Investigation of the humidity regime of multilayer enclosing structures of buildings and structures

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Abstract. The article describes an approximate analytical method for calculating the moisture regime of multilayer building envelope structures. The novelty of the proposed method lies in the use an analytical dependence for determination the position of the flatness possible condensation, obtained as a result of studying the function which is the difference between the partial pressures of water vapor in the considered section the enclosing structure and the partial pressure of saturated water vapor at the extremum. The article presents the results of calculating the moisture regime of the outer wall of a residential building under construction in Samara using monolithic sandless expanded clay blocks with a density equal to 600 kg/m$^3$. The calculation showed that during the heating period the coordinate of flatness of possible condensation in sandless expanded clay concrete, measured from the inner surface of the wall moves from 0.444 m to 0.5 m. The made assessment of moisture accumulation in the considered outer wall, both for the annual period of operation of the building, and for the period of months with negative temperatures, showed compliance with the regulatory requirements for heated rooms.

1. Introduction

One of the most important conditions for a person's stay in buildings and structures is the absence of moisture on the inner surfaces of the enclosing structures. The accumulation of moisture in external walls, coatings and ceilings can lead to the formation of molds, which are very dangerous for humans, as well as to the destruction of building structures. The main reasons for the accumulation of moisture in the outer walls are considered in work [1]. In works [2, 3] is considered the application of the theory of moisture potential in the study of the moisture regime of enclosing structures. Experimental studies of this problem are reflected in the works as well as domestic [4, 5] and foreign [6, 7] scientists. In works [3, 8, 9] are considered the methods of determining the plane of possible condensation.

In work [9] is considered an approximate analytical method for determining the plane’s position of possible condensation, convenient for manual counting.

By developing the above method was used the dependence of the partial pressure of saturated water vapor from temperature, given in the reference book edited by I.G. Staroverov. [10].

At present, according to the current standards, the protection calculation against water logging of building enclosing structures is made for months with negative outside temperatures. The average temperature and partial pressure of water vapor for the cold period are taken as the calculation parameters of the outside air.
2. Method for calculating the moisture regime of enclosing structures
By actualization the author's method for calculating the moisture regime of multilayer enclosing structures, described in detail in work [8], is suggested a more accurate dependence of the partial pressure of saturated water vapor $E$ from the temperature $\tau$ of the form [°C]

$$ E = 611 \left(1 + \frac{t}{100}\right)^{7.6} \quad (1) $$

Figure 1 shows a schematic diagram of the heat transfer process through a multilayer outer wall. Temperature values on the outer surface of the $i$-th layer are determined according to [7] by the formula [°C]

$$ \tau_i = t_{in} - t_{out} \cdot \left(\frac{1}{\alpha_{in} + \sum_{j=1}^{i} R_j}\right) \quad (2) $$

where $t_{in}$, $t_{out}$ - the temperature of the indoor and outdoor air, respectively, [°C]; $R_{0^{con}}$ - heat transfer resistance of the surface of the outer wall, [m²·°C/W]; $\alpha_{in}$ - heat transfer coefficient from the inner and outer wall [W/(m²·°C)]; $R_i = \frac{\delta_i}{\mu_i}$ - resistance to vapor permeation of the $i$-th layer, [m²·h·Pa/mg]; $\delta_i$, $\lambda_i$ - thickness, [m], and thermal conductivity of the $i$-th layer, respectively, [W/(m·°C)].

The partial pressure of water vapor contained in humid air passing through the outer wall is determined by the formula

$$ e_i = e_{in} - e_{out} \frac{1}{R_{p_i}} + \sum_{j=1}^{i} R_{p_j} \quad (3) $$

where $e_{in}$, $e_{out}$ is the partial pressure of water vapor inside the heated room and outside air, respectively, Pa; $R_{p0}$ - resistance to vapor permeation of the outer wall [m²·h·Pa/mg]; $R_{pi} = \frac{\delta_i}{\mu_i}$ - resistance to vapor permeation of the $i$-th layer [m²·h·Pa/mg]; $\mu_i$ - is the vapor permeability coefficient of the material of the $i$-th layer [mg/(m·h·Pa)].
To determine the coordinate $x_i$ of the plane of possible condensation, it is necessary to investigate the function $\Phi = e^{-E_i}$ for an extremum. For this, the first derivative of the function $\Phi$ is equated to zero. Then we get

$$\frac{d\Phi}{dx_i} = \frac{d(e_i - E_i)}{dx_i} = 0$$

(4)

