Humidity Distributions in Multilayered Walls of High-rise Buildings

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Abstract. The limitation of free territories in large cities is the main reason for the active development of high-rise construction. Given the large-scale projects of high-rise buildings in recent years in Russia and abroad and their huge energy consumption, one of the fundamental principles in the design and reconstruction is the use of energy-efficient technologies. The main heat loss in buildings occurs through enclosing structures. However, not always the heat-resistant wall will be energy-efficient and dry at the same time (perhaps waterlogging). Temperature and humidity distributions in multilayer walls were studied in the paper, and the interrelation of other thermophysical characteristics was analyzed.

1 Introduction

Thermal insulators are structural elements that reduce the heat transfer process and act as the main thermal resistance in the structure. Thermal insulators have low thermal conductivity, low strength and are porous media with increased hygroscopicity, so the heat insulator should alternate with a strong wall. Consequently, the operability of the construction of a multilayered wall is determined by the distribution of temperature and the distribution of moisture across the layers.

In this article we want to show that even in independent processes of thermal conductivity and diffusion, the temperature and humidity distributions are related: the wall temperature sets the pressure of saturated water vapor and thereby determines the moisture level.

Is the “dry” wall energy-efficient? We will try to prove that this is so. Is the heat-resistant wall energy-efficient and dry at the same time? We will try to prove that these conditions are not fulfilled simultaneously [1-4].

2 Materials and Methods

To assess the humidity of the wall, we need to know the average wall temperature, which determines the average moisture level. The average temperature of the wall is determined by the construction of the wall, that is, by alternating layers [3,5]. The best combination of layers, providing a maximum of average temperatures, is achieved with a monotonic decrease

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in the thermal conductivity coefficient along the course of the heat flux, that is, achieved with the average temperature that is the least different from the maximum wall temperature [10, 12-14].

Quantitative analysis of the distribution of temperature and humidity will be carried out on the basis of a structure consisting of 10 layers ($i=\overline{1,10}$); the thickness of each layer is 0.05 m. The values of the thermal conductivity coefficients are given by the following conditions:

$$\begin{aligned} \lambda_x^a &= 0.1+0.1(i-1) \\ \lambda_x^g &= 1-0.1^{\frac{1}{2(i-1)}} \end{aligned} \tag{1}$$

The temperature inside the room (T_h) is taken as 18 °C, outside (T_c) – 0 °C.

The distribution of temperature across the wall is defined as follows:

$$\theta_x = \frac{T_h - T_x}{T_h - T_c} = \frac{\sum_{i=0}^{x} \frac{\delta_i}{\lambda_i}}{\sum_{i=0}^{N} \frac{\delta_i}{\lambda_i}}, \tag{2}$$

θ - dimensionless temperature difference;

T_x – the temperature of the layer x.

From the formula (2) it is possible to determine the temperature in the layer x:

$$\theta_x = \frac{T_h - T_x}{T_h - T_c} \quad \rightarrow \quad T_x = T_h - \theta_x (T_h - T_c) \tag{3}$$

The diffusion coefficient (D) is given in relative units in the form of an arithmetic progression with a difference of 0.1 in the range [1,2]:

$$D_x = 1 + 0.1 \cdot (i-1), \quad D \in [1, 2], \quad i = \overline{1, 10} \tag{4}$$

Using equations (5) and (6), we find the relative humidity (φ_x) and the reduced relative humidity (ω_x).

$$\varphi_x = \omega_x (\varphi_c - \varphi_h) + \varphi_h \tag{5}$$

$$\omega_x = \frac{\varphi_x - \varphi_h}{\varphi_c - \varphi_h} = \frac{\sum_{i=1}^{x} \frac{\delta_i}{D_i}}{\sum_{i=1}^{N} \frac{\delta_i}{D_i}} \tag{6}$$

The value of the relative humidity inside the room (φ_h) is taken equal to 50% (in accordance with the average normative values). Relative humidity outside the room (on the cold side) (φ_c) is determined by the temperature-humidity regime of the air. The air can be dry to saturation $\varphi_c \le 1$ or waterlogged (water is in a wet steam state). Then $\varphi_c > 1$. From the point of view of the humidity regime of the wall, the second case is dangerous. Therefore, further calculations and analysis will be carried out with respect to the case for $\varphi_c > 1$. The values calculated using formulas (1 - 6) are summarized in Table 1.

Table 1. The values of thermophysical characteristics in the alternation of layers 1-10.

