Features of the Heat Engineering Calculation of the Enclosing Structures Industrial Buildings Operated in a Variable Thermal Conditions

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Abstract. In recent years’ special attention has been paid to energy conservation. The need to reduce the consumption of mineral raw materials and fossil organic fuel is primarily associated with a reduction their reserves and, consequently, a constant increase in the cost. Therefore, a very actual task is to reduce the energy costs for heating and ventilation of industrial enterprises. The use of on duty heating during the non-working period can significantly increase the energy efficiency of an industrial building. On the basis the thermal regime of an industrial building, considered in the article, is shown the need to develop an engineering method for calculating the process of non-stationary heat transfer in buildings operated with a stand-by heating mode. This article presents the method of heat engineering calculation of building enclosing structures used in buildings with variable power of the heating system, which allows to determine the minimum allowable thickness of insulation from the condition of limiting the heating time of the outer wall. An example of the design calculation of the wall sandwich panel an industrial building is made. An assessment of the specific energy consumption for heating external walls was made. A study conducted by the authors, allows to determine the range of thickness the enclosing structures, operated in conditions of a variable thermal regime.

1. Introduction

Most production workshops do not work around the clock. Therefore, in single-shift or double-shift operation, there is a need to use the district heating during the non-working period. A typical graph of changes the internal air temperature in the production hall on weekdays is presented in figure 1.

The thermal regime of an industrial building is 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 is determined from the condition that there is no condensate on the internal surfaces of the building envelope, depending on the severity of physical labor according to the normative sources for heating buildings.

At the second stage, the heating of the room is carried out, during which the temperature of the inside air rises from value to. 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 figure 1 the heating of the production hall premises should not exceed 2 hours. In this connection, the enclosing structures of an industrial building must be low inertia and provide regulatory requirements for heat protection.

![Temperature Graph](image)

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

The process of heating the enclosing structures is non-stationary, which greatly complicates the method of heat engineering calculation. To assess the energy consumption for heating the building and the warm-up time of the enclosing structures, it is necessary to consider the process of non-stationary heat transfer. In work [1], using the operational method, the exact solution of the problem of non-stationary thermal conductivity of a single-layer and two-layer walls was obtained in the absence of heating on duty. When a solution was found, the initial wall temperature was taken to be equal to the outside air temperature.

An approximate analytical solution to the problem of unsteady heat transfer in a multilayer wall in the absence of heating on duty was obtained by B. A. Semenov in work [2]. In the works [3, 4, 5, 6, 7, 9, 10, 11, 12] the results of the study of the thermal conditions of rooms operated in intermittent heating conditions are presented by numerical methods.

In this connection, it became necessary to develop an engineering method for calculating the process of non-stationary heat transfer in buildings in the presence of heating on duty.

In work [8], the author’s methodology based on the use of an approximate analytical method is described in detail.

2. The method of heat engineering calculation of the exterior walls industrial buildings’ operated in the conditions of intermittent heating

According to standard sources on thermal protection of buildings the required thickness of the insulating material must be determined on the basis of the energy saving condition:

\[
R_{0}^{mp} \geq R_{0}^{tr} \cdot (m^{2} \cdot ^\circ C)/W
\]  

(1)

where \(R_{0}^{mp}\) is the reduced resistance to the heat transfer of the outer wall, \((m^{2} \cdot ^\circ C)/W\); \(R_{0}^{tr}\) – the required resistance to heat transfer of the outer wall, determined according to Order Book 50.1333.2012 by the magnitude of the degree-day of the heating period, \((m^{2} \cdot ^\circ C)/W\).

The reduced resistance to the heat of the enclosing structure is determined by the formula
$$R_0^{\alpha} = \left( \frac{1}{\alpha_6} + \sum R_i + \frac{1}{\alpha_4} \right)$$, \hspace{1cm} (2)

where \(\alpha_6\), \(\alpha_4\) – the values of heat transfer coefficients from the inner and outer surfaces, respectively, \(W/(m^2\cdot^\circ C)\), \(R_i = \frac{\delta_i}{\lambda_i}\) - the thermic resistance of the enclosing construction’s layer, \((m^2\cdot^\circ C)/W\), \(\delta_i\) - thickness of the enclosing construction’s layer, m, \(\lambda_i\) - thermal conductivity of the material of the enclosing structure layer, \(W/(m\cdot^\circ C)\).

