Heat Loss through External Enclosure Structures in the Stage of their Wetting and Freezing

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Abstract. An approximate estimate of the thermal conductivity of the material of the external enclosure structure is given under stationary heat transfer conditions, taking into account the various humidity of material and conditions of freezing of outside layer. There were given the calculated values of resistance to heat transfer for two considered designs of external enclosures: single-layer wall of inorganic material and the same with a screen (siding), separated from the wall by a ventilated air layer. The computational model showed an increase in the thermal conductivity of the material in the wet and frozen zones of the structures, a decrease in their total value of resistance to heat transfer, and rise in heat loss, compared to the normative method of calculation.

1. Consideration of the moisture and freezing phases states

Significant changes in the temperatures of indoor and outdoor air in most of the territory of Russia [1] lead to the emergence of intense flows of diffusing vapor through the external enclosure structures of heated buildings. Process analysis of vapor permeability of materials under operating conditions performed in [2,3].

The thermal conductivity of the enclosing structure material under operating conditions is determined in [4] with incomplete accounting of the phase state of moisture in capillary-porous structure of the material, that leads to a certain error in the estimation of the specific heat characteristic of the building.

Phase transitions of moisture in capillary–porous structure of the material (icing, melting, condensation) take place in conditions of high humidity of the structural layer of enclosing structure and low temperatures of outdoor air, while in the pores and capillaries along with non-frozen water can be water vapor, hoarfrost and ice crystals. The appearance of condensate and its freezing can occur in the larger voids of external walls [5].

Excess sorption humidification of the material of external enclosure structures takes place in the event of errors in the design, construction and operation of buildings and also by long-term exposure to moist environments. Analysis of the zone location of maximum moistening in the insulated wall system was considered in [6].

The probability of the occurrence of phase transitions of moisture in the capillary-porous structure of the material depends on the features of the constructive solution of the external enclosure. In those of them, that are insulated from the outside, the layer of thermal insulation keeps the main array of wall in the zone of positive temperatures. However, in single-layer, homogeneous external enclosure structures the moisture, contained in the capillaries and pores of the material, can be freezed under
long-term exposure to low temperatures to the boundary, where the line of temperature drop falls below zero along the thickness of the structure. As is known, the temperature of the early freezing of the main mass of free moisture in the pore space of the material of the outer enclosure ranges within -1 ... 3 °C. Phase state of moisture causes a noticeable change thermophysical characteristics of the material and affects the value of heat loss through external enclosure structures.

Heat and mass transfer in these designs at negative temperature and in the absence of filtration movement is described by the differential equation [7]

$$c \cdot \gamma_0 \cdot \frac{\partial t}{\partial z} = dtr(\lambda \cdot \nabla t) + \frac{\xi_1}{1-\xi_1} \cdot r \cdot \gamma_0 \cdot \frac{\partial u_w}{\partial z}$$  \hspace{1cm} (1)

where $r$ – heat of icing; $u_w$ – the weight content of unfrozen water; $\xi_1$ – coefficient of icing.

The equation of thermal balance on the border of freezing of the outer enclosure is described by equation [8]:

$$r \cdot i \cdot u_f \cdot \gamma_0 \cdot \frac{\partial \delta_f}{\partial z} = \lambda_f \frac{\partial t_f}{\partial z} - \lambda_w \frac{\partial t_w}{\partial z}$$  \hspace{1cm} (2)

where $\lambda_f$, $\lambda_w$, $t_f$, $t_w$ respectively, coefficients of thermal conductivity of material and its temperature in the frozen and wet layers of the enclosing structure; $i$ – the share of freezing of moisture; $\gamma_0$ – the density of the material in dry condition.

The solution of practical problems during heat and mass transfer, using equations (1-3), represents known mathematical difficulties, taking into account the phase transformations of moisture and the speed of their passage through the thickness of the external enclosure structures in real (non-stationary) operating conditions.

2. Accepted design model

Below is considered a simpler model, that takes into account only the freezing of the moistened material and makes it possible to estimate the change the thermal conductivity of the material. Herewith were made the following assumptions:

1. The temperature on the outer surface of the enclosing structure was reduced to a constant negative value $t_{ext} = \text{const.}$ with the beginning of a long-term period of cold snap.
2. The temperature $t_f$ in the thickness of this enclosing structure on the movable freezing boundary remains the same as at the beginning of freezing of moisture.
3. The temperature varies linearly in the frozen and humid layers.

For the conditions of stationary heat transfer the equation (2) has the following form, if the rate of advance of the freezing front $\frac{\partial \delta_f}{\partial z} \rightarrow 0$ and the magnitude $r$ is negligibly small

$$\lambda_f \cdot \frac{t_f - t_{ext}}{\delta_f} - \lambda_w \cdot \frac{t_w - t_f}{\delta - \delta_f} = 0 \hspace{1cm} (3)$$

where $t_{ext}$ – temperature on the outer surface of the enclosing structure; $t_f$ – temperature of beginning of freezing moisture, °C; $\delta$ – the thickness of the enclosing structure; $\delta_f$ – depth of the frozen area of the enclosing structure.

