The position of the maximum wetting plane in building enclosing structures

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Abstract. We investigate the maximum wetting plane position in two enclosing structures: the first enclosing structure is with aerated concrete base and mineral wool insulation, the second enclosing structure is with aerated concrete base and expanded polystyrene insulation. Two fundamentally different cases of the maximum wetting plane are obtained. For the enclosing structure with mineral wool insulation, the maximum wetting plane is located between the insulation and the external stucco. It was found that when the indoor climate parameters or thicknesses of layers change, the position of the maximum wetting plane does not change. For the enclosing structure with expanded polystyrene insulation, the maximum wetting plane is located inside the insulation layer. It was found that when the indoor climate parameters or thicknesses of layers change, the position of the maximum wetting plane also changes. In terms of application result for calculation, an enclosing structure with aerated concrete base and expanded polystyrene insulation is significantly more sensitive to climate parameters than an enclosing structure with mineral wool insulation. It becomes possible not to obtain the maximum wetting plane position in encloses with mineral wool, and to use described calculated position, therefore, it can save time of engineers during the moisture regime calculation.

1. Introduction
The moisture regime of building enclosing structures is one of the most important directions in construction [1–6], which can improve the heat resistance properties of houses [7–11]. Various authors developed some different mathematical models for unsteady-state moisture regime calculation [12–21].

However, the method of assessing the moisture transfer balance is more comfortable to use for engineering work [22–24]:

\[
F(w, t) = E_i(t) \cdot \phi(w) + \frac{1}{\mu} \int_{0}^{w} \beta(\zeta) d\zeta. \tag{1}
\]
where $F$ – moisture potential, Pa; $E_e$ – saturated water vapor pressure, Pa; $\varphi$ – relative air humidity; $\mu$ – vapor permeability coefficient, kg/(m·s·Pa); $\beta$ – moisture conductivity coefficient, kg/(m·s·kg/kg); $w$ – material humidity, kg/kg (1 kg/kg = 100% by weight); $\zeta$ – current material moisture value, kg/kg.

In this case, total density of flow vapor and liquid moisture can be obtained as [22–24]:

$$g = -\mu \frac{\partial F}{\partial x}. \quad (2)$$

where $g$ – total density of flow vapor and liquid moisture, kg/(m$^2$·s); $x$ – coordinate, m.

The problem of the steady-state moisture balance equation is used in the engineering method, so the moisture transfer equation can be formulated as [22–24]:

$$\frac{\partial}{\partial x} (\mu \frac{\partial F(w,t)}{\partial x}) = 0. \quad (3)$$

Inside each layer of enclosing structure the moisture transfer equation is written as [22–24]:

$$\frac{\partial^2 F(w,t)}{\partial x^2} = 0. \quad (4)$$

Thus, inside each layer of enclosing structure we can see the steady-state distribution of the moisture potential [22–24]:

$$F(w,t) = A \cdot x + B. \quad (5)$$

where $A$ and $B$ – constants ($A = Pa/m$; $B = Pa$).

The maximum wetting plane is calculated for using in moisture balance equation.

The derivative of the moisture potential by the coordinate is calculated to obtain the position of the maximum wetting plane:

$$\frac{\partial F(w,t)}{\partial x} = \frac{\partial F(w,t)}{\partial w} \cdot \frac{\partial w}{\partial x} + \frac{\partial F(w,t)}{\partial T} \cdot \frac{\partial T}{\partial x}. \quad (6)$$

where $T$ – absolute temperature, K.

$$\frac{\partial w}{\partial x} = \frac{\partial F(w,t)}{\partial x} \cdot \frac{\partial T}{\partial F(w,t)} \cdot \frac{\partial F(w,t)}{\partial w}. \quad (7)$$

Position of the maximum wetting plane is agreed with place where derivation of the moisture by the coordinate is equal zero:
\frac{\partial w}{\partial x} = 0. \quad (8)

As a result, we need to solve the next equation to obtain the position of the maximum wetting plane:

\frac{\partial F(w, t)}{\partial x} - \frac{\partial F(w, t)}{\partial T} \cdot \frac{\partial T}{\partial x} = 0. \quad (9)

