------------------------------------|-----------------------------|---------------------------|-------------------------------------------------|-------------------------------------------------|
| First wall structure                  |                             |                           |                                                 |                                                 |
| Exterior plaster layer                | 0.007                       | 1260                      | 0.93                                            | $3.61 \times 10^{-11}$                           |
| Insulation of mineral wool plates     | 0.12                        | 145                       | 0.042                                           | $1.42 \times 10^{-10}$                           |
| Base of aerated concrete blocks       | 0.3                         | 400                       | 0.15                                            | $6.39 \times 10^{-11}$                           |
| Interior plaster layer                | 0.02                        | 1800                      | 0.93                                            | $2.5 \times 10^{-11}$                            |
| Second wall structure                 |                             |                           |                                                 |                                                 |
| Exterior plaster layer                | 0.007                       | 1260                      | 0.93                                            | $3.61 \times 10^{-11}$                           |
| Insulation of mineral wool plates     | 0.3                         | 145                       | 0.042                                           | $1.42 \times 10^{-10}$                           |
| Base of aerated concrete blocks       | 0.3                         | 400                       | 0.15                                            | $6.39 \times 10^{-11}$                           |
| Interior plaster layer                | 0.02                        | 1800                      | 0.93                                            | $2.5 \times 10^{-11}$                            |
| Third wall structure                  |                             |                           |                                                 |                                                 |
| Exterior plaster layer                | 0.007                       | 1260                      | 0.93                                            | $3.61 \times 10^{-11}$                           |
| Insulation of mineral wool plates     | 0.4                         | 145                       | 0.042                                           | $1.42 \times 10^{-10}$                           |
| Base of aerated concrete blocks       | 0.3                         | 400                       | 0.15                                            | $6.39 \times 10^{-11}$                           |
| Interior plaster layer                | 0.02                        | 1800                      | 0.93                                            | $2.5 \times 10^{-11}$                            |

These walls are built in Moscow city, which is the capital of Russian Federation. Inside the building the relative humidity is 55 % and the temperature is 20 °C.

Calculation for the average outside temperature for a period with negative monthly average temperatures is done.

The outside partial pressure of water vapor of 364 Pa and the outside temperature is – 4.58 °C. Calculation by the graphical method [26, 27] for the maximum wetting plane position for three different type of walls with mineral wool insulation is presented. Graphic determination of maximum wetting plane position for the enclosing structure consisting of aerated concrete block base and insulation of mineral wool plates of 0.12 m, exterior and interior plaster layers is given (Fig. 1). Graphic determination of maximum wetting plane position for the enclosing structure consisting of
aerated concrete block base and insulation of mineral wool plates of 0.3 m, exterior and interior plaster layers is given (Fig. 2).

![Diagram of wetting plane position](image1)

**Figure 1.** Graphic determination of maximum wetting plane position for the enclosing structure consisting of aerated concrete block base and insulation of mineral wool plates of 0.12 m, exterior and interior plaster layers (1 – temperature distribution; 2 – maximum wetting temperature distribution; 3 – maximum wetting plane position).

![Diagram of wetting plane position](image2)

**Figure 2.** Graphic determination of maximum wetting plane position for the enclosing structure consisting of aerated concrete block base and insulation of mineral wool plates of 0.3 m, exterior and interior plaster layers (1 – temperature distribution; 2 – maximum wetting temperature distribution; 3 – maximum wetting plane position).

Graphic determination of maximum wetting plane position for the enclosing structure consisting of aerated concrete block base and insulation of mineral wool plates of 0.4 m, exterior and interior plaster layers is given (Fig. 3).
As we can see, in the first two graphs the maximum wetting plane position is between insulation layer and exterior plaster layer. However, if the insulation thickness is higher than a certain value, the second maximum wetting plane will appear in the base of wall. This effect was called “Overheating effect”.

**Figure 3.** Graphic determination of maximum wetting plane position for the enclosing structure consisting of aerated concrete block base and insulation of mineral wool plates of 0.4 m, exterior and interior plaster layers (1 – temperature distribution; 2 – maximum wetting temperature distribution; 3 – maximum wetting plane position).

**4.2. Dependence of relative displacement coordinate of the second maximum wetting plane on insulation thickness**

Further studies show at what thickness values of the insulation layer the second maximum wetting plane appears in the considered enclosing structure. Relative displacement coordinate of the maximum wetting plane was calculated by formula (7). Dependence of relative displacement coordinate of the second maximum wetting plane on insulation thickness is given (Fig. 4).
5. Conclusion

Thus, the maximum wetting plane position is always between insulation layer and exterior plaster layer for inclosing structures consisting of aerated concrete block base and insulation of mineral wool. If insulation thickness of this inclosing structure is within 0.33 – 0.59 m, the second maximum wetting plane will appear in the base of enclosing structure. This phenomenon is called “overheating effect” and it is crucial to consider this effect when you evaluate the moisture balance transfer.

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