Equation (3) yield the result:

$$\lambda_f = \frac{\lambda_w (t_w - t_f) \delta_f}{(t_f - t_{ext})(\delta - \delta_f)}$$  \hspace{1cm} (4)

In the model under consideration, the maximum possible value of $\delta_f$ is assumed, which reaches the limit of the onset of freezing of moisture in capillaries and pores (-2°C) on the temperature distribution line over the thickness of the structure.

The value of the coefficient of thermal conductivity of the wet area of material $\lambda_w$ in equation (4) can be found from the known dependence

$$\lambda_w = \lambda_d \cdot \left(1 + \omega_0 \cdot \frac{\delta_1}{100}\right)$$  \hspace{1cm} (5)
where $\lambda_d$ – coefficient of thermal conductivity of dry material; $\omega_0$ – the moisture content of the material, % by volume; $\delta_t$ – increase in the coefficient of thermal conductivity by 1% of the volumetric moisture content of the material.

The value $\delta_t$, which depends on the type of capillary-porous material, is difficult to systematize in order to obtain a general relationship between the thermal conductivity of the material and its moisture content. Therefore, a more accurate value of the coefficient $\lambda_w$ at the building construction stages can be taken, as a result of the experimental study of the dependence $\lambda_w=f(\omega_0)$ for the material used.

For the purpose of more correct description of the patterns of change in the heat-conducting properties, it is required to consider in more details features of formation of thin layers of water on a surface of cells of material.

Based on the idea of the surface mosaicity of the crystals of the ceramic matrix, on the border with the water film are the $K^+$ cations, which are the poles of the packet dipoles $K^+\cdot OH^−$ with the electric dipole moment $P=18D$ ($D$ – deby). They create an electric field in a film with an intensity in the first monolayer of water ($\varepsilon=1$, $r=0.35$ nm) [9]

$$E = \frac{2P}{4\pi\varepsilon_0 r^3} \quad (6)$$

Under the action of an electric field water molecules orient themselves normally to the surface of crystals, forming a strong adsorption-bonded layer, different from the structure of bulk water, formed by hydrogen bonds between molecules. Due to the strong electric field, the bound water molecules are immobile, and the hydrogen bonds are deformed and substantially weakened. Earlier in [9,10], it was found, that the thermal conductivity of water films in crystals is 1,5 orders of magnitude greater, than that of bulk water. In this regard, the correcting calculation is divided into two stages:

1. The thermal conductivity of the first component of the material system «air-adsorbed moisture» is determined by

$$\lambda_{comp.1} = \frac{k \cdot \lambda_w \cdot \lambda_{air}}{\lambda_{air} \cdot (1 - \frac{3}{\sqrt{V_{air}}}) + k \cdot \lambda_w \cdot \frac{3}{\sqrt{V_{air}}}} \cdot \left(1 - \frac{3}{\sqrt{V_{air}}} \right) \quad (7)$$

where $k$ – the coefficient, taking into account the increase in thermal conductivity of bound water ($k=6$); $V_{air}$ and $V_w$ – the relative content of air and water in the cell of the material ($V_{air}+V_w = 1$).

For materials within the range of sorption moisturizing 0...12% (by volume) the value of the coefficient $k$ was determined by the least squares method, using experimental data [11].

2. Presenting the moistened material in the form of the «first component-matrix material» system, the final thermal conductivity is defined as:

$$\lambda_{mat.} = \lambda_{mat.} \cdot \frac{\lambda_{comp.1} \cdot \lambda_{air}}{\lambda_{comp.1} \cdot (1 - \frac{3}{\sqrt{P_{sum}}}) + \lambda_{mat.} \cdot \frac{3}{\sqrt{P_{sum}}}} \cdot \frac{P_{sum}^2}{\sqrt{P_{sum}^2}} + \lambda_{mat.} \cdot \left(1 - \frac{3}{\sqrt{P_{sum}}} \right) \quad (8)$$

where $P_{sum}$ – total porosity of material, rel. units ($P_{sum}=1-\rho_m/\rho$); $\lambda_{mat.}$ – thermal conductivity of the matrix material; $\rho_m$ and $\rho$ – average and true density of material.

In accepted design model were reviewed for the materials of the external enclosure structures three design schemes of the outer walls, that are often used in the practice of construction, and three moisture states, which are typical during the heating period of the year.

Design schemes:

1. Single-layer design of inorganic material.

2. The same wall with a screen (siding), separated from the wall by a ventilated air layer.

3. Design as in the second scheme with an external heat-insulating layer behind the screen.

Moisture states:

1. Stable state of sorption humidity.
2. Maximum permissible value of sorption humidity due to its increase by the end of the heating season.
3. Supersorption humidity of the material, when exposed to drip-liquid moisture.

