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Buildings quasi-stationary thermal behavior

Квазистационарные температурные режимы ограждающих конструкций

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Key words: enclosure structure; thermal stability; energy-efficiency; average temperature; construction materials

Ключевые слова: ограждающие конструкции; теплоустойчивость; энергоэффективность; средняя температура; температурный режим; температурная волна

Abstract. The typical building constructions absorb the temperature wave caused temperature fluctuations of external air. It means this building construction has a thermal stability. Therefore, there is a reserve for warmth accumulation which can be used for decreasing of thermal losses. The developed mathematical model of temperature distribution in an enclosure structure allows estimating the cooling velocity of assorted designs of enclosure structures. And it shows the time which it is possible to turn off heating during the non-working period with maintenance required temperature condition in working period. This method allows reducing losses of heat energy considerably. It gives the chance to perform the optimum choice of periodic schedules of heating. Cost efficiency of implementation of the periodic mode of heating of the building is proved.

Аннотация. Ограждающие конструкции поглощают температурную волну, вызываемую температурными колебания наружного воздуха, т.е. конструкция обладает аккумулирующей способностью. В связи с этим возникает резерв для управления потоками теплоты, которые можно использовать для снижения тепловых потерь. Данная работа посвящена решению проблемы максимально эффективного использования энергетических ресурсов, расходуемых на отопление здания. Были выведены зависимости для определения распространения температурной волны в стене. Разработанная модель позволяет оценить скорость остывания различных конструкций стен, а также время, на которое можно отключить отопление в нерабочий период. Время зависит от аккумуляционной способности стены. Данный метод, позволяет значительно сократить потери тепловой энергии. В работе приведены экономические и энергетические последствия предложенных решений по повышению энергоэффективности конструкции и обеспечению периодического режима отопления.

Introduction

The the most effective use of energy resources is one of the important tasks of state policy in the field of energy saving for economic recovery and worthy life of the population.

It is possible to attain the economy of heat energy by applying a periodic duty of heating system for the buildings functioning only in the afternoon (sports, administrative, educational buildings, etc.).

However, it is necessary to solve a problem about optimum control of periodic duty for getting the maximum effect.

The papers deal with international research activities in the field of climate specific building design. Various comfort and energy monitoring surveys of office buildings as well as residential buildings provide substantial information about the occupants' behaviour and their needs during specific situations under different outdoor climates. This information allows summarizing basic climate dependent design principles which architects should keep in mind during the early stages of the design process. It also helps to develop strategies aiming at reducing building energy demand and at the same time consider comfort aspects [1–5].

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The papers present the results of the research into energy balance of enclosure walls depending on geometric characteristics and glazed areas of a building [6–9].

This paper show how the building automation systems (BAS) are a powerful tool for companies face some permanent or temporary changes that can occur in the surrounding environment, which can affect the welfare of users, increase the energy consumption and/or demand more financial investment to strengthen or to replace the actual systems to attend the needs of users [10–22].

However, all stated methods of management of the thermal mode have the approximate disorder nature, also nobody researched the parameter of time on which it is possible to turn off heating in the conditions of maintenance of the set level of thermal comfort indoors in working hours and economic feasibility of this method.

The purpose of this work is to develop a method of costs minimization for heating with maintains the set level of thermal comfort and optimum control of the thermal duty of the buildings functioning only in the afternoon.

Materials and Methods

The subject of the research

The subject of the research is the Federal State-Funded Educational Institution of Higher Professional Education.

The model of the studied subject is a multilayered enclosing structure. The scheme of this model is represented at the Figure 1.