The solution of the equation (9) can be found as:

\begin{align*}
    f_i(t_{m,m}) &= 5330 \cdot \frac{r_i \cdot (t_m - t_{ext, neg})}{R_i \cdot (e_m - e_{ext, neg})} \cdot \mu_i \cdot \lambda_i \\
\end{align*} \quad (10)

where \( f_i \) – function that corresponds to the temperature of the layer \( i \) in the maximum moisture zone «maximum wetting complex», \((\degree C)^2/Pa\); \( r_i \) – vapor permeability total resistance of enclosing structure, \((m^2\cdot s\cdot Pa)/kg\); \( t_m \) – inside air average temperature, \( \degree C \); \( t_{ext, neg} \) – outdoor air average temperature in the period of monthly average temperature below zero, \( \degree C \); \( R_i \) – heat transfer total resistance of enclosing structure, \((m^2\cdot \degree C)/W\); \( e_m \) – partial pressure of inside air water vapor, \( Pa \); \( e_{ext, neg} \) – 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, \( kg/(m\cdot s\cdot Pa) \); \( \lambda_i \) – thermal conductivity coefficient of \( i \)-th layer material, \( W/(m^2\cdot \degree C) \); \( t_{m,m} \) – maximum wetting temperature, \( \degree C \).

Maximum wetting complex \( f_i \) is calculated by table 1.

**Table 1.** Dependence of maximum wetting complex value on layer maximum wetting temperature value.

| \( t_{m,m} \), \( \degree C \) | \( f_i \), \((\degree C)^2/Pa \) | \( t_{m,m} \), \( \degree C \) | \( f_i \), \((\degree C)^2/Pa \) | \( t_{m,m} \), \( \degree C \) | \( f_i \), \((\degree C)^2/Pa \) | \( t_{m,m} \), \( \degree C \) | \( f_i \), \((\degree C)^2/Pa \) |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| -30             | 1554            | -12             | 313.9           | 6               | 83.15           |
| -27             | 1187            | -9              | 245.4           | 9               | 69.27           |
| -24             | 898.6           | -6              | 193.2           | 12              | 57.89           |
| -21             | 682.8           | -3              | 153.15          | 15              | 48.65           |
| -18             | 520.2           | 0               | 121.98          | 18              | 41.03           |
| -15             | 403.4           | 3               | 100.36          | 21              | 34.74           |

2. Problem
This method can obtain position of the maximum wetting plane. However, some different cases can exist in different enclosing structures.

We work with two crucial instances. The first enclosing structure is with aerated concrete base and mineral wool insulation. The second enclosing structure is with aerated concrete base and expanded polystyrene insulation.

3. Materials and methods
Determination of the maximum wetting plane position is obtained by graphical method that consists of three rules [25, 26].

First rule can search for maximum wetting plane inside enclosing structure layer. If temperature and maximum wetting temperature intersect in any layer, then maximum wetting plane coincides with the section in which the intersection is [25, 26].

Second rule can search for maximum wetting plane at the boundary of enclosing structure layers. If maximum wetting temperature distribution is higher than temperature distribution in the coldest layer, and maximum wetting temperature distribution is lower than temperature distribution in the hottest layer, then the maximum wetting plane is located at the joint of these layers [25, 26].

Third rule can search for maximum wetting plane outside the enclosing structure. If maximum wetting plane cannot be found using the first two rules, then it is located outside the enclosing structure [25, 26].

4. Results and discussion

The graphical method for determination of the maximum wetting plane position is used for two different enclosing structures, which have the same scheme (Fig. 1).

![Graphical method](image)

**Figure 1.** Enclosing structure with the base and insulation (1 – exterior plaster layer; 2 – insulating layer; 3 – basic layer; 4 – interior plaster layer; 5 – required maximum wetting plane; \( \delta_m \) – insulation thickness, \( m; \delta_x \) – coordinate of maximum wetting plane, \( m \)).

Although enclosing structures have the same base, which is made of aerated concrete blocks, they have different insulation layers. There is mineral wool insulation and expanded polystyrene insulation.
These walls are considered in Moscow region (Russian Federation). Inside the building, the temperature is 20 °C and the relative humidity is 55%.

