Determination of Maximum Moisture Zone on Enclosing Structures

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Abstract. Engineering methods of determining the position of the maximum moisture zone in enclosing structures have been theoretically justified. Calculation formulas have been determined with the use of moisture potential. This method has been used for studying positions of the maximum moisture zones in a enclosing structure wall made of aerated concrete blocks, with facade composite thermal insulation, external plaster with various layer thicknesses. It has been calculated that with the thermal insulation thickness over 37 cm the maximum moisture zone is located in the internal layer of the aerated concrete blockwork. The phenomenon has been called "the over-insulation effect".

Keywords: enclosing structures, moisture potential, maximum moisture zones.

1 Introduction

In the course of Building Rules 50.13330.2012 updating [1] the modifications were made to the "Protection Against Enclosing Structures Over-Moistening" calculation procedure. This comprises introduction of the maximum moisture zone position in enclosing structures into the calculation procedure. This method was first proposed by V.V. Kozlov in 2004 [2]. It was further confirmed in the regulatory document in 2005. Building Rules [1] has demonstrated the applicability of this method for enclosing structure with facade composite thermal insulation with external plastering. This article reviews the theoretical justification of this method, and analyses the influence of thermal insulation layer thickness on the maximum moisture zone location in energy-saving enclosing structure.

2 Maximum Moisture Zone Location Calculation

The calculation procedure as per [1, 2] consists in the following. The value of $f_i(t_{m.m.})$ array shall be calculated for each layer of a multi-layer enclosing structure, which value shall be representative of the temperature in the maximum moisture zone.

$$f_i(t_{m.m.}) = 5330 \cdot \frac{r_{t,v}\left(T_{in} - T_{ext,neg}\right)}{R_t\left(e_{in} - e_{ext,neg}\right)} \cdot \frac{\mu_i}{\lambda_i} \quad (1)$$

where R_t — enclosing structure heat transfer total resistance, (m^2·°C)/W;
$f_i(t_{m.m.})$ — function that corresponding to the temperature of the layer *i* in the maximum moisture zone;
$t_{m.m.i}$ — maximum moisture zone temperature of the layer *i*, °C;
$r_{t,v}$ — enclosing structure water vapor permeability total resistance, m^2·s·Pa/g;
T_{in} — inside air average temperature, °C;
$T_{ex,neg}$ — outdoor air average temperature in the period of monthly average temperature below zero, °C;
e_{in} — 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;
μ_i — vapor permeability coefficient of *i*-th layer material, g/(m·s·Pa);
λ_i — thermal conductivity coefficient of *i*-th layer material, W/(m^2°C);
5330 — coefficient of the semi-empirical equation for the dependence of the quantities *E* on *T* (see equation (10)).

Based on the determined values of $f_i(t_{m.m.})$ array with the help of the table 11 in Building Rules [1] the maximum moisture zone temperature $t_{m.m.i}$, shall be defined for each layer of the multi-layer structure. The structure has only one maximum moisture zone — the maximum moisture zone in one of the structure layers. Item 8.5 of Building Rules [1] describes the procedure of determining this zone.

This method has been proven by the moisture potential *F* theory [2, 3]. The theory of this method is explained in Chapters 3 and 4

3 Applied Moisture Potential of Structure Materials

The method of determining the maximum moisture zone in enclosing structures is based on the use of moisture potential. In this case, the moisture potential *F* developed by [2, 3] has been used as the functional relation *F* between material moisture content and temperature determined with the formula:

$$F(w,T) = \frac{1}{\mu}\int_0^w \beta(\varsigma)d\varsigma + E(T)\varphi(w) \quad (2)$$

where *F(w,T)* — moisture potential depending on the moisture content and temperature, Pa;
w — material moisture content, kg/kg;
T — temperature, K;
μ — material water vapor permeability, g/(m·s·Pa);
β — material water content conductivity coefficient, g/(m·s·kg/kg);
ς — argument in the integrand;
E — saturated water vapor pressure, Pa;

φ- relative air humidity or relative pressure of water vapor in material pores, unit fractions.

The potential is comfortable to use because it allows to consider the liquid moisture carryover and water-vapor diffusion in enclosing structure materials simultaneously. Input data needed to calculate the potential F shall be collected as per the standard techniques for measuring coefficients of vapor permeability [4], water content conductivity [5] and thermal conductivity [6]. Therefore, when working with the potential F the data on material characteristics collected in the previous years shall be used.

The practical application of the potential F in the calculations is similar to the application of water vapor partial pressure, however it allows to make the calculations both in the sorption zone of structure materials moisturizing and in the supersorption zone of moisturizing simultaneously. This potential, unlike other moisture potentials such as [7, 8 etc.], considers the various energies of moisture bond to the material structure in the above mentioned moistening zones. This was the purpose, for which Professor V.N. Bogoslovsky created and developed the theory of moisture potential in early 1950th as described in [7].