After transformation, the expression for finding the coordinate of the plane of possible condensation will take the form [m]

$$x_i = \lambda_i \left\{ \frac{t_{in} - 55.9 \left( \frac{e_{in} - e_{out}}{t_{in} - t_{out}} \frac{R_{0}}{R_{0} + \lambda_i} \right)^{0.1515} + 100}{R_{0}} - \frac{1}{\alpha_{in}} - \sum_{i=1}^{l} R_i \right\}$$

(5)

Substitution of values $x_i$ in the expression of the second derivative of the function $\Phi$ leads to a positive value, which indicates its maximum value in the plane of possible condensation. If the value $x_i$ exceeds the layer thickness $\delta_i$, then the outer surface of the calculated layer is taken as the plane of possible condensation, i.e. $x_i = \delta_i$.

3. Calculating’s results the moisture regime of a multilayer enclosing structure

According to the above methodology, the calculation the humidity regime of the outer wall of a residential building under construction in Samara was carried out. The considered enclosing structure is shown in figure 2.

![Figure 2. Outer wall of a residential building.](image-url)
Table 1. Thermal characteristics of the outer wall materials.

| Material names                        | Layer thickness $\delta_i$ m | Density $\rho_i$ kg/m$^3$ | Thermal conductivity coefficient $\lambda_i$ W/(m°C) | Vapor permeability coefficient $\mu_i$ mg/(m·h·Pa) |
|---------------------------------------|------------------------------|---------------------------|-----------------------------------------------------|--------------------------------------------------|
| Lime-sand mortar                     | 0.02                         | 1600                      | 0.7                                                 | 0.12                                             |
| Monolithic expanded clay concrete    | 0.5                          | 600                       | 0.14                                                | 0.155                                            |
| Cement-sand mortar                   | 0.02                         | 1800                      | 0.76                                                | 0.09                                             |
| The textured layer of the facade system | 0.0035                      | 1600                      | 0.7                                                 | 0.05                                             |

By calculating the moisture regime of the outer wall shown in figure 2 the following initial data were taken:

1. Construction area of Samara
2. Temperature of the coldest five-day period $t_{out} = -30°C$
3. Average temperature for the heating period $t_h = -4.7°C$
4. Duration of the heating period $Z_{h.p} = 197$ days
5. Air temperature inside the building $t_{in} = 20°C$
6. Relative humidity inside the building $\varphi_{in} = 50%$

The calculation to find the plane of possible condensation was carried out in the following sequence:

1. The resistance to heat transfer the surface of the outer wall was determined by the formula [m$^2$·°C/W]

$$R_{0}^{con} = \frac{1}{\alpha_{in}} + \sum_{i=1}^{4} R_i + \frac{1}{\alpha_{out}}$$  \hspace{1cm} (6)

2. The resistance to vapor permeation of the outer wall was found by the formula [m$^2$·h·Pa/mg]

$$R_p = \frac{\delta_1}{\mu_1} + \frac{\delta_2}{\mu_2} + \frac{\delta_3}{\mu_3} + \frac{\delta_4}{\mu_4} = \frac{0.02}{0.12} + \frac{0.5}{0.155} + \frac{0.02}{0.09} + \frac{0.0035}{0.05} = 3.69$$  \hspace{1cm} (7)

3. By formulas (2) and (3) were determined the values of temperature $\tau_i$ and partial pressure of water vapor on the outer surface of each layer of the outer wall. The calculation results are summarized in table 2.

4. The obtained values of $\tau_i$ were used to calculate the values of the partial pressure of saturated water vapor according to the following formulas given in the reference book [10].

$$E_i = 2.88 \left(1.098 + \frac{\tau}{100}\right)^{0.02}, \tau \geq 0$$  \hspace{1cm} (8)

$$E_i = 4.688 \left(1.486 + \frac{\tau}{100}\right)^{12.3}, \tau \leq 0$$  \hspace{1cm} (9)

5. By comparing the values of $e_i$ and $E_i$ for months with negative outside temperatures and the entire cold period was found that condensation of water vapor occurs in sandless expanded clay concrete from December to February. Slight condensation in the third layer was noted in December.