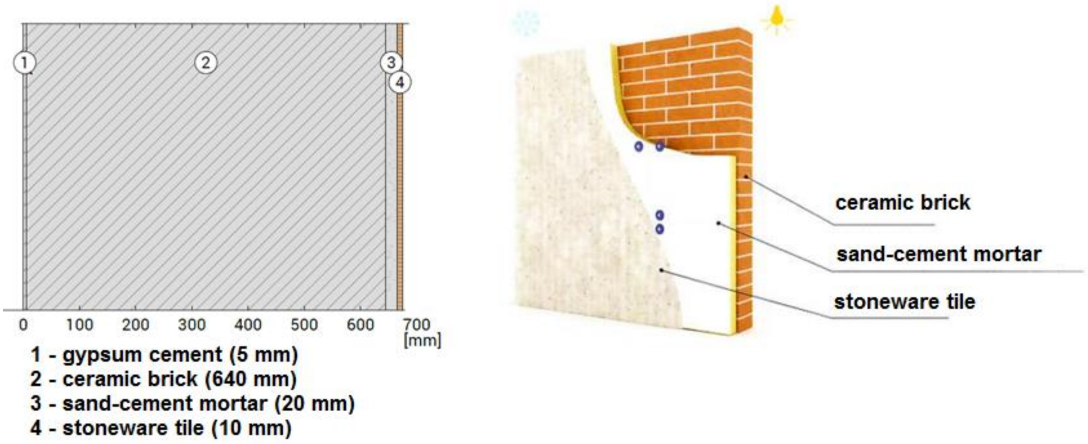

Figure 1. The scheme of multilayered enclosing structure

The characteristics of external structure of the building are presented at the Table 1.

Table 1. The Characteristic of external structure

Type of structure	**Characteristic**	**Materials**			
		gypsum cement	ceramic brick	sand-cement mortar	stoneware tile
External structure	δ, mm	5	640	20	10
	λ, (W/m^{2}·ºC)	0.35	0.47	0.025	0.8
	ρ, kg/m^{3}	1500	2000	1.25	2400
	c, J/kg·°C	840	880	1000	200

The advanced model of the studied subject is a multilayered enclosing structure. The scheme of this model is represented at the Figure 2.

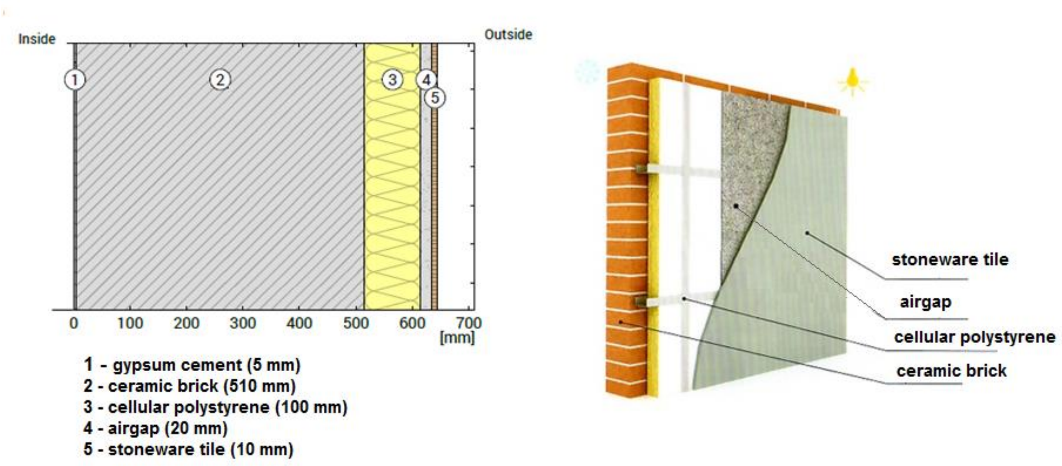

Figure 2. The scheme of advanced multilayered enclosing structure

Design structure of the advanced multilayered enclosing structure is presented at Table 2.

Table 2. The Characteristic of advanced external structure

Type of structure	Characteristic	Materials				
		gypsum cement	ceramic brick	cellular polystyrene	air gap	stoneware tile
External structure	δ, mm	5	510	100	20	10
	λ, (W/m^2·ºC)	0.35	0.47	0.033	0.025	0.8
	ρ, kg/m^3	1500	2000	100	1.25	2400
	c, J/kg·°C	840	880	1340	1000	220

Distribution of a temperature wave in a wall

The analysis of literature has shown that the one-dimensional motion of heat energy in a wall can be presented in the form of the differential equation Fourier:

$$\frac{\partial T}{\partial t} = a \cdot \frac{\partial^2 T}{\partial x^2}, \tag{1}$$

where T – temperature in any part of a body, °C;

t – time point, s;

x – wall coordinate, m;

a – internal coefficient of heat transfer, W/ (m^2·°C).

The initial differential Fouriers equation is replaced by an integral relation:

$$\frac{d}{d\tau}\int_0^\infty T(\tau,\xi)\,d\xi = -\left(\frac{\partial T}{\partial \xi}\right)_{\xi=0}. \tag{2}$$

where $\tau := \frac{t}{t_0}, \xi := \frac{x}{\sqrt{at_0}}, h := \alpha\sqrt{\frac{t_0}{\lambda\rho C_p}}$