Moisture potential simplifies considerably the calculation of moisture steady-state distribution. In the steady state (without air leakage considered) the equation of moisture carryover in the structures shall be formulated with the potential F:

$$\frac{\partial^2 F}{\partial x^2} = 0 \qquad (3)$$

Therefore, the solution to this equation is the linear function.

$$F = Ax + B \qquad (4)$$

where A and B are the constants determined on the basis of boundary conditions and conditions at material joints respectively, Pa/m and Pa.

In the equation (4) the constant A is equal to the gradient of the potential F. Consequently $\mu \cdot A$ is the specific moisture flow with dimensionality of mg/(m^2·hr). In the multilayer enclosing structures the equation (3) solution is piecewise.

The Building Rules [1] Chapter "Protection Against Enclosing Structures Over-Moistening" calculation procedure is based on the calculation of the moisture carryover under steady conditions that consider only vapor permeability of construction materials. It is necessary to consider the supersorption moisture transfer in materials as well. One of the interesting aspects of this approach used in the regulatory documents was the search for the maximum moisture zone position, with respect to which the enclosing structures moisture balance was calculated and for which the verification of non-availability of over-moistening was made. The potential F application makes it possible to find the exact position of the maximum moisture plane in the used model.

4 Method of Calculating the Maximum Moisture Zone Location

To find the maximum moisture zone it is necessary to determinate the points in the drawing of the section of the enclosing structure, where the coordinate derivative of moisture function is equal to zero, as well as the points where the moisture function has breaks. The use of potential F allows to find such points avoiding the determination of moisture distribution as per the civil structure thickness, which makes the calculation much simpler.

The x coordinate derivative of potential F.

$$\frac{\partial F}{\partial x}=\frac{\partial F}{\partial w}\frac{\partial w}{\partial x}+\frac{\partial F}{\partial T}\frac{\partial T}{\partial x} \tag{5}$$

Let us find the moisture coordinate derivative.

$$\frac{\partial w}{\partial x}=\frac{\dfrac{\partial F}{\partial x}-\dfrac{\partial F}{\partial T}\dfrac{\partial T}{\partial x}}{\dfrac{\partial F}{\partial w}} \tag{6}$$

To find the point coordinates, where $\frac{\partial w}{\partial x}=0$, it is necessary to solve the following equation:

$$\frac{\partial F}{\partial x}-\frac{\partial F}{\partial T}\frac{\partial T}{\partial x}=0 \tag{7}$$

Potential F dependence on the coordinate is defined in the equation (4), and the same on the temperature in the equation (2). Therefore (7) can be rearranged with the use of (2) and (4):

$$A-\varphi(w)\frac{\partial E}{\partial T}\frac{\partial T}{\partial x}=0 \tag{8}$$

Temperature distribution along the enclosing structure thickness in the one-dimensional steady state case is defined by the formula:

$$T=T_{ext}+\frac{T_{in}-T_{ext}}{R_t\lambda(x)}x \tag{9}$$

where R_t — enclosing structure heat transfer total resistance, (m^2·K)/W;

T_{in} and T_{ext} — temperature of inside and outdoor air respectively, K;

$\lambda(x)$ — thermal conductivity coefficient of the cladding layer material (accepted as constant within the cladding homogeneous layer), W/(m·K).

To determine $\frac{\partial E}{\partial T}$ it is undesirable to use various formulas involving the approximation of $E(T)$ dependence in the form of polynomials with various powers, as the E function derivative is being approximated. That is why the semi-empirical expression [4] determined on the basis of the Clapeyron-Clausius equation [4] is used:

$$E=1{,}84\cdot 10^{11}\,exp\left(-\frac{5330}{T}\right) \tag{10}$$

After inserting the formulas (9) and (10) the equation (8) will look as follows:

$$A-\varphi\frac{5330}{T^2}E\frac{T_{in}-T_{ext}}{R_t\lambda(x)}=0 \tag{11}$$

The first component of the formula (11) is the moisture potential gradient in the structure material layer, and the second component is the moisture potential gradient at constant moisture content (caused by the temperature drop). The difference is the isothermal gradient of the moisture potential allowing to find out the moisture distribution in the structure layers.

To determine the location of the maximum moisture zone, the equation (11) components are grouped in such a way that all values depending on the structure and boundary conditions are on the right,

$$\frac{T^2}{E} = \frac{\left(T_{in} - T_{ext}\right)}{R_t A} \cdot \frac{5330}{\lambda} \tag{12}$$

On the left of the equation (12) there remains the physical value of water vapor in the atmosphere with the certain pressure. In our case of the standard atmospheric pressure this value depends on temperature only. For the easy use of the formula (12) the T^2/E dependence on temperature is shown in the Table 1.

Table 1. Dependence of $\frac{T^2}{E}$ value on temperature.

t, °C	$\frac{T^2}{E}$, K²/Pa	t, °C	$\frac{T^2}{E}$, K²/Pa	t, °C	$\frac{T^2}{E}$, K²/Pa
-30	1554	-12	313.9	6	83.25
-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

SP 50.13330.2012 [1] contains the similar table of different format, with different interval and other limits needed for engineering calculations.

