The thermal and physical aspects of designing facade heat insulation at capital repairs and reconstruction of civic buildings

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Abstract. The brief analysis of civic buildings condition has been presented in this paper. It has been demonstrated that at present the housing stock doesn’t meet the up-to-date heat engineering, energy saving and energy performance requirements. To create the necessary indoor climate of living accommodations and to provide the comfortable living environment, most of civic buildings, built at different times, are in need of large-scale reconstruction. The leading role in solving these problems is assigned to capital repairs. For its satisfactory implementation an integrated approach to repairs and construction works with the use of up-to-date energy-efficient technologies and materials is needed. The efficient heat insulation of enclosing structures should be preceded with professional engineering survey of structures and with providing the scientifically-grounded recommendations, based on present-day scientific achievements in this sphere, for the subsequent making of design specification. It has been pointed out that the economic and processing efficiency of the selection and installation of heat insulation can be achieved only by means of scientific approach and the knowledge of physical and chemical processes and phenomena, taking place in enclosing structures under the influence of internal and external operational environment.

Key words: housing and utility sector, housing stock, civic buildings, enclosing structures, capital re-pairs, energy efficiency, energy saving, heat insulation, heat transfer, heat conductivity, convection, radiation, heat flux, heat-transfer resistance of an enclosing structure.

1. Introduction
Nowadays, in order to provide the comfortable living environment and comply with the requirements of improving the energy efficiency, energy saving, operational reliability and architectural expressiveness of civic buildings, the special norms are specified for these buildings. Meeting these requirements is the issue of national importance in terms of construction sector and housing and utility sector of Russia [1].

At present the capital housing facilities stock make up over 26% of the total amount of the Russian economy’s funds, most of it presented by civic buildings. About 20 mln of housing stock units, with total area about 3 bln m², consume over 20% of energy resources of the country [2]. The yearly turnover in the sphere of housing and utilities sector is over 4,1 tln rubles and makes up more than 5,7% gross domestic product of Russia. Nevertheless, it is the most problematic branch of economy. The depreciation of its fixed assets is over 60%, and according to some indices even higher [3].
Due to the fact that the state of housing and utility complex directly determines the level of the country's welfare, the sector faces a very acute problem of finding a way out of the critical situation. Over the past few decades, during which the sector has been constantly reformed, numerous legislative and regulatory legal acts in this sphere have been developed, including the «Strategy of Housing and Utilities Sector Development in the Russian Federation for the Period up to 2020», adopted on January, 26, 2016 [4]. The development of this strategy intended improving the comfort of the living environment, modernization and increasing the energy efficiency of buildings and constructions, switching to the principles of using advanced and efficient materials and technologies in construction and modernization of communal infrastructure facilities and housing stock, availability of apartments in multi-apartment residential buildings for incapacitated persons and other people with limited mobility [5].

But due to the fact that the approaches specified in the strategy, are mostly of subjective nature, the efficiency of its implementation is far from what was expected. For the satisfactory performance of tasks, faced by this sector of industry, it is necessary to carry out a number of measures, taking into account its objective state. The examples of the domestic experience of the past clearly demonstrate the possibilities of using the little-known and unconventional mechanisms and technologies. The work [6] elaborates on the topics, which are rather urgent for implementing reforms in urban housing and utilities sector.

2. The main part

The civic buildings, which are under construction at the moment, mostly comply with the requirements of energy performance. As for the other buildings, built at different times, most of them are in need of large-scale modernization [7]. A special role in this process is played by capital repairs. But the program of capital repairs suggested by the Ministry of Housing and Building, turned out to be a politically charged material for various un economical ventures [8]. The program of capital repairs, as the author notes, should be considered not only in terms of social initiatives, but also of the design terminology. It means that not only the sources and order of financing should be discussed, but, first of all, such basic elements as the state of housing stock, the further use of land resources and faulted facilities. An important role in this is played by preventive measures – the engineering survey of the housing stock, certification of buildings and forming on their basis the plans of capital repairs conduct. The key element in solving this problem is the availability of highly-qualified specialists. Taking these factors into account would allow achieving the desired efficiency in carrying-out capital repairs and, first of all, by means of improving the level of repair and construction industry itself, by basing it on the results of professional engineering survey of buildings before reconstruction [9]. To solve this problem an integrated approach to building and repair works technology is needed, with the use of up-to-date energy-saving technologies and differing from the traditional, conventional ways of organizing construction and repair operations [10].