	Layer thickness, m	Coefficient of thermal conductivity		Temperature, °C		The diffusion coefficient	Reduced relative humidity	Relative humidity
x	λ	λ^a	λ^g	T^a	T^g	D	ω	φ
1	0.05	0.1	1.00	11.85	17.60	1	0.139	0.583
2	0.05	0.2	0.68	8.78	17.01	1.1	0.266	0.659
3	0.05	0.3	0.44	6.73	16.09	1.2	0.382	0.729
4	0.05	0.4	0.32	5.20	14.84	1.3	0.489	0.793
5	0.05	0.5	0.25	3.97	13.23	1.4	0.588	0.853
6	0.05	0.6	0.21	2.94	11.28	1.5	0.681	0.908
7	0.05	0.7	0.17	2.07	8.98	1.6	0.768	0.961
8	0.05	0.8	0.15	1.30	6.34	1.7	0.849	1.010
9	0.05	0.9	0.13	0.61	3.34	1.8	0.927	1.056
10	0.05	1	0.12	0.00	0.00	1.9	1.000	1.100

3 Results and Discussion

For a more detailed analysis of moisture distributions in multilayered walls of high-rise buildings, we will additionally consider how the temperature, relative humidity and order of alternation of layers affect the vapor pressure (absolute humidity).

Absolute humidity (or vapor pressure) is determined by the formula:

$$p_{n_x} = \varphi_x \cdot p_{s.s._x} = \varphi_x \cdot \left(\frac{T_x}{100}\right)^4 \tag{7}$$

$p_{s.s.}$ - pressure of saturated steam;

The found values are reduced to the Table 2.

Table 2. The values of thermophysical characteristics in the alternation of layers 1-10

	Layer thickness, m	Coefficient of thermal conductivity		The diffusion coefficient	Temperature, °C	Steam pressure, 10^{-6}, Pa	Temperature, °C	Steam pressure, 10^{-6}, Pa
x	λ	λ^a	λ^g	D	T^a	p^a	T^g	p^g
1	0.05	0.1	1.00	1	11.85	115.227	17.60	269.332
2	0.05	0.2	0.68	1.1	8.78	39.214	17.01	265.749
3	0.05	0.3	0.44	1.2	6.73	14.982	16.09	235.387
4	0.05	0.4	0.32	1.3	5.20	5.785	14.84	184.900
5	0.05	0.5	0.25	1.4	3.97	2.114	13.23	125.773
6	0.05	0.6	0.21	1.5	2.94	0.682	11.28	70.778
7	0.05	0.7	0.17	1.6	2.07	0.175	8.98	30.084
8	0.05	0.8	0.15	1.7	1.30	0.029	6.34	7.830
9	0.05	0.9	0.13	1.8	0.61	0.002	3.34	0.634
10	0.05	1	0.12	1.9	0.00	0.000	0.00	0.000

For a monotonically increasing sequence of coefficients of thermal conductivity and diffusion, and for an ordered alternation of layers (from 1 to 10), the dependence of the vapor pressure and temperature will have the form (Fig. 1).

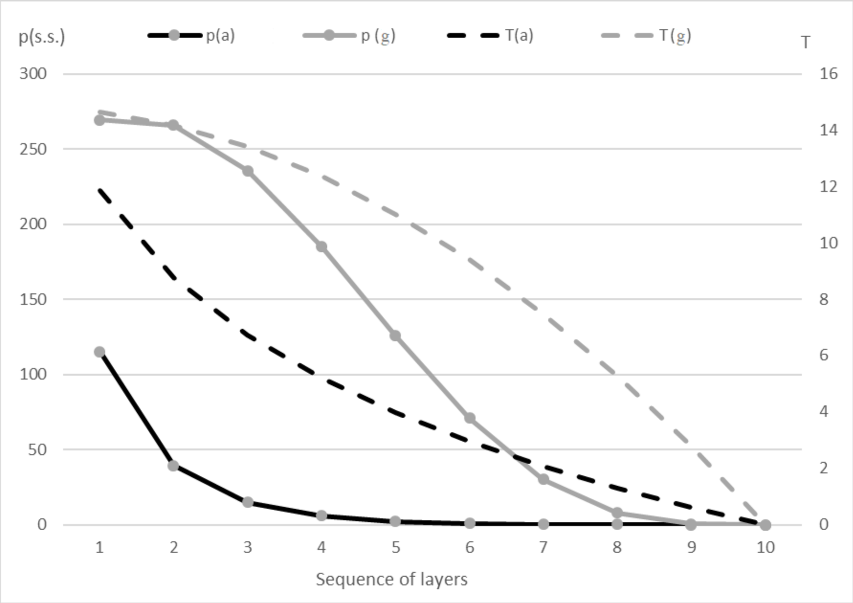

Fig. 1. Distribution of vapor pressure and temperature in a multilayer structure

Average values of temperature and humidity serve as representative values. As analysis of the values obtained with successive permutation of layers shows, they depend on the alternation of the transfer coefficients (that is, on the alternation of layers).

