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NUMERICAL ANALYSIS OF THERMAL EFFICIENCY OF EXTERNAL WALLS WITH HEAT-CONDUCTING INCLUSIONS

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Abstract. In the practice of design and construction, methods of numerical calculations using modern software package are widely used, which make it possible to effectively solve the problems of designing, erecting and operating buildings and structures of various functional purposes. A comparative analysis of numerical, theoretical and experimental studies in the field of building structures, buildings and structures shows that accurate calculation methods provide reliable data on the subject of research. This article presents the results of numerical studies of the thermal efficiency of inhomogeneous vertical fences on the example of several options for constructive solutions for the outer walls of a building. The studies were carried out using the TEPL software package, developed for calculating three-dimensional temperature fields based on the control volume method. The results of the analysis of the temperature distribution on the heat exchange surfaces are presented, which made it possible to determine the zones of excessive heat losses in the structures under study. Significant heat losses on the slopes of window openings are revealed, which should be taken into account when calculating the reduced resistance to heat transfer of the fence. The TEPL software package allows not only to correctly estimate heat losses, but also automatically obtain the value of the reduced heat transfer resistance of the fence structure, taking into account all the features of its design solution.

Keywords: 3D numerical method, reduced heat transfer resistance, external walls, heat losses, thermal efficiency

ЧИСЛЕННЫЙ АНАЛИЗ ТЕПЛОВОЙ ЭФФЕКТИВНОСТИ НАРУЖНЫХ СТЕН С ТЕПЛОПРОВОДНЫМИ ВКЛЮЧЕНИЯМИ

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Аннотация. В практике проектирования и строительства широко применяются численные расчеты с использованием современных вычислительных комплексов, позволяющие эффективно решать задачи по проектированию, возведению и эксплуатации зданий и сооружений различного функционального назначения. Сравнительный анализ численных, теоретических и экспериментальных исследований в области строительных конструкций, зданий и сооружений показывает, что точные методы расчета дают достоверные данные о предмете исследования. В настоящей статье приводятся результаты численных исследований тепловой эффективности неоднородных вертикальных ограждений на примере нескольких вариантов конструктивного решения наружных стен здания. Исследования проводились с использованием вычислительного комплекса TEPL, разработанного для расчета трехмерных температурных полей на основе метода контрольного объема. Приведены результаты анализа распределения температур на поверхностях теплообмена, позволившие определить зоны излишних тепловых потерь в исследуемых конструкциях. Выявлены значительные тепловые потери на откосах оконных проемов, которые следует учитывать при расчете приведенного сопротивления теплопередаче ограждения. Вычислительный комплекс TEPL позволяет не только корректно оценить тепловые потери, но и автоматически получить величину приведенного сопротивления теплопередаче конструкции ограждения с учетом всех особенностей её конструктивного решения.

Ключевые слова: трехмерный численный расчет, приведенное сопротивление теплопередаче, наружные стены, тепловые потери, тепловая эффективность

1. INTRODUCTION

The parameter that characterizes the thermal qualities of the envelope is the total heat transfer resistance. For multilayer structures, this parameter is defined as the sum of thermal resistance to heat transfer of all layers of the structure and the resistance to heat perception and heat dissipation of its internal and external surfaces, respectively. The thermal transmission resistance of a multilayer structure without thermal conductive inclusions is determined by the formula:

$$R = \frac{1}{\alpha_{int}} + \sum_{1}^{n} \frac{\delta_i}{\lambda_i} + \frac{1}{\alpha_{ext}} \quad , \qquad (1)$$

where α_{int} is the heat transfer coefficient of the internal surface of the structure, W/ m$^2\cdot$°C;
α_{ext} is the heat transfer coefficient of the external surface of the structure, W/ m$^2\cdot$°C;
δ_i is the depth of the i^{th} structure's layer, m;
λ_i is the heat transfer coefficient of the i^{th} layer of the structure, W/ m·°C.
Design solutions of external vertical enclosures of modern buildings are quite diverse. Most of them are complex heterogeneous systems with heat-conducting inclusions. It is not possible to determine correctly the heat transfer resistance of such structures by the formula (1). Therefore, approximate methods are used in design practice to account heat-conductive inclusions in a structure by means of application of coefficient of thermo-technical homogeneity *r*. This coefficient characterizes the effectiveness of insulation of the structure. It is determined by the formula:

$$r = \frac{R_{red}}{R} ,$$

where R_{red} is the reduced heat transfer resistance of a fragment of the building's thermal envelope, m$^2\cdot$°C/W;
R is the conditional resistance to heat transfer of the building envelope averaged over area or a dedicated enclosing structure, m$^2\cdot$°C/W.

