

Optimization of structural solutions building envelopes of industrial buildings operated in variable thermal conditions

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Abstract. The article presents the methodology of thermo-technical calculation of low-heat enclosing structures industrial buildings operated in conditions of variable thermal conditions. According to the proposed methodology, the thickness of the sandwich panel of the outer wall of the industrial building is determined on the basis of the fulfillment of energy saving conditions and the given time of room's heating. To solve the problem of unsteady heat transfer through the outer wall was applied an approximate analytical method developed by the authors of this article. The presented analytical method by choosing a building envelope allows taking into account not only heat-shielding but also the dynamic characteristics of the fence. This calculation method can be applied at the stage of developing structural solutions for the external fence and detailing of building units in this construction. The results of the heat engineering calculation of the outer wall of a production building under construction are presented as an example. Based on the presented calculation results, it becomes possible to determine the optimal thickness of the insulation layer, at which the designed enclosing structure will satisfy not only the modern requirements of thermal protection, but also provide a given time for the heating of the room.

1. Introduction

By realizing duty heating in industrial buildings both on workdays and on weekends, an unsteady heat transfer process is observed in building envelopes due to the changing temperature of the indoor air in the premises. In the process of heating the premises, carried out before the start of work of production shops, there is an increase in the temperature of the internal air from the value t_{e1} to t_{e2} . The temperature during duty heating is set from the condition for the absence of condensation on the building envelope, t_{e2} - from the condition of energy conservation. A typical graph of changes in the temperature the internal air in the production workshop on working days is presented in Figure 1.

The thermal conditions of an industrial building are characterized by four stages. At the first stage, the building is operated under conditions of on duty heating. The estimated temperature of the internal air during off-hours t_{e1} is determined from the condition that there is no condensate on the internal surfaces of the building envelope, t_{e2} - depending on the severity of physical labor according to Order Book 60. 13330.2016 "Heating, ventilation and air conditioning."



At the second stage, the heating of the room is carried out, during which the temperature of the inside air rises from value t_{e_1} to t_{e_2} .

Operation of the building during working hours is characterized by the third stage. At the fourth stage, the workshop room is cooled after completion of the work.

According to the temperature graph presented in Fig. 1 the heating of the production hall premises should not exceed 3 hours. In this connection, the enclosing structures of an industrial building must be low inertia and provide regulatory requirements for heat protection.

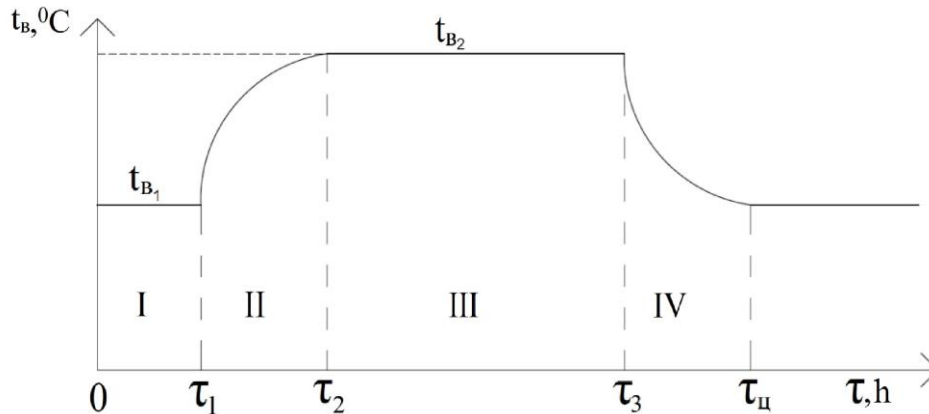


Figure 1. Graph of the change in temperature of the internal air in the production hall during a single shift work

Due to the complexity of mathematical modeling the processes of unsteady heat transfer in building envelopes are less studied. The regulatory literature provides an engineering methodology for calculating the heat resistance of buildings with periodic fluctuations in the temperature of the outside air. The solution of problems of unsteady heat transfer during intermittent heating is considered in works [1–6].