The experience of carrying-out capital repairs has shown that dealing with fragmentary, random or local problems didn’t help solving the global problem of reducing the excessive energy consumption of constructions. This resulted only in the extra costs for these works; and the ageing of housing stock and its insufficient repairs only increased the amounts of hazardous dwellings and dilapidated housing and reduced the comfort level [11].

At carrying out capital repairs, apart from providing the required parameters of the indoor climate and service reliability, a special role is assigned to improving the energy performance and energy saving of the repaired buildings. The main tool of implementing this task is the outer enclosing structures [12]. Since the enactment of the Federal Law № 261-ФЗ «About energy saving and energy efficiency improvement … » [13], virtually all regions of Russia have started activities in carrying out capital repairs of outer enclosing structures of all types of buildings as part of implementation of the requirements under this law. But the main efficiency indicators of construction and repair works were the number of repaired houses and the amount of cash disbursement. The issues of quality and durability of facades heat insulation were relegated to the background, and the scientific justification for performing these works was not done at all. The performance of repair works must be preceded with the
professional and detailed engineering survey of structures and with providing the scientifically-grounded recommendations, based on up-to-date scientific achievements in the sphere of enclosing structures heat insulation, for the subsequent making of design specification. But the financing of such survey works have always been a great problem [14].

Nevertheless, the conduction of works in making the efficient facade heat insulation requires serious scientific approach with the purpose of providing the economic and processing efficiency of its selection and installation. It should be borne in mind that the direct source of innovative and groundbreaking technologies, including those in construction sector, is the applied and fundamental scientific research [15].

Enclosing structures, exposed to the action of external and internal operational environment, are a complex thermodynamic system, subject to physical and chemical laws, processes and phenomena. So, its thermal-physical properties can be efficiently managed only on the basis of the scientific approach. This becomes especially important when it comes to using advanced building technologies, materials and heat-insulation systems [16].

The durability of enclosing structures, especially their thermal-physical properties, are greatly influenced by the climatic conditions: atmospheric precipitations, daily and seasonal temperature fluctuations, wind loads, solar radiation, biocorrosion processes, as well as the processes and phenomena within the constructions, caused by these conditions. The influence of these factors results in the reduction of service reliability of both the enclosing structures themselves, and of the building in general. In the course of time, their thermophysical properties considerably deteriorate as well [17].

An exterior enclosing structure is a phase contact area of the interaction between the cold external and the warm internal operational environment. Both on the surfaces of this contact area and within it the new processes and phenomena take place, which considerably influence the quality of heat insulation, the indoor climate and the service reliability and durability of the building [18]. So, the exterior enclosing structures of civic buildings must meet a number of requirements. They should be low-cost in construction and operation, sturdy and durable, should fulfill their functional purpose, providing the energy efficiency of the building with the required indoor climate and architectural expressiveness. This paper considers the heat transfer processes, taking place in the enclosing structures of buildings.

The sense of using thermal insulation consists in minimizing the heat exchange with the environment, which results in reducing the heat energy losses and cutting costs for heating. Thermal insulation has low heat conductivity and reduces heat transfer by means of heat conduction and radiation. Applying heat-insulating coatings on the surface of walls increases the heat transfer resistance of the structure in general; this, in its turn, reduces the heat flux from the structure to the environment (heat losses). At this, the heat-transfer resistance of the structure is directly proportional to the insulating layer thickness. But there is also such concept as critical insulation thickness – the thickness of insulation, over which the increase of insulation thickness doesn't cause any substantial reduction of heat losses and is economically unviable.

Following from the conditions of outer wall’s operation, the heat within wall structure is moved from the warm inner surface to the cold external surface under the action of temperature gradient. In classical thermodynamics this phenomenon is called heat transfer and is performed by means of three ways of heat exchange: heat conductivity, convection and emission (radiation) [19].