The best option is a design in which the average vapor pressure (absolute humidity) will be less, because this guarantees the preservation of the thermal characteristics of the structure.

Limit distributions of vapor pressure along the layers (worst and best) for $\lambda_x^a = 0.1 + 0.1(i-1)$ and $\lambda_x^g = 1 - 0.1^{\frac{1}{2(i-1)}}$ shown on Fig.2.

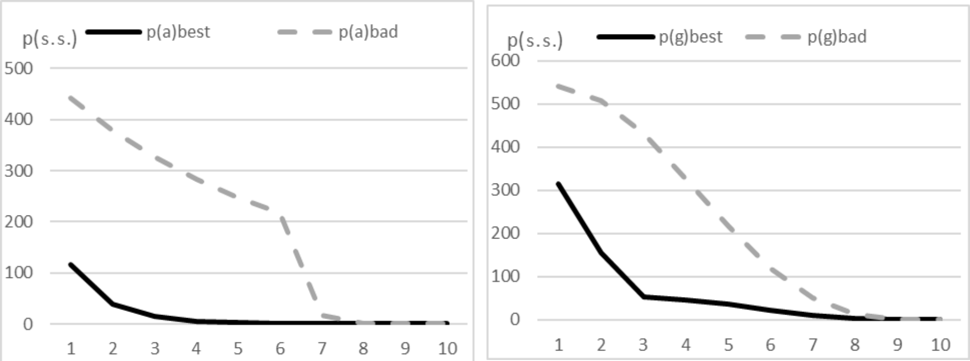

Fig.2. Limit distributions of vapor pressure along the layers (worst and best) for $\lambda_x^a = 0.1 + 0.1(i-1)$ and $\lambda_x^g = 1 - 0.1^{\frac{1}{2(i-1)}}$

The best design from the point of view of moisture distributions will be achieved by alternating the layers (1,2, ..., 9,10) for $\lambda_x^a = 0.1 + 0.1(i-1)$, as well as alternating layers (9,10,1,2, ..., 7,8) for $\lambda_x^g = 1 - 0.1^{\frac{1}{2(i-1)}}$. In this case, the diffusion coefficient varies along the layers, increasing monotonically from 1 to 1.9 in steps of 0.1. At the same time, absolute humidity naturally decreases with decreasing wall temperature.

Energy efficiency requirements is the low thermal conductivity and, consequently, low average layer temperatures. In this case, the absolute humidity decreases with the same value of relative humidity.

Simply put, an energy-efficient wall is drier than a wall with high thermal stability and a high average temperature, leading to a high absolute moisture content of the layers.

The moisture state of the enclosing structures, including high-rise buildings, determines their heat-shielding and sanitary-hygienic qualities, has a significant effect on the durability of the structure as a whole. The reduction in the heat-shielding properties of the enclosing structures during their wetting is associated with an increase in the thermal conductivity of moistened materials, that is, a decrease in the resistance to heat transfer of the entire structure. The increase in the thermal conductivity of materials occurs due to replacement of air in the pore space with water, the thermal conductivity of which is much higher than the thermal conductivity of the air.

To keep the heat in the room, it is necessary to have a coefficient of thermal resistance not less than the required, i.e. the normative value of the reduced resistance to heat transfer should be taken at least normalized values. To fulfill this requirement, multi-layer wall structures with heat insulators are necessary.

Having a sequence of n-layers with different coefficients of thermal conductivity and diffusion, we can construct 2n! Combinations of layers. It is quite obvious that alternating layers by even transpositions, we have 2n-combinations of layers, of which for small n (for example, 4, 5, ...), it is easy to choose the best combination that ensures low humidity while maintaining thermal resistance. This was done. The best options are shown in Fig.2. These options simultaneously demonstrate minimum absolute humidity and high thermal resistance.

4 Conclusions

Energy efficiency requirements are low coefficients of thermal conductivity and, as a consequence, low mean layer temperatures. In this case, the absolute humidity decreases with the same value of relative humidity.

Simply put, an energy-efficient wall will be drier than a wall with high thermal stability and a high average temperature, leading to a high absolute moisture content of the layers.

The article showed that even in independent processes of thermal conductivity and diffusion, the temperature and humidity distributions are related: the wall temperature sets the saturated vapor pressure of water and thereby determines the moisture level.

It is shown that the “energy-efficient” is a “dry” wall. In this case, the heat-resistant wall is not both energy-efficient and "dry" at the same time.

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