In the works [1, 2] analytical solutions to the problem under consideration in enclosing structures in the absence of on duty heating were obtained. The initial wall temperature was taken equal to the outdoor temperature. The results of solving the unsteady conjugate heat transfer problem in the premises of buildings by numerical methods are given in works [3–9].

The analysis of the above mentioned works showed the absence of an engineering methodology for thermotechnical calculation of the building envelope, operated in conditions of variable power of the heating system.

Currently, in connection with the implementation of modern requirements for thermal protection of industrial buildings, wall and roof sandwich panels are widely used in new construction.

2. Mathematical modeling of the process of unsteady heat transfer the outer wall

Let us consider the task of determining the optimal thickness of a wall sandwich panel, based on the conditions of energy conservation and a given time for warming the production workshop.

Schematization of the heat transfer process in the outer wall of an industrial building made of sandwich panels is shown in Figure 2. The solution of this problem was carried out under the following assumptions:

- heat transfer is carried out only in the direction of the x axis;
- condition of the ideal contact between the layers was considered;
- the specific heat flux coming from the heating devices during the heating of the outer wall was assumed to be constant;
- at the initial moment of time, the temperature distribution in the thickness of the outer wall was assumed to be correspond the stationary mode during duty heating.

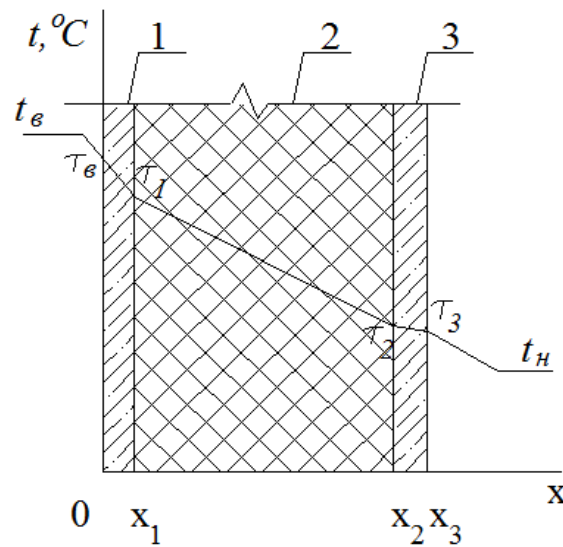


Figure 2. Schematization of the heat transfer process in a sandwich panel: 1, 3 – profiled galvanized steel sheets, $\delta_1 = \delta_3 = 0,001$ m; $\rho_1 = \rho_3 = 7800$ kg/m³; $\lambda_1 = \lambda_3 = 50$ W/(m·°C); $c_1 = c_2 = 0,48$ kJ/(kg·°C); 2 – basalt mineral wool, $\rho_2 = 120$ kg/m³; $\lambda_2 = 0,036$ W/(m·°C); $c_2 = 0,84$ kJ/(kg·°C)

Under the above mentioned assumptions, the mathematical formulation of the consideration problem was written in the form of the following system of differential equations:

$$-\lambda \frac{\partial t_1}{\partial x} = q; x = 0; \tau > 0 \quad (1)$$

$$\frac{\partial t_1}{\partial \tau} = a_1 \frac{\partial^2 t_1}{\partial x^2}; 0 \leq x \leq x_1; \tau > 0 \quad (2)$$

$$\frac{\partial t_2}{\partial \tau} = a_2 \frac{\partial^2 t_2}{\partial x^2}; x_1 \leq x \leq x_2; \tau > 0 \quad (3)$$

$$\frac{\partial t_3}{\partial \tau} = a_3 \frac{\partial^2 t_3}{\partial x^2}; x_2 \leq x \leq x_3; \tau > 0 \quad (4)$$

$$\lambda_1 \frac{\partial t_1}{\partial x} = \lambda_2 \frac{\partial t_2}{\partial x}; x = x_1 \quad (5)$$

$$t_1 = t_2 = \tau_1; x = x_1 \quad (6)$$

$$\lambda_2 \frac{\partial t_2}{\partial x} = \lambda_3 \frac{\partial t_3}{\partial x}; x = x_2 \quad (7)$$