Heat conductivity is the main thermal characteristic of any material. In the enclosing structures of buildings heat exchange is carried out mostly by heat conductivity. The process of one-dimensional steady-state heat conduction in homogeneous material is described with Fourier equation:

\[
qT = -\lambda \frac{dt}{dx},
\]  

where: \(qT\) – surface density of heat flux, passing through the plane, perpendicular to the heat flux, \(W/m^2\); \(\lambda\) – heat conductivity coefficient of the material, \(W/m/°C\); \(t\) – temperature, which alters along the \(x\) axis of heat flux, \(°C\).
Heat conductivity coefficient $\lambda$ is one of the basic thermal characteristics of any heat-insulating materials. As follows from the equation, the material’s heat conductivity is the measure of heat, conducted by the material, which is numerically equal to the heat flux, passing through 1 m$^2$ area of the material, perpendicular to the heat flux direction, at temperature difference between the inner and outer surface equal to 1°C. The higher is the $\lambda$ value, the more intensive is the heat conduction process. That’s why the special heat-conductivity requirements are specified for heat-insulating materials; $\lambda$ for these materials should be below 0.3 W/m·°C. The heat conductivity of a material at its constant density and structure can be influenced by a number of physical and chemical factors and phenomena. The most significant of them are humidity and structure can be influenced by a number of physical and chemical factors and phenomena. The most significant of them are humidity and structure can be influenced by a number of physical and chemical factors and phenomena.

Another way of heat exchange in enclosing structures is convection. At different temperature values of the inner and outer surface of the wall and the circumambient air, convective heat exchange takes place - the combined convection and heat conductivity process at the surface of the wall [21]. Convection can be natural and forced. Natural convection occurs due to the temperature difference between the wall surface and the circumambient air. Forced convection is created by means of various ventilation systems. Convection plays an important role in creating the comfortable indoor climate [22]. The value of convective heat flux is determined through the Newton equation:

$$q_k = \alpha_k (t_a - \tau),$$

where: $q_k$ – heat flux, W, transferred by convection from the flowing air to the surface or vice versa; $t_a$ – air temperature at the wall surface, °C; $\tau$ – temperature of the wall surface, °C; $\alpha_k$ – convective heat-transfer coefficient on the wall surface, W/m$^2$·°C.

The convective heat-transfer coefficient is a physical value, numerically equal to the amount of heat, transferred from the ambient air to the wall surface by means of convective heat exchange at temperature difference between air and surface equal to 1°C.

The third way of heat transfer is radiation or radiative heat exchange, which plays an important role in heat exchange between the inner surfaces of enclosing structures and the heating equipment. The intensity of heat transfer between surfaces by means of radiative heat exchange can be determined in simplified form by the temperature difference between these surfaces:

$$q_r = \alpha_r (T_1 - T_2),$$

where: $T_1$ and $T_2$ – temperature of surfaces, participating in radiative heat exchange, °C; $\alpha_r$ – radiant heat transfer coefficient on the wall surface, W/m$^2$·°C.

The characteristic of heat transfer process concerning the enclosing structures of buildings and constructions is a heating-performance coefficient, known as heat-transfer resistance of an enclosing structure and characterizing the level of heat-insulating properties of enclosing structures [23]. The higher is the heat-transfer resistance of an outer wall, the better is its heat-insulating ability, i.e. the lesser is the amount of heat transferred through it, and, consequently, the lesser are the heat losses. Heat-transfer resistance is measured in m$^2$·°C/W and is denoted as $R$. The physical significance of its numerical value can be explained from two perspectives. In the first case the numerical value of heat-transfer resistance shows the surface area in m$^2$, through which the heat flux of 1 W passes at temperature gradient at the surface equal to 1 °C. In the second case the numerical expression of $R$ shows which temperature gradient in °C at the inner and outer surface of the enclosing structure would provide its thermal protection at the heat flux 1 W, passing through 1 m$^2$ of this structure's surface. Speaking about the heat-transfer resistance it's necessary to understand two of its elements: total heat-transfer resistance of the structure $R_o$ and thermal resistance of the structure $R_k$. 