In the first and second schemes the moisture, contained in the capillaries and pores of the material, in contrast to the third scheme, can be subjected to freezing under a sufficiently long exposure to low temperatures to the boundary, where the temperature falls below zero. According to [4] the external thermal insulation layer is arranged for all newly constructed walls of residential buildings, which the resistance to heat transfer is below the required value. This layer implies the possibility of keeping the main array of wall in the zone of positive temperatures.

Use of air interlayer in the second and third schemes has a drying effect on the construction material and ensures the moisture content of the material within the regulatory requirements.

For enclosing structures in accordance with schemes 2 and 3 is a typical the first of the listed moisture states of the material, since the ventilated layer removes excess moisture, that can accumulate during the diffusion of water vapor. In this case, the screen (siding) protects the structure from the penetration of dripping liquid during precipitation.

Approximate estimate of thermal conductivity of the above constructive schemes under water undergoing phase change was performed with the following initial data [12,13]:

Temperature values: \( t_f = -2 \, ^\circ \text{C}, \quad t_{ext} = -25 \, ^\circ \text{C} \). Temperature on the inner surface of the wall \( t_{int} = 20 \, ^\circ \text{C} \).

The main massif of the wall - is plastered brickwork \( \delta = 0.64 \, \text{m} \).

Thermal insulation for the wall - expanded polystyrene \( \gamma =100 \, \text{kg/m}^3 \), thickness 0.1 m. The heat transfer coefficients of the inner and outer surfaces of the wall are \( a_{inn} = 8.7 \) and \( a_{out} = 23 \, \text{W/(m}^2\cdot\text{C}) \), respectively. The maximum possible depth of the freezing area of the wall \( \delta_f =0.37 \, \text{m} \).

For scheme 1 to determine the moisture content and the thermal conductivity of the material of the wet area of the structure, the second moisture state of the material is adopted. Then \( \omega_{max}^{sorp} =1.5\% \) [4], and \( \lambda_w = 0.94 \) (according to the experimental data [8]).

For the design schemes No.2 and No.3 one of the two recommended operating conditions A or B of moisture states of the material can be selected. The condition A was accepted, taking into account the drying effect of the air interlayer. Then, for brickwork, \( \lambda_w =0.7 \), and for expanded polystyrene \( \lambda_w = 0.041 \) [4].

For the design schemes No.1 and No.2 from equation (4) were found: the coefficient of thermal conductivity of the material in the freezing zone (1,23 and 1,06 \text{W/(m}^2\cdot\text{C}), respectively), thermal resistance of frozen \( R_f \) and wet \( R_w \) zones, the total resistance to heat transfer \( R_o \) of the outer wall and heat loss \( Q \) through it.

The formula for determining \( R_o \) included the sum of the values \( R_f \) and \( R_w \), since the wet and frozen zones in this model can be considered as separate layers with a certain value of thermal resistance.

\[
R_0 = \frac{1}{a_{inn}} + R_f + R_w + \frac{1}{a_{out}} \tag{9}
\]

The results of the calculation with the accepted assumptions are shown in table 1.

### Table 1. Calculated thermal resistances of frozen and wet layers of external walls and heat loss through them.

| № of design schemes | \( R_f \), (m\(^2\cdot\text{°C})/\text{W} \) | \( R_w \), (m\(^2\cdot\text{°C})/\text{W} \) | \( R_o \), (m\(^2\cdot\text{°C})/\text{W} \) | \( Q \), W/m\(^2\) |
|---------------------|-----------------|-----------------|-----------------|--------|
| 1 | 0.30 | 0.29 | 0.75 | 60 |
| 2 | 0.35 | 0.39 | 0.90 | 50 |

The freezing depth \( \delta_f \) of the enclosing structure depends on the outside temperature \( t_{ext} \). For example, at \( t_{ext} = -10 \, ^\circ \text{C} \) for the design scheme №1 the value of \( \delta_f \) is 0.17 m.
The application area of the considered design model, which greatly simplifies the real mechanism of heat and mass transfer, is limited to stationary conditions of heat transfer. For unsteady conditions the thermal lag of the structure will impact on the moving freezing boundary and define a different, more complex nature of the temperature distribution line through the thickness of the structure.

The regulatory requirements [4] do not consider the influence on the thermal conductivity of the material as a super-sorption state of moisture, so and the presence of freezing zone in the enclosing structure- parameters, that change its thermophysical characteristics and thermal efficiency.

3. Summary
Thus, taking into account the supersorption humidification and freezing of the material of enclosing structures, the heat loss through the considered designs of external enclosures is 1.1...1.2 times more, than by the normative method of calculation.

For this reason, the heat transfer coefficient through the external enclosure structures and the specific heat protection characteristic of the building, which directly determine its energy efficiency class, can get respectively underestimated and overestimated values.

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