Thermal analysis according to the regulatory methodology is based on the representation of a fragment of the thermal protection envelope of the building as a set of independent elements affecting the heat losses. The specific heat losses through the linear thermal heterogeneity are determined as analysis result of the two-dimensional temperature field in the enclosing structure. Determination of the reduced heat transfer resistance R_{red} by the proposed methodology leads to significant errors in assessing the thermal efficiency of complex heterogeneous structures of enclosures that does not allow to take into account the influence of local thermal inclusions in the form of brackets, anchors, etc. elements available in the facade systems of modern buildings
The reduced heat transfer resistance of an inhomogeneous structure with thermal inclusions [1] can be determined correctly using the results of the analysis of the three-dimensional temperature field:

$$R_{red} = (t_{int} - t_{\mathrm{ext}})/\ q ,$$

where t_{int} is the temperature of internal air, °C ;
t_{ext} is the temperature of external air, °C;
q is the heat flow's density related to the design surface of the enclosure, W/m^2.
The reliability of the thermal efficiency assessment of inhomogeneous structures with thermal inclusions based on the numerical analysis of spatial temperature fields has been confirmed by numerous studies. The numerical calculation efficiency of the reduced heat transfer resistance of enclosing structures has been established by the authors of studies [2], who developed a calculation model of visual programming for building design. Work [3, 4] was devoted to the numerical analysis of increasing the thermal protection of a building with passive solar heat supply through the integration of elements of active solar units in the absorbing layer of the accumulating envelope structure. The calculation results for the three-dimensional temperature field of the curtain facade system given in [5] showed good

convergence with the experimental data, while the calculation results according to the normative methodology differed significantly from the experimental values. The authors of work [6] conducted a numerical analysis of the thermal efficiency of exterior walls, which allowed to choose the most optimal structures for the reconstruction of buildings. The authors of [7, 8] performed a 3D numerical simulation using the ANSYS Fluent computing complex to study the effect of heat losses through "cold bridges" in the areas of adjoining floor structures to the exterior walls of the building. Studies of the dynamic process of heat transfer through the enclosing structures of buildings in various climatic conditions using numerical simulation are devoted to the works [9, 10]. Using computer simulation [11], the effect of the mortar joint thickness on the thermal efficiency of buildings with heterogeneous walls with insulation is studied. Work [12] presents the numerical research results for the thermal efficiency of composite wall structures with an air gap. Those study was based on a calculation module developed by the authors using the MATLAB, which solves a one-dimensional heat flow diffusion equation with convective periodic boundary conditions. Significant heat losses through exterior walls with windows were revealed by the authors of [13, 14] by the results of numerical calculation of three-dimensional temperature fields. The index of thermal comfort of a room taking into account radiator heating was determined on the basis of numerical analysis [14]. Studies [15] are devoted to creating energy three-dimensional models of buildings on the basis of computer modeling. The issue of accuracy of numerical thermal calculations is dedicated to the work [16], which provides a comparative analysis of the results of numerical and experimental methods for research of heat transfer in enclosing structures for compliance with the calculated and experimental models.
This study was aimed at investigating the heat transfer through exterior building envelopes and evaluating their thermal efficiency based on the calculation of a three-dimensional temperature field using the TEPL computational complex [17].

2. METHODS

The TEPL computational complex [17] allow calculation of three-dimensional steady-state fields in order to analyze the temperature distribution in a building envelope and determine its reduced resistance. The computational program allows: entering and correcting initial data; performing graphical control of the computational scheme; performing numerical calculation of three-dimensional temperature fields of complex facade systems containing thermal inclusions in the form of bars; performing graphical analysis of temperature distribution in the structure; calculating the reduced heat transfer resistance of a multi-layer heterogeneous structure.
The numerical method has been developed on the basis of the control volume method for three-dimensional temperature fields under steady-state thermal conductivity conditions. The differential equation of three-dimensional steady-state thermal conductivity has the following form:

$$\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right)+S=0, \quad (2)$$

where x, y, z are the coordinates;
T is the temperature;
λ is thermal conductivity coefficient;
S is the power of thermal emission per unit volume.
Numerical integration of differential equation (2) is applied to calculate temperature distribution in the structure. One of the variants of the numerical solution can be a variation of the weighted discrepancy method in the form of the control volume method [18]. The essence of the method is that the differential equation is integrated over the elementary control volumes into which the structure under consideration is separated (Figure 1).

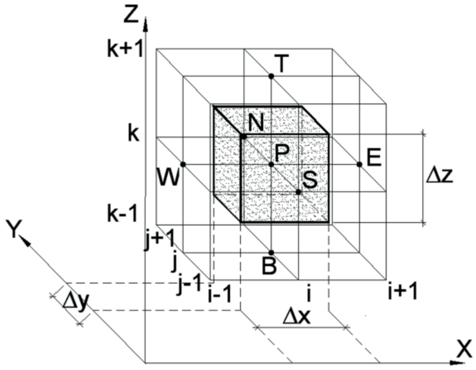

Figure 1. Calculation scheme

A nodal point P is located in the center of the control volume (highlighted with shading lines in Fig. 1). The mesh is divided into control volumes so that one material is located within each control volume, and the boundary of the control volume is in the middle between the nodal points. Neighboring node points B, E, N, S, T, W should be located in the centers of neighboring control volumes. The exceptions are the node points on the boundary planes of the structure partition. These points are located on the outer boundaries of the structure, i.e. the outermost control volumes have node points located on the outer boundaries of the volume and not inside it.

In the numerical simulation, the temperature within each control volume is assumed to be constant and equal to the temperature at the corresponding node point. The peculiarity of the control volume method is that the law of conservation of energy is observed regardless of the mesh partition of the computational model. That is, the heat flow through any surfaces does not depend on the partition mesh. However, the mesh should be thickened in order to obtain an accurate value of temperature in places of its high gradient, since the temperature at the node points depends on the division mesh.

For the three-dimensional problem, the discrete analogue of equation (2), which is expressed by the energy conservation law, according to the recommendations [18], has the form:

$$a_p T_p = a_E T_E + a_W T_W + a_N T_N + a_S T_S + a_T T_T + a_B T_B + b, \qquad (3)$$

where $T_E, T_W, T_N, T_S, T_T, T_B$ are the temperature at the nodal points;

the coefficients at temperatures:

$$a_p = a_E + a_W + a_N + a_S + a_T + a_B;$$

$$a_E = \frac{\lambda_e\, \Delta y\, \Delta z}{(\delta x)_e}; \qquad a_S = \frac{\lambda_s\, \Delta x\, \Delta z}{(\delta y)_s};$$

$$a_W = \frac{\lambda_w\, \Delta y\, \Delta z}{(\delta x)_w}; \qquad a_T = \frac{\lambda_t\, \Delta x\, \Delta y}{(\delta z)_t};$$

$$a_N = \frac{\lambda_n\, \Delta x\, \Delta z}{(\delta y)_n}; \qquad a_B = \frac{\lambda_b\, \Delta x\, \Delta y}{(\delta z)_b}.$$

The thermal conductivity coefficients at the boundaries of the control volume λ_b, λ_e, λ_n, λ_s, λ_t, λ_w are determined using the thermal conductivity coefficients of materials of the control volumes. As the test analyses have shown, the most exact correspondence of heat flows at the boundary of the test volumes is obtained if the thermal conductivity coefficients at the boundaries of the test volumes are determined by the formulas:

$$\lambda_b = \frac{2\lambda_P\, \lambda_B}{\lambda_P + \lambda_B}; \qquad \lambda_e = \frac{2\lambda_P\, \lambda_E}{\lambda_P + \lambda_E};$$

$$\lambda_n = \frac{2\lambda_P\, \lambda_N}{\lambda_P + \lambda_N};$$

$$\lambda_s = \frac{2\lambda_P\, \lambda_S}{\lambda_P + \lambda_S}; \qquad \lambda_t = \frac{2\lambda_P\, \lambda_T}{\lambda_P + \lambda_T};$$

$$\lambda_w = \frac{2\lambda_P\, \lambda_W}{\lambda_P + \lambda_W}.$$

The following dimensions are used when constructing the discrete equation:

Δx, Δy, Δz are the dimensions of the control volume in which the node point P is located;

$(\delta x)_e$ is the distance along the X axis from point P to point E;

$(\delta x)_w$ is the distance along the X-axis from point P to point W;

$(\delta y)_n$ is the distance along the Y axis from point P to point N;

$(\delta y)_s$ is the distance along the Y axis from point P to point S;

$(\delta z)_t$ is the distance along the Z axis from point P to point T;

$(\delta z)_b$ is the distance along the Z axis from point P to point B;

If there are thermal inclusions between node points, for example in the form of rod elements, in equation (2) the coefficients a_B, a_E, a_W, a_N, a_S, a_T are calculated as follows:

$$a_E = \frac{\lambda_e \, \Delta y \, \Delta z + \lambda_s A}{(\delta x)_e}; \qquad a_W = \frac{\lambda_w \, \Delta y \, \Delta z + + \lambda_s A}{(\delta x)_w};$$

$$a_N = \frac{\lambda_n \, \Delta x \, \Delta z + \lambda_s A}{(\delta y)_n}; \qquad a_S = \frac{\lambda_s \, \Delta x \, \Delta z + \lambda_s A}{(\delta y)_s};$$

$$a_T = \frac{\lambda_t \, \Delta x \, \Delta y + \lambda_s A}{(\delta z)_t}; \qquad a_B = \frac{\lambda_b \, \Delta x \, \Delta y + \lambda_s A}{(\delta z)_b},$$

where λ_s is the thermal conductivity coefficient of the rod, A is the area of the bar.

$b = S_c \, \Delta x \, \Delta y \, \Delta z$, where S_c is the power of heat emission in the control volume.

To calculate the temperature distribution in the structure, in addition to assigning the geometry and material distribution, it is necessary to set the boundary conditions. Three variants of boundary conditions are possible:

- the temperature at the point is set, then in the calculation the temperature at the node point is taken equal to the set temperature;
- the heat flux density is given, then:

$$b = q_x \, \Delta y \, \Delta z + q_y \, \Delta x \, \Delta z + q_z \, \Delta x \Delta y \; + S_c \, \Delta x \, \Delta y \, \Delta z,$$

where q_x, q_y, q_z are the heat flux density in the direction of the X, Y, Z axes, respectively;

- there is heat exchange with the medium having a given temperature at the point, then at the heat exchange coefficient α and the temperature of the medium T_f:

$$a_p = a_E + a_W + a_N + a_S + a_T + a_B + \alpha$$

$b = S_c \, \Delta x \, \Delta y \, \Delta z + \alpha T_f \Delta y \, \Delta z$ is the heat exchange at the surface with the normal along the X-axis,

$b = S_c \, \Delta x \, \Delta y \, \Delta z + \alpha T_f \Delta x \, \Delta z$ is the heat exchange at the surface with the normal along the Y-axis,

$b = S_c \, \Delta x \, \Delta y \, \Delta z + \alpha T_f \Delta x \, \Delta y$ is the heat exchange at the surface with the normal along the Z-axis.

Equation (3) is formed for all N nodal points. This equation takes into account the presence of areas of different materials in the structure, thermal inclusions, boundary conditions. Aggregate of equations for all nodal points forms a system of N linear equations with N unknown temperatures. The solution to this system of equations allows defining the temperature at the nodal points.

Systems of linear equations can be solved using the Gaussian method or the iterative method. The computational complex for calculating three-dimensional temperature fields TEPL [17] implements the iterative method. As shown in [18], the iterative process converges taking into account the boundary conditions. To accelerate the convergence along the lines of node points in the direction of the Y axis, a direct solution of the system of order N_y (N_y is the number of partition points along the Y axis) is performed, which is then iteratively refined by running along all axes. The solution process continues until, at the next iteration step, the temperature refinement for all points does not exceed the specified error. In this case, for an error of 0.01 ºC, in most cases the temperature distribution is close to the actual one. In case of significant temperature gradients, e.g. due to the presence of thermal inclusions, the error should be reduced to 0.001-0.0001 ºC.

The TEPL computational complex [17] allows to reliably investigate heat losses through multi-layer heterogeneous enclosures with the identification of areas where condensation may occur due to thermal inclusions, as well as to determine the value of the reduced heat transfer resistance of the structure under study. The automation of determining the heat transfer resistance in the TEPL calculation complex makes it possible to take into account the temperature at all points on the heat transfer surfaces and the surface area, while ensuring a high accuracy of determining the heat loss through the enclosure.

3. RESULTS AND DISCUSSION

The thermal efficiency of multi-layer exterior walls with different structural solutions was evaluated using the TEPL computational complex. There were considered designs of walls with inner layers made of bricks and gas concrete blocks, insulation and curtain facade systems, as well as brick walls with different arrangement of insulation layer and finishing made of facing gypsum boards and brick walls without insulation layer. The design schemes included wall fragments with windows, reinforced concrete slabs, and partitions adjacent to the walls.

It is necessary to note, that approximate analysis does not allow estimating heat losses through window linings and thermal conductive inclusions, which should be considered in thermal-technical calculations of heterogeneous structures of enclosures. Because of the presence of materials with different coefficients of thermal conductivity such as thermal inclusions, air gaps associated with the outside or inside air, windows are formed areas with increased heat losses, reducing the thermal efficiency of fencing. Increased heat losses on individual wall surfaces arise due to the presence in the construction of areas with low thermal resistance, which are the so-called "cold bridges", through which heat flows outward, bypassing the thermal insulation of the wall.

For exterior wall structures, such areas are the surfaces of the window opening slopes, which, depending on the design solution, may include elements with thermal conductivity coefficients several times lower than the thermal conductivity coefficient of the main walls of the building. Such elements can be reinforced concrete lintels or metal profiles framing the window openings.

Figure 1 shows the temperature distribution in the wall of aerated concrete blocks with windows, clearly demonstrating the areas of low temperatures on the surface of the window jambs.

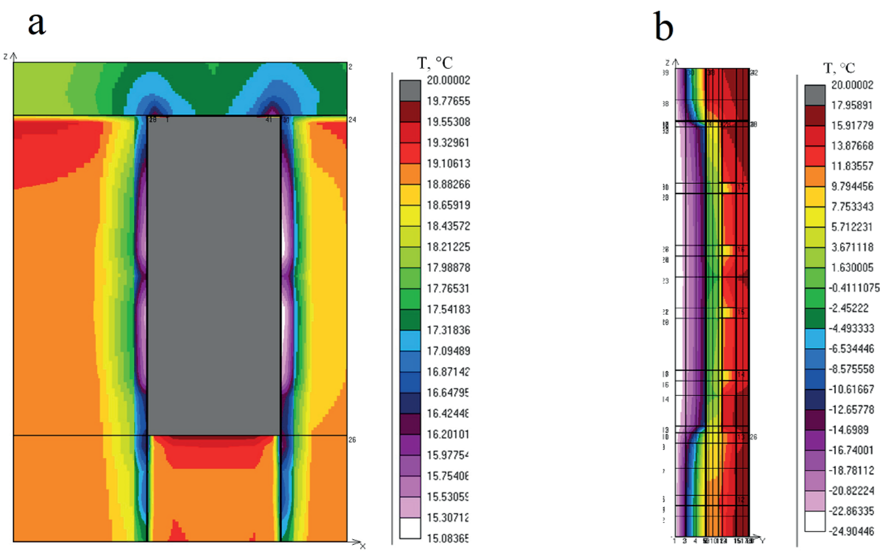

Figure 1. Temperature distribution in the wall structure made of aerated concrete blocks with a window: a - on the inner surface of the wall along the Y axis; b - on the inner surface of the window slope along the X axis

According to the calculation results, the temperature on the inner surface of the wall does not decrease below the dew point temperature everywhere. For living quarters it is 10.2°C with a normal humidity level of 55% and an interior air temperature of +20°C, which corresponds to the regulatory requirements for housing design. However the calculation shows that the temperature on some parts of the window lining surfaces is between 5.71 - 9.79 °C, which indicates a possible condensation of water vapor on these wall surfaces. This can lead to the appearance of mold and mildew, which will negatively affect the operational reliability of the structure of the outer walls of the building.

As a result of numerical analysis of the thermal efficiency of aerated concrete block walls, it was found that half of the total heat loss through the structure of such a wall accounts for its inner surface and window soffits. At the same time, the heat losses occurring through the slopes of the window openings accounted for almost half of the heat losses through the inner surface of the wall (Table 1).

Table 1. Heat loss through the walls of aerated concrete blocks with windows

Потери тепла в различных областях стены, W/%		
На внутренней поверхности	На оконных откосах	На окнах
38,49/24	39,57/26	79,02/50

The thermal transmittance of exterior walls made of gas concrete blocks without windows and thermal conductive inclusions R determined by the formula (1) is 2.108 m2-°C/W, and obtained by numerical calculation taking into account all inhomogeneities of the wall structure - R_{red} = 1.538 m^2°C/W. This is the thermal transmittance value that must be accounted for to evaluate the thermal efficiency of the building envelope, which correctly evaluates all heat loss (Q) through the envelope. As can be seen from Table 1, the value of total heat loss through the wall structure is 157.08 W, and the value of heat loss obtained from the calculation of heat transfer resistance according to the formula (1) is 103.37 W, which is 1.52 times lower than that determined by the numerical calculation, which takes into account all the heterogeneities existing in the fence.

The temperature distribution patterns on the heat transfer surfaces show that large heat losses occurred mainly through the surfaces of the window soffits, where there is no thermal insulation layer (Figure 2, a). As evidenced from the calculation of a wall with additional insulation made of material with a thermal conductivity coefficient of λ = 0.05 W/m°C, placed on all vertical and horizontal window opening soffits (Figure 2, b), a more favorable temperature distribution was observed in the wall structure (Figure 3). All wall surfaces recorded a temperature of at least 15.91 °C, which eliminates condensation and does not impair the performance of the exterior envelope.

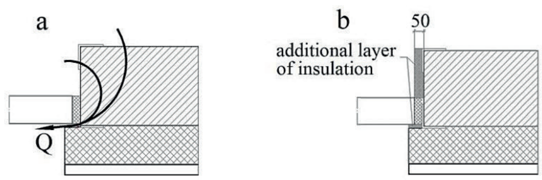

Figure 2. Window slopes surfaces: a - without thermal insulation; b - with thermal insulation

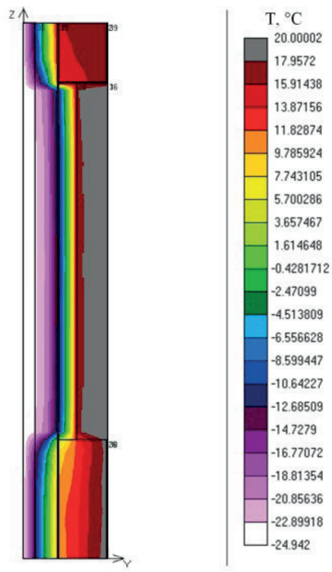

Figure 3. Temperature distribution on the inner surface of the insulated window lining along the X axis

As can be seen from Table 2, the value of total heat loss through the walls of aerated concrete blocks with insulated window soffits is 113.55 W, which is 72% of the heat loss in the wall without additional insulation of window soffits.

The heat losses through the window and the inner surface of the wall are reduced by 5-12%.

Table 2. Heat loss through the walls of aerated concrete blocks with insulated slopes of window openings

Heat loss in different areas of the wall, W/ %		
On the inside surface	On window jambs	On windows
36,41/32	7,52/7	69,62/61

It should be noted that the total heat losses through the enclosure, obtained by numerical calculation, exceed the heat losses determined by the approximate method by only 10%, which makes it possible to use an approximate method of assessing the thermal efficiency of the enclosing structure, provided that the areas with higher heat losses are insulated.

The TEPL computational complex allows to estimate correctly the heat losses through the enclosing structures and to obtain the reduced heat transfer resistance R_{red}, considering the heat flows through all surfaces of the structure, including the presence of "cold bridges".

The results of three-dimensional calculations of temperature fields of hinged ventilated facades have shown that the elements of fastening contained in their structures in the form of steel brackets and anchors, which are "cold bridges", significantly reduce the coefficient of thermal homogeneity of such systems. The study of the effect of the structural solution of hinged facades on their thermal efficiency, in terms of the material of the substructure fastening elements and their location in the outer enclosure system, was conducted on the samples of two structures: with flexible and rigid ties of cladding fastening. As a result of numerical analysis, it was found that the system on flexible links, in which the bearing brackets are installed in the floor of the building, and the insulation is attached to the wall with threaded anchor studs, has a greater heat transfer resistance (R_{red} = 1.352 m^2°C/W) than the system with rigid ties (R_{red} = 1.199 m^2°C/W).

Figure 4 shows the temperature distribution in a curtain type ventilated facade with flexible links, showing areas of reduced temperatures on the wall surface around the brackets and anchor studs. Moreover, these areas are much larger at the bracket locations than at the anchor studs. This is due to the difference in the size of the sections and the physical and mechanical properties of the fasteners

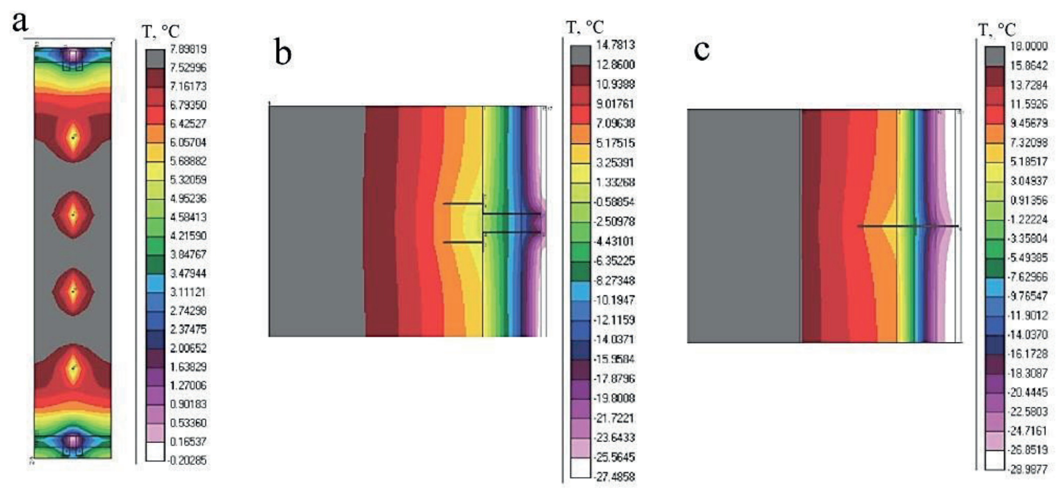

Figure 4. Temperature distribution in the structure of the curtain-type ventilated facade: a - along the facade plane; b - along the horizontal section of the wall at the attachment point of the load-bearing bracket; c - the same at the attachment point of the anchor-threaded rod

It should be noted that it is possible to increase the coefficient of thermal homogeneity of the structure of hinged facade systems, by applying the fastening elements of the substructure made of materials with a lower coefficient of thermal conductivity. For example, replacing galvanized steel load-bearing brackets (λ = 47 W/m°C) with corrosion-resistant steel brackets (λ = 20 W/m-°C) or steel anchors with fiberglass ones, thereby reducing heat loss through these elements, which are "cold bridges" in curtain type facades.

Three options for the structural solution of the exterior walls of a residential building with precast reinforced concrete floor slabs and brick partitions were investigated using the TEPL computational complex. Three types of walls were considered:

- with a 0.51 m thick inner brick layer, insulated with 0.1 m thick polystyrene foam boards and clad with 0.08 m thick gypsum boards (type 1);
- with 0.51 m thick outer brick layer, 0.05 m thick polystyrene foam insulation and 0.08 m thick gypsum boards inside (type 2);
- 0.51 m thick solid brick walls (type 3).

The heat losses in such buildings occur on all internal surfaces of the enclosure: walls, window jambs, windows, and partitions and floors adjacent to the walls.

The heat losses through the listed surfaces of the three types of walls are shown in Table 3.

Table 3. Heat loss through brick walls

Type of wall	Heat loss in different areas of the wall, W/%				Total heat losses
	On the inside surface	On window jambs	On the windows	On partitions and ceilings	
1	50,96	27,88	106,83	14,44	200,11
2	37,71	45,76	118,86	18,92	221,25
3	137,78	46,75	114,96	39,33	338,82

Analysis of the distribution of heat flows showed that on the inner surface of the wall, the maximum heat loss occurs in the wall structure of type 3, and the minimum - type 2. The minimum heat flow through the window soffits is noted in the wall structure of type 1, and these flows are almost equal for types 2 and 3. Heat fluxes through the partitions and floors differ slightly for the walls of types 1 and 2, and for the walls of type 3 it is 2.1-2.7 times more. Heat losses through windows in the walls of the considered types differ not more than by 11%. It should be noted that heat losses through the internal surface of the wall in the total heat flow amount from 17% for a wall of the 2nd type to 41% for a wall of the 3rd type. Window jambs in the walls of the 1st and 3rd types lose up to 14% of heat, and in the wall of the 2nd type these losses make up to 21% of the total heat losses. Heat losses through the partitions and ceilings are insignificant. Their share in the total heat losses is 7% for the walls of the 1st type, 9% for the walls of the 2nd type and 12% for the walls of the 3rd type. Almost a half of all the heat losses in the walls of 1st and 2nd types account for windows, and in the 3rd type wall only one third of the heat energy is lost through the window. Total heat losses in the walls of types 1 and 2 are 1.5-1.7 times less than in the wall of type 3, respectively.

For the considered brick wall structures the heat transfer resistance values were determined taking into account the heat losses on the following heat transfer surfaces: internal wall surfaces R_1; internal surfaces and window jambs R_2; internal surfaces, window jambs and adjoining partition and floor structures R_3, as well as the total resistance R_{red}.

Numerical analysis of the thermal efficiency of the brick walls considered using the TEPL computational complex showed that if we do not take into account the heat losses through the window apertures, the resistance value on the inner wall surface R1 may be greater than the conventional resistance R, as it takes place in the walls of the 2nd and 3rd types. This is explained by the effect of temperature increase on the inner surface of the wall as you approach the window. Such excess of heat transfer resistance R1 over heat transfer resistance R is 1.3 times for a wall of type 2 and 1.1 times for a wall of type 3. The walls of types 1 and 2 have heat transfer resistance more than required, which confirms the inadmissibility of using the heat transfer resistance without taking into account the heat losses on the slopes of window apertures in the design of exterior walls with windows. According to Table 4, heat transfer resistance values R_2 and R_3 are 2.2 and 2.7 times lower than the conventional resistance value R respectively for the first type wall, and 1.7 and 2.1 times lower for the second type wall. Despite the small difference in resistance R_2 and R_3 for the walls of types 1 and 2, they differ significantly from the resistance R. At the same time, compared to the required resistance, these resistances are 1.3 and 1.7 times lower, respectively.

Table 4. The heat transfer resistance of brick walls

Wall type	Heat transfer resistance, $m^2 \cdot °C/W$				
	Nominal resistance *R*	On the inside surface R_1	On interior surfaces and window jambs R_2	On interior surfaces, soffits, partitions and slabs R_3	Total actual one R_{red}
1	3,368	2,320	1,490	1,267	0,804
2	2,368	3,134	1,414	1,154	0,717
3	0,788	0,858	1,641	0,525	0,475

4. CONCLUSIONS

According to the results of numerical analysis of exterior walls with thermal inclusions, it can be concluded that the determination of the reduced heat transfer resistance of such structures by approximate methods leads to unacceptable errors affecting their operational reliability. The actual heat transfer resistance of heterogeneous external walls with windows and thermal inclusions should be determined on the basis of a numerical calculation of the three-dimensional temperature field. Such calculation allows considering all heat losses through the enclosure: windows and their soffits, partitions and floor structures adjacent to walls, as well as heat conductive inclusions in the form of brackets, anchors and other fastening elements, which are "cold bridges" in complex facade systems, which was confirmed by the present research using the TEPL computing complex. The verification of the TEPL computational complex is confirmed by numerous studies of the thermal efficiency of various enclosure structures, the results of which were compared with experimental data and the results of numerical calculations in other computational complexes [19, 20].

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