6. According to the formula (4) were determined the values of the coordinates of the plane of possible condensation in sandless expanded clay concrete.
From the data presented in table 2 follows that when the outside temperature drops, the plane of possible condensation moves from the outer to the inner surface of the wall. The value \( x_2 \) varies from 0.444 to 0.5 m. The calculation of moisture accumulation in the outer wall for the annual period of operation of the building and the period of months with negative outside temperatures, presented in Table 3 showed conformity with the regulatory documents for heated buildings. Based on the calculated data was plotted a graphical dependence of the distribution of the elasticity of water vapor \( E_x \) and \( e_x \) in the thickness of the outer wall in January, shown in figure 3.

**Figure 3.** Distribution of water vapor elasticities \( E_x \) and \( e_x \) in the thickness of the outer wall in January: \( E_x \) - the value of the elasticity of saturated water vapor, \( e_x \) - the calculated value the elasticity of water vapor in the layers of the outer wall, \( x \) – the current coordinate of the outer wall layer.

**Table 2.** Estimated and required values of resistance to vapor permeation of the outer wall.

| Coordinate of the plane of possible condensation \( x_2 \), m | Resistance to vapor permeation, m²·h·Pa/mg | Required resistance to vapor permeation, m²·h·Pa/mg |
|----------------------------------------------------------|---------------------------------------------|--------------------------------------------------|
| \( 0.5 \)                                              | \( 0.292 \) \( 3.39 \)                  | \( 0.0405 \) \( 0.116 \)             |
| \( 0.444 \)                                            | \( 0.653 \) \( 3.03 \)                  | \( -0.034 \) \( 0.145 \)             |

From the data presented in table 3, it can be concluded that the resistance to vapor permeation \( R_{p0}^* \) significantly exceeds the values \( R_{p0}^{req} \) and \( R_{p2}^{req} \) obtained by the known regulatory method. Consequently, moisture accumulation in the wall is unlikely. Taking this into account, we can conclude that the accumulation of moisture in the wall does not occur over the year of the building’s operation.
Table 3a. Results of calculating the values of temperature $\tau_i$ and partial pressure of water vapor $e_i$ on the outer surface of each layer of the outer wall.

| Months          | $t_{in}$ °C | $e_{in}$ Pa | $\tau_1$ °C | $\tau_2$ °C | $\tau_3$ °C | $\tau_4$ °C | $x_2$, m |
|-----------------|-------------|-------------|-------------|-------------|-------------|-------------|----------|
| November        | -2.1        | 450         | 19.16       | -1.66       | -1.82       | -1.85       | -        |
| December        | -8.3        | 300         | 18.93       | -7.74       | -7.94       | -7.98       | 0.489    |
| January         | -11.2       | 220         | 18.82       | -10.58      | -10.80      | -10.84      | 0.444    |
| February        | -10.6       | 220         | 18.84       | -10.00      | -10.21      | -10.25      | 0.448    |
| March           | -3.7        | 360         | 19.10       | -3.23       | -3.40       | -3.43       | -        |
| months with negative temperatures | -7.18 | 310         | 19.00       | -6.66       | -6.85       | -6.88       | 0.500    |

Table 3b. Results of calculating the values of temperature $\tau_i$ and partial pressure of water vapor $e_i$ on the outer surface of each layer of the outer wall.

| Months          | $t_{in}$ °C | $e_{in}$ Pa | Pressure of saturated water vapor, Pa | Pressure of water vapor on the outer surface of the layer, Pa |
|-----------------|-------------|-------------|--------------------------------------|-------------------------------------------------------------|
| November        | -2.1        | 450         | $E_1$ 532.70 $E_2$ 526.70 $E_3$ 524.70 $E_4$ 1136.50     | $e_1$ 507.90 $e_2$ 464.60 $e_3$ 451                        |
| December        | -8.3        | 300         | $E_1$ 316.97 $E_2$ 311.20 $E_3$ 310.20 $E_4$ 1129.70     | $e_1$ 369.90 $e_2$ 317.70 $e_3$ 301                        |
| January         | -11.2       | 220         | $E_1$ 246.30 $E_2$ 241.70 $E_3$ 240.70 $E_4$ 1126.00     | $e_1$ 296.40 $e_2$ 239.30 $e_3$ 221                        |
| February        | -10.6       | 220         | $E_1$ 259.60 $E_2$ 254.80 $E_3$ 253.90 $E_4$ 1126.00     | $e_1$ 296.40 $e_2$ 239.30 $e_3$ 221                        |
| March months with negative temperatures | -3.7 | 360         | $E_1$ 466.70 $E_2$ 460.10 $E_3$ 458.90 $E_4$ 1132.00     | $e_1$ 425.10 $e_2$ 376.50 $e_3$ 361                        |
|                | -7.18       | 310         | $E_1$ 348.20 $E_2$ 342.60 $E_3$ 340.70 $E_4$ 1130.00     | $e_1$ 379.10 $e_2$ 327.40 $e_3$ 311                        |

Analyzing the graphical dependencies shown in figure 3, it can be concluded that the condensation zone is located in sandless expanded clay concrete at a distance from 0Y to 0.52 m from the inner surface of the wall.