In case of steady conditions, it is a lot easier to find the moisture flow being transferred through the enclosing structure than the moisture distribution throughout the enclosing structure. That is why it is assumed that during initial consideration stage the moisture flow shall be found, and the coordinate of the maximum moisture shall be determined with formula (12) and Table 1.

In a general case there are two boundary condition variants, which lead to two different formulas describing moisture flow thought a structure. However checking a structure over-moistening as per [1] assumes a structure to be dry, besides, the entire method of further calculation as per [1] allows only to consider the water vapor diffusion. That is why one of the variants, which corresponds to the oversorption moistening of the external edge of the structure and high level of the structure moistening in general, can be disregarded. Therefore, the formula for moisture flow through a structure (11) shall be considerably simpler, and it is necessary to proceed to determining the coordinate of the moisture maximum in the structure.

$$\frac{T^2}{E} = 5330 \frac{r_{t,v}\left(T_{in} - T_{ext}\right)}{R_t\left(F_{in} - F_{ext}\right)} \cdot \frac{\mu}{\lambda} \tag{13}$$

Under the conditions, for which the structure is being checked for over-moistening as per [1] the potential F is equal to the relevant partial pressure of outdoor and inside air water vapor. No additional concepts are to be introduced for the use of the proposed method. In the final revision, the right side of the equation (13) looks as in the formula (1).

Item 8 of [1] stipulates the algorithm of determining the maximum moisture zone that foresees the sequential calculation on all structure layers. It is interesting that this calculation can be made substantially simpler as the enclosing structure layers moistening is changed systematically, and the method helps to determine the direction of the moistening change in the structure. Three variants are possible, when we analyze any of the structure layers. The first variant is that where the temperature of the maximum moisture zone $t_{\mathrm{m.m.}i}$, is achieved in the layer being studied. This means that the moisture maximum has been found. The second variant is that where the temperature of the maximum moisture zone of the layer being studied is higher than its temperature calculated with the formula (9). Therefore the maximum moisture zone is located to the warm side of the layer being studied. The third variant is that where the temperature of the maximum moisture zone of the layer being studied is lower than its temperature calculated with the formula (9). So in this case the maximum moisture zone is located to the cold side of the layer being studied. In the most of the up-to-date Enclosing structures, the maximum moisture zone is usually located in the thermal insulation layer or in the layer neighboring to it.

5 Practical Application of Moisture Conditions Calculation Method in Various Enclosing Structures with Facade Systems

Several calculations of the maximum moisture zone position have been made for energy-saving structures. Below you can find the results of calculations for the wall structure of a residential house in Moscow; the wall was made of aerated concrete blocks, with facade composite thermal insulation with external plaster layer. The internal side of the wall was coated with cement and sand mortar. The thermal insulating material was mineral wool with thickness varying in the course of study.

The thermal insulation layer was varying from 0.37 to 0.65 m. As a result, in case of small insulation thickness values the maximum moisture zone was located between the external plaster layer and the mineral wool layer. It is interesting that when thermal insulation layer thickness achieved 37 cm, the maximum moisture zone shifted to aerated concrete and remained there with further increase of thickness (Table 2). It is proposed to name this effect as “the effect of over-insulation” of enclosing structure.

“The over-insulation effect” is substantiated by the fact that in case of increasing the mineral wool layer thickness the gradient of moisture potential F in the thermal insulation decreases, and its value becomes insufficient for moisture carryover trough the mineral wool layer. That is why moisture remains in the layer of aerated concrete.

Substantial thicknesses of enclosing structure thermal insulation layer reaching 0.40–0.50 m are applied in “passive houses”. Along with some energy saving effect, the high thermal insulation layer thickness results in negative consequences, such as increased materials moistening. Lars-Erik Harderup and Olof Hagersedt [9] describe this phenomenon in wooden passive houses in Sweden. The method described in the

Russian Building Rules [1] allows making calculation of such phenomenon as “the over-insulation effect”.

Table 2. The calculated values of the maximum moisture zone coordinates in enclosing structure with the increase of thermal insulation layer thickness from 0.37 m to 0.65 m — “the effect of over-insulation” of enclosing structure.

Item No.	Thermal insulation layer thickness, m	Distance from the mineral wool and aerated concrete contact layer to the maximum moisture zone in aerated concrete, m
1	0.37	0.027
2	0.45	0.073
3	0.5	0.123
4	0.55	0.176
5	0.6	0.231
6	0.65	0.289

6 Conclusion

The substantiation has been given for the procedure of calculating the protection against over-moistening as per SP 50.13330.2012. This procedure yields results without sophisticated calculations with specialized computer software, unlike the known methods used in Russia and abroad. The results of determining the maximum moisture zone for facades with composite thermal insulation with thin plaster layers have been given as an example of the SP procedure use. “The over-insulation effect” having great importance for “passive houses” designing has been described. This effect has been substantiated within the framework of the present theory. The further development of the theory based on the moisture potential F will make it possible to quantify materials moisture in the maximum moisture zone.

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