The minimum allowable thickness of the insulation sandwich panel, presented in figure 1, determined on the basis of inequality (1), according to the formula

$$\delta_{2}^{min} \geq \lambda_2 \left( \frac{R_{0mp}}{r} - \frac{1}{\alpha_6} - R_1 - R_2 - \frac{1}{\alpha_4} \right) m \hspace{1cm} (3)$$

where \(r\) – is the coefficient of heat engineering uniformity of the wall sandwich panel, determined by the results of certification tests.

Figure 2. The wall sandwich panel’s design of an industrial building: 1, 3 – profiled galvanized steel sheets \(\delta_i = \delta_s = 0.001\) m; \(\gamma_i = \gamma_s = 7800\) kg/m\(^3\); \(\lambda_i = \lambda_s = 50\) W/(m\(^\circ\)C); 2 – basaltic mineral wool \(\gamma_2 = 120\) kg/m\(^3\); \(\lambda_2 = 0.036\) W/(m\(^\circ\)C); \(c_2 = 0.84\) kJ/(kg\(\cdot\)g).

The minimum allowable thickness of the insulation is determined from the condition of limiting the heating time the outer wall according to the formula given in [8].

According to the temperature chart the time of the room’s heating \(\tau\) heating is 2 hours.

$$\delta_{2}^{max} \geq \lambda_2 \left( \frac{2}{\alpha_4} + \frac{\lambda_2 \cdot \tau_{mp} \cdot t_{s2} - t_{h}}{\rho_2 \cdot c_2 \cdot A \cdot t_{s2} - t_{s1}} \right) m \hspace{1cm} (4)$$
where \( A = \frac{1+2\varphi}{1+\varphi} \); \( \varphi = \frac{1}{\alpha_1} + \frac{\delta_1}{\lambda_1} + \frac{\delta_2}{\lambda_2} + \frac{\delta_3}{\lambda_3} \) - dimensionless criterion of boundary conditions.

The coefficient \( A \) depends on the thickness of the insulation layer. In order to simplify the solution of the problem, its value is preset.

3. The results of heat engineering calculation the outer wall
As an example, consider the definition of the required thickness of the insulation of the outer wall of the reinforcement-welding shop of factory of reinforced concrete products. The design of this wall panel is shown in figure 2.

At degree-day of the heating period=4303.6 °C•days for the city of Samara, \( R_0^{mp} = 1.86 \) (m²•°C)/W.

The minimum allowable thickness of insulation is determined by the formula (3):

\[
\delta_2^{\min} \geq 0.036 \left( \frac{1.86}{0.88} - \frac{1}{8.7} - \frac{0.001}{50} - \frac{0.001}{50} - \frac{1}{23} \right) = 0.0703 \text{m.}
\]

Taking preliminarily \( \delta_2 = 71 \) mm, we define \( \delta_2^{\max} \):

\[
\varphi = \frac{0.0435}{0.0435 + 0.00004 + 1.97} = 0.0216; \quad A = \frac{1 + 2 \times 0.0216}{1 + 0.0216} = 1.02;
\]

\[
\delta_2^{\max} = -\frac{0.036}{23} + \sqrt{\frac{0.036^2}{23^2} + \frac{0.036 \cdot 3600 \cdot 2}{120 \cdot 840 \cdot 1.02} \cdot \frac{16 + 30}{16 - 5}} = -0.00157 + 0.1027 = 0.101 \text{ m.}
\]

By the formula (3) were determined the values \( \delta_2^{\max} \) for different values of the heating time of the external walls \( \tau_{mp}^{\tau} \). Graphically, the dependence is presented in figure 3.