$$t_2 = t_3 = \tau_2; x = x_2 \quad (8)$$

$$-\lambda_3 \frac{\partial t_3}{\partial x} = \alpha_n (\tau_3 - t_n); x = x_3 \quad (9)$$

$$t_i / \tau = 0 = f_i(x); i = 1 \div 3 \quad (10)$$

where $f_i(x)$ is the initial temperature distribution in the presence of the duty heating; t_e, t_n - air temperature inside and outside, respectively, °C; t_i - current temperatures in the layers of the outer wall, °C; a_i - thermal diffusivity of the layer material, m²/s; x_i - the distance from the inner surface to the joints of the layers and the outer surface of the wall, m; λ_i - the coefficient of thermal conductivity of the layers the outer wall, W/(m·°C); α_n - heat transfer coefficient on the outer surface of the wall, W/(m²·°C).

The exact solution to the above mentioned system of differential equations is impossible to obtain due to mathematical difficulties. Therefore, the problem was solved by an approximate analytical method, described in detail in work [6].

According to this method, the heating time of a multilayer outer wall was determined by the formula

$$\tau_n = 2 \frac{Q_n \cdot 10^3}{q_{om}} \cdot \frac{1 + 2\varphi}{1 + \varphi} \quad (11)$$

where Q_n - specific energy consumption for heating the external wall in the room's heating process,

$$\text{kJ/m}^2, q_{om} = \frac{t_{e2} - t_n}{R_0^{ycn}} - \text{specific heat flux transmitted from the heating system, W/m}^2; \varphi = \frac{\frac{1}{\alpha_n}}{\frac{1}{\alpha_n} + \sum_{i=1}^n R_i} -$$

dimensionless criterion of boundary conditions; $R_i = \frac{\delta_i}{\lambda_i}$ - thermal resistance of the i-th layer, (m²·°C)/W.

The value Q_n is determined by the formula

$$Q_n = \sum_{i=1}^n c_i \cdot \rho_i \cdot \delta_i \cdot \Delta\tau_i, \text{ kJ/m}^2, \quad (12)$$

where c_i - is the specific heat of the i-th layer of the wall, kJ/(kg·°C); ρ_i - the density of the i-th layer of the outer wall, kg/m³; δ_i - the thickness of the i-th layer of the outer wall, m; $\Delta\tau_i$ - temperature change of the i-th layer the outer wall, °C.

$$\Delta\tau_i = t_{e2} - t_{e1} - \frac{t_{e2} - t_{e1}}{R_0^{ycn}} \left(\frac{2}{\alpha_e} + \sum_{i=1}^{i-1} R_i \right), \text{ °C}. \quad (13)$$

3. Results of the calculation of the heating time the external walls and specific energy consumption

Using the above mentioned method, the specific energy consumption for heating the external walls made of sandwich panels, as well as the time of their heating was estimated.

Figures 3, 4 show the dependencies specific energy consumption and heating time on the thickness of wall panels, respectively.