R_o is determined with the sum of the thermal resistance of the structure R_o, equal to the sum of its layers' thermal resistances (R_1 + R_2 + R_3 + ⋯ + R_n), and heat-transfer resistances of the near-wall air layers at the inner and outer surfaces of the structure R_i and R_o:

\[
R_o = R_k + R_i + R_o = (R_1 + R_2 + R_3 + \cdots + R_n) + R_v + R_o, \text{ m}^2{\cdot}^\circ\text{C}/W, \tag{4}
\]

The thermal resistance of homogeneous layers is determined by the formula:

\[
R_n = B_n/\lambda_n, \text{ m}^2{\cdot}^\circ\text{C}/W, \tag{5}
\]

where: \( B_n \) – thickness of \( n \)-layer in m; \( \lambda_n \) – heat conductivity coefficient of the material of \( n \)-layer, W/m{\cdot}°C.

The heat-transfer resistance of near-wall air layers is determined by the formulas:

\[
R_v = 1/\alpha_v \quad \text{and} \quad R_o = 1/\alpha_o, \tag{6}
\]

where: \( \alpha_v \) and \( \alpha_o \) – heat conductivity coefficients of the inner and outer near-wall air layers, respectively, W/m\(^2\){\cdot}°C.

Due to the fact that the surface of real enclosing structures can have dissimilar temperatures because of their inhomogeneous structure, for practical calculations a concept of the «corrected value of heat-transfer resistance of the enclosing structure» – \( R_{pr} \) was introduced, which denotes the heat-transfer resistance of a one-layer enclosing of the same area, which the heat flux, similar to the one in the real structure, of the same temperature difference between the internal and external air, passes through [24]. It is determined as the weighted-average in area \( R_o \) value, with account of \( R_o \) of all the nonuniform parts of the structure:

\[
R_{pr} = (R_{o1} \cdot F_1 + R_{o2} \cdot F_2 + R_{o3} \cdot F_3 + \cdots + R_{on} \cdot F_n)/(F_1 + F_2 + F_3 + \cdots + F_n), \tag{7}
\]

or

\[
R_{pr} = (t_v - t_o)/Q/A, \tag{8}
\]

where: \( Q \) – heat flux, passing through the structure (or its part), W; \( A \) – area of the structure (or its part), m\(^2\).

Expression \( Q/A \) is the averaged density of the heat flux, passing through the averaged are of an enclosing structure, i.e.:

\[
q^{pr} = \frac{Q}{A} \quad \text{or} \quad q^{pr} = \frac{(t_v - t_o)}{R_{o}^{pr}}, \tag{9}
\]

At making facade heat insulation with the use of efficient insulating materials the role of heat-conducting inclusions of the enclosing structure is minimized, and can be neglected [25]. Such part of the outer wall is characterized with the relative heat-transfer resistance \( R_{o}^{usl} \). By its value we can judge about the heat transfer-performance uniformity of the enclosing structure through heat transfer performance uniformity factor \( r \). It is the ratio of the corrected heat-transfer resistance of the structure to the relative heat-transfer resistance of its certain part:

\[
r = \frac{R_{o}^{pr}}{R_{o}^{usl}}, \tag{10}
\]
This coefficient is always less than 1. In the practice of using facade heat insulation it is necessary to try to use its functional capacities in full. With that, the technological uniformity coefficient should tend to 1. Apart from solving the problem of heat-protective indices, it is of significant economic importance at determining the cost of heat insulation.

An important measure, associated with the corrected heat-transfer resistance is the heat-conductivity coefficient of the outer enclosing structure – the value, reciprocal to:

\[ K = \frac{1}{R_{pr}}, \]

which is equal to the heat flux density, passing through the enclosing structure, at the temperature difference on its surfaces of 1°C. Hereof it follows, that the heat flux \( q \), W/m², passing through the enclosing structure by means of heat transfer, is equal to:

\[ q = K \cdot (t_v - t_n). \]

According to the requirements of SNIP 23-02-2003 «Buildings Heat Insulation» [26] the actual value of \( R_{pr} \) of the structure should not be less than the heat-transfer resistance, which provides the standard value of temperature gradient \( \Delta T \) between the indoor air temperature \( t_v \) and the temperature of the inner surface of the enclosing structure \( t_n \). This sanitary requirement is expressed through condition:

\[ R_{pr} \geq n \cdot \frac{t_v - t_n}{\Delta T} \cdot \alpha_v, \]

where: \( n \) – coefficient, taking into account the arrangement of the enclosing structures' outer surface towards the outdoor air; \( t_n \) – design outdoor air temperature in the cold season, °C.