4. Discussions

Comparative data on the partial pressure of saturated water vapor, taken from various sources, are presented in table 4.

Comparison with the experimental values given in the reference literature showed that by negative outside temperatures, the error in determining the partial pressure of saturated water vapor ranges from 5% to 16% when the temperature changes from -5°C to -20°C. When developing an approximate analytical method, the outside air temperature and partial pressure were determined according to climatic data for the coldest month.

According to the current requirements for thermal protection of buildings and in work [9] is used an auxiliary function to find the plane of possible condensation, the numerical values of which are given in a special table, by interpolation is determined the temperature value in the plane of possible condensation, which is then used to find the coordinate of the plane of possible condensation. According to formula (5), it is possible to obtain an approximate solution to the problem of determining the position of the plane of possible condensation in the form of an analytical dependence convenient for manual calculation.
Table 4. Values of the partial pressure of saturated water vapor $E$, Pa, for temperatures from -30°C to +30°C.

| Temperature, $t$, °C (the denominator shows the error) | -30 | -20 | -10 | 0   | +10 | +20 | +25 |
|--------------------------------------------------------|-----|-----|-----|-----|-----|-----|-----|
| Experimental value                                      |     |     |     |     |     |     |     |
|                                                        | 38  | 103 | 260 | 611 | 1228| 2338| 3168|
| $E = 10^{1.251 + 5 + 1.12 \frac{236 + t}{236 + t}}$, according to [11] |     |     |     |     |     |     |     |
|                                                        | 50.1| 124.5| 285.8| 610.9| 1227.4| 2339| 3162|
|                                                        | 31.8| 26.9 | 9.9 | 0   | 0   | 0   | 0.18|
| $E = 1.84 \cdot 10^3 \exp\left(-\frac{5370}{273+t}\right)$ (regulatory requirement) |     |     |     |     |     |     |     |
|                                                        | 55.3| 130.8| 291.3| 611.7| 1221 | 2319.4| 3146|
|                                                        | 45.5| 27.0 | 12.0| 0   | -0.6| -0.8 | 0.7 |
| $E = 4.688 \left(1.486 + \frac{t}{100}\right)^{12.3}$ for $t \leq 0$ °C |     |     |     |     |     |     |     |
|                                                        | 38.2| 103  | 260 | 611 | 1228 | 2340 | 3169|
|                                                        | 0   | 0    | 0   | 0   | 0    | 0    | 0    |
| $E = 288.58 \left(1.098 + \frac{t}{100}\right)^{8.02}$ for $t \geq 0$ °C, according [12] |     |     |     |     |     |     |     |
|                                                        | 40.6| 112  | 274.3| 611 | 1260.7| 2442| 3331|
|                                                        | 6.8 | 8.7  | 5.5 | 0   | 2.66 | 4.4  | 5.1  |

From the above it follows that the technique proposed by the authors of the article significantly simplifies the solution of the problem of finding the plane of possible condensation with a higher accuracy.

The analytical method proposed by the authors of the article for determining the plane of possible condensation due to the simplicity of implementation can be recommended both for manual counting and when using personal computers. Compared with the existing method for calculating the humidity regime of enclosing structures, set out in the regulatory requirements, this method more accurately determines the temperature of the plane of possible condensation at low outdoor temperatures typical for northern regions.

5. Conclusions

1. An analytical dependence to determine the position of the plane of possible condensation in a multilayer building envelope is obtained. In comparison with the existing regulatory methodology, the obtained dependence allows us to obtain more accurate results for construction areas with low negative outdoor temperatures.
2. The results of calculating the coordinates of the plane of possible condensation for the outer wall of a residential building under construction in Samara are presented.
3. An assessment of moisture accumulation in the outer wall for the annual period the building’s exploitation and for the period of months with negative temperatures was made.

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