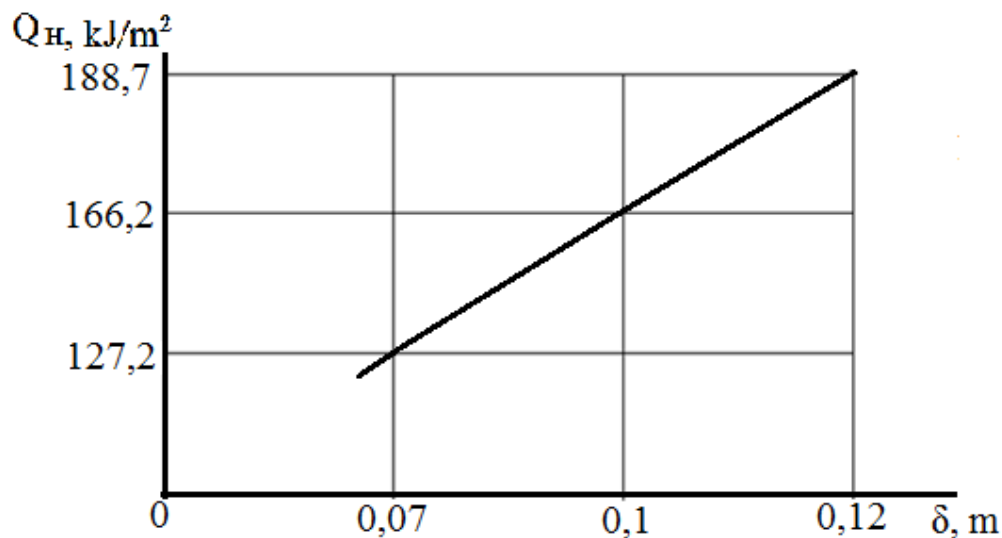


Figure 3. Unit costs dependence for the of heating wall panels on the thickness of the insulation

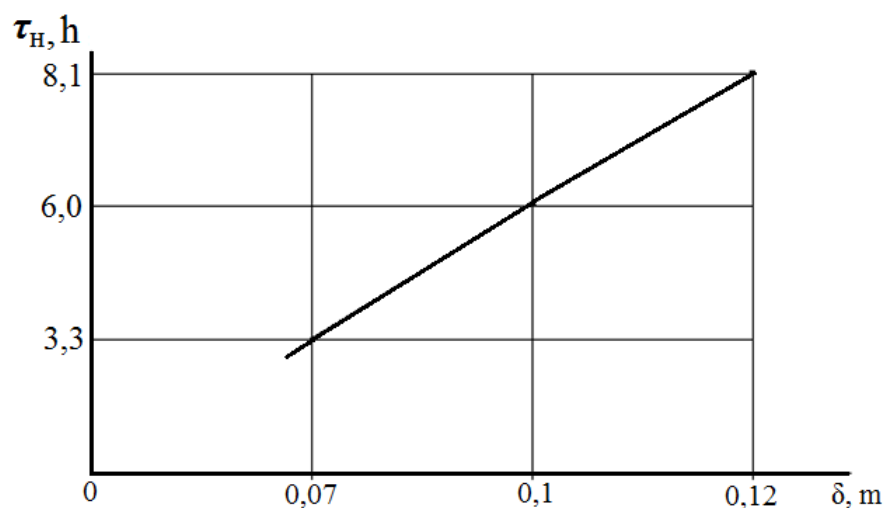


Figure 4. Heating time dependence of wall panels on the thickness of the insulation

The analysis of the calculation results showed that when the heating time of the premises of industrial buildings is from 3 to 4 hours, it is necessary to use wall panels with basalt mineral wool insulation from 70 to 80 mm thick that meet the regulatory requirements for energy saving for industrial buildings constructed in the geographical location considered in the example.

4. Discussion

Currently, by the thermal calculation of building envelopes, including the regulatory literature, special attention is paid to numerical methods for determining heat-shielding characteristics. However, it is necessary to take into account that the choice of enclosing structures is a multi-stage task that includes the development of constructive solutions with a detailed study of building units and clarification of the heat-shielding characteristics of the adopted enclosing structure.

At the stage of developing constructive solutions for the building envelope, the reduced heat transfer resistance is determined by the method of successive approximations, as a result of which the use of numerical methods implemented in software systems is not entirely convenient. From the point of view of the authors of the article, by choosing the layers of the building envelope, the designer should be able to apply analytical methods of calculation, allowing taking into account not only the

thermal, but also the dynamic characteristics of the designed fence. Determining the coefficient of thermal engineering uniformity of the outer wall, taking into account all the heat-conducting inclusions and multidimensionality, is a very difficult task when analytical methods are used. It is advisable to refine further the results obtained by the analytical method using numerical methods. Therefore, the choice of enclosing structures, depending on the stage of solving this problem, should be made with the rational use of both analytical and numerical methods of calculation.

5. Conclusion

A mathematical formulation of the problem of unsteady heat transfer an industrial building through the outer wall which is made of sandwich panels is presented.

Approximate analytical dependencies for determining the specific energy costs and the time of their heating are obtained.

According to the results of the study, the optimal thickness of the sandwich panel for an industrial building operated in conditions of variable thermal conditions should be in the range from 70 to 80 mm.

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