Calculation for the average outside temperature for a period with negative monthly average temperatures is done. The outside temperature is –4.58 °C and the outside partial pressure of water vapor of 364 Pa.

Calculation by the graphical method for the maximum wetting plane position for two different walls is presented.

4.1. Calculation for the maximum wetting plane position in the first enclosing structure, which is with aerated concrete base and expanded polystyrene insulation

The wall structure and physical properties of the layers are presented in table 2.

Table 2. Characteristics of the enclosing structure, consisting of aerated concrete block base, and insulation of expanded polystyrene plates.

| Wall structure | Layer thickness, m | Density, kg/m³ | Thermal conductivity coefficient, W/(m⋅°C) | Vapor permeability coefficient, kg/(m⋅s⋅Pa) |
|----------------|-------------------|----------------|-------------------------------------|------------------------------------------|
| Exterior plaster layer | 0.007             | 1260           | 0.93                               | 3.61⋅10⁻¹¹                                |
| Insulation of expanded polystyrene plates | 0.12             | 25             | 0.044                               | 1.39⋅10⁻¹¹                                |
| Base of aerated concrete blocks | 0.3              | 400            | 0.15                               | 6.39⋅10⁻¹¹                                |
| Interior plaster layer | 0.02              | 1800           | 0.93                               | 2.5⋅10⁻¹¹                                 |

Graphic determination of maximum wetting plane position for the enclosing structure consisting of aerated concrete block base and insulation of expanded polystyrene plates, exterior and interior plaster layers is given (Fig. 2).

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

As we can see, the maximum wetting plane position is inside insulation layer.

4.2. Calculation for the maximum wetting plane position in the second enclosing structure, which is with aerated concrete base and mineral wool insulation

The wall structure and physical properties of the layers is presented in table 3.

Graphical determination of maximum wetting plane position for the enclosing structure consisting of aerated concrete block base and insulation of mineral wool plates, exterior and interior plaster layers is given (Fig. 3).

As we can see, the maximum wetting plane position is between insulation layer and exterior plaster layer.

Table 3. Characteristics of the enclosing structure, consisting of aerated concrete block base and insulation of mineral wool plates.

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

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, exterior and interior plaster layers (1 – temperature distribution; 2 – maximum wetting temperature distribution; 3 – maximum wetting plane position).

If we analyze the tables 2 and 3 we will see that the vapor permeability coefficient of mineral wool insulation is more than vapor permeability coefficient of expanded polystyrene insulation. This
explains the difference in results of the maximum wetting plane position in separate inclosing structures.

5. Conclusion
Thus, we analyzed two different enclosing structures in Moscow region. The first enclosing structure is with aerated concrete base and mineral wool insulation. The second enclosing structure is with aerated concrete base and expanded polystyrene insulation. Inside the building the temperature is 20 °C and the relative humidity is 55 %. We used a graphical method to determine the maximum wetting plane position.

As a result, two crucial instances are obtained. The maximum wetting plane position can be inside insulation layer for inclosing structures consisting of aerated concrete block base and insulation of expanded polystyrene plates or between insulation layer and exterior plaster layer for inclosing structures consisting of aerated concrete block base and insulation of mineral wool. The difference is explained by different vapor permeability coefficient. We can conclude that an enclosing structure with aerated concrete base and expanded polystyrene insulation is significantly more sensitive to climate parameters than an enclosing structure with mineral wool insulation. Moreover, when the indoor climate parameters or thicknesses of layers change for an enclosing structure with aerated concrete base and mineral wool insulation, the position of the maximum wetting plane does not change. However, the indoor climate parameters or thicknesses of layers change for an enclosing structure with aerated concrete base and mineral wool insulation, the position of the maximum wetting plane also changes.

This data can be included in the calculation of the moisture transfer balance. For example, for enclosing structures with aerated concrete base and mineral wool insulation a design engineer may not to calculate the exact position of the maximum wetting plane and just appoint the maximum wetting plane position between insulation layer and exterior plaster layer. This opportunity can simplify moisture balance calculation.

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