![Figure 3. Dependence of the thickness of the layer basalt’s mineral wool on the heating time](image-url)
The standard thickness of basalt mineral wool $\delta^b_2$ is determined from the inequality

$$\delta_2^{\text{min}} < \delta^b_2 < \delta_2^{\text{max}}.$$ 

In this example, we accept the thickness of the sandwich panel as 80 mm.

The energy consumption for heating the outer wall is determined according to [6] by the formula:

$$Q_H = \frac{n}{\sum_{i=1}^{n} c_i \cdot \rho_i \cdot \delta_i \cdot \Delta \tau_i} \text{ kJ/m}^2$$  \hspace{1cm} (5)

where $c_i, \rho_i, \delta_i$ - specific heat, density, and thickness of the $i$-th layer the outer wall;

$\Delta \tau_i$ - temperature change of the $i$-th layer of the outer wall, °C.

We neglect the accumulation of heat from metal layers due to the high thermal conductivity of steel. With this assumption, we consider the sandwich panel as a single-layer wall. In this case, the value according $\Delta \tau_2$ to [6] is determined by the formula:

$$\Delta \tau_2 = \frac{0.5 \cdot (t_2 - t_{\text{in}})}{\frac{t_2 - t_{12}}{2R^{\text{con}}_0} \left( \frac{1}{\alpha_u} - \frac{1}{\alpha_n} \right)},$$  \hspace{1cm} (6)

where $R^{\text{con}}_0 = \frac{1}{\alpha_u} + \frac{\delta_2}{\lambda_2} + \frac{1}{\alpha_n}$ - heat transfer resistance of the external wall surface, (m$^2\cdot$°C)/W.

$$\Delta \tau_2 = 0.5 \cdot (16 - 5) \cdot \frac{16 - 5}{2 \cdot 2.38} \left( \frac{1}{8.7} - \frac{1}{23} \right) = 5.5 - 2.31 \cdot (0.115 - 0.0435) = 5.33 \text{ °C}.$$  

$$Q_H = 0.84 \cdot 120 \cdot 0.08 \cdot 5.33 = 43 \text{ kJ/m}^2.$$  

We specify the heating time of the outer wall according to [6] according to the formula

$$\tau_n = 2 \cdot \frac{Q_H}{q_{\text{con}}} \cdot \frac{1 + 2\phi}{1 + \phi} C$$  \hspace{1cm} (7)

where $q_{\text{con}} = \frac{t_2 - t_{\text{in}}}{R^{\text{con}}_0}$ - specific heat flux transmitted from the heating system, W/m$^2$.

$$q_{\text{con}} = \frac{16 + 30}{2.38} = 19.3 \text{ W/m}^2.$$  

$$\tau_n = 2 \cdot \frac{43 \cdot 10^3}{19.3 \cdot 3600} \cdot \frac{1 + 2 \cdot 0.0192}{1 + 0.0192} = 1.264 \text{ h}.$$  

**4. Discussions**

The calculation results show that the outer wall of the production building with a standard insulation thickness of 80 mm heats up in 1.26 hours. This heating time does not exceed the permissible value, which is actually for enclosing structures operated in variable thermal conditions. According to the above method, it is also possible to determine the energy consumption for heating the production building, given the geometrical dimensions of the enclosing structures.

The choice of the thickness of the insulation the enclosing structure in this case requires a reasonable approach. The graph shown in figure 3, obtained for the considered wall by calculation, allows you to select other values of the standard thickness of the basalt mineral wool layer. This is possible due to the fact that the remaining layers in the design are low inertia and practically do not accumulate heat. In addition, with increasing thickness of insulation increases the energy consumption and warm-up time of the enclosing structure.
5. Conclusions
1. The technique of heat engineering calculation of non-stationary heat transfer through building fencing structures of industrial buildings is presented.
2. The results of the heat engineering design of the exterior walls of an industrial building made of wall sandwich panels are presented.
3. The specific energy consumption for heating the outer wall in the process of the heating of reinforcement welding shop is determined.

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