At selecting material for heat-insulating and protective layer it is necessary to keep in mind that the proceeding of the above-mentioned heat-transfer processes is greatly influenced by the humidity conditions of the internal volume of the building and of the enclosing structures material. Ignoring this parameter at the design stage is a widespread mistake, which can reduce the functional and economic efficiency of façade systems to minimum [27]. The increase of humidity deteriorates the heat-saving properties of enclosing structures due to the increase of materials’ heat conductivity coefficient, which in its turn results in the increase of heat losses and power consumption for heating. In this regard it is essential to determine in every particular case the ways of moisture penetration into the enclosing structures and to take measures for their waterproofing. This is especially important at the reconstruction of old housing stock with various extent of wear. The errors or over-optimism in the use of waterproof and water-repellent plastering or protective coatings at façade repairs have in many cases resulted in the aggravation of the already adverse conditions of the indoor climate [28].

The humidification of the indoor air and of the enclosing structures’ materials is inevitable and has an adverse effect on sanitary and performance characteristics. Firstly, there are no absolutely solid and waterproof natural materials. Secondly, the outer enclosing structures should «breathe», so they should be vapor-permeable. As for such apparent sources of moisture as service, telluric and atmospheric moisture, the enclosing structures can be protected from them at the work execution stage. But in a structure in service the inadvertent natural processes take place, which are accompanied with humidification and can’t be avoided. It is service moisture and hydrosopic moisture. The saturation of enclosing structures with service moisture is caused by internal sources, which can’t be removed at the normal building operation. It is not only household and industrial moisture and moisture from environment control systems. Moisture is contained in the exhaled air as well. Under the manometric pressure the vaporous moisture moves outward, filling the pores of material. The ability of materials to adsorb moisture from the air results in the accumulation of hydrosopic moisture in its pores. Depending on the type and thickness of the outer wall it condensates on its inner surface or inside the wall, turning into condensed moisture.
Temperature drops cause the phase transition of water to the ice with the considerable increase of volume. This, in its turn, results in the formation of internal stresses in the material of the enclosing structure, which cause mechanical corrosion. At the rise of temperature the reverse phase transition of ice to water takes place. The internal stresses are released, leaving a network of microfractures from the previous freezing in the bulk of the structure. Then the process is repeated, and each new cycle contributes to the deeper penetration of moisture, and consequently, to even stronger deterioration. The larger is the difference between the seasonal and daily temperature fluctuations, the more frequent and intensive these processes are (the frost deterioration mechanism). The permanent action of alternating load on the dampened wall results in its intensive destruction. So, at selecting materials for façades heat insulation it is necessary to take into account their vapor permeability – i.e. the ability of materials and the structure, made of them, to let water vapor through it, and the vapor penetration – the process of vapor passing though material or enclosing structure.

Vapor permeability $\mu$ depends on the physical properties of material and reflects its ability to let the diffusing water vapor through it. It is numerically equal to the diffusion water vapor flux, mg/h, passing through $m^2$ of the area, perpendicular to the flux, at the partial pressure gradient of water vapor along the flux, equal to 1 Pa/m.

3. Conclusions
So, all the above-mentioned details allow us making a conclusion that taking into account the heat-transfer processes in enclosing structures and the conditions of their proceeding would allow efficiently designing heat insulation with the least possible costs. The real improvement of civic buildings’ energy performance at installing façades heat insulation is possible only by using scientific approach in solving these problems. This would allow the economically and technologically viable selection of the type of heat insulation depending on the climatic location of an object, as well as of the materials and the installation technology. The most important thing in solving these problems is to ensure that instead of thermotechnical processes and phenomena influencing the operation of outer enclosing structures, an efficiently designed structure would regulate these processes by itself.

Acknowledgments
The article was prepared within development program of the Flagship Regional University on the basis of Belgorod State Technological University named after V.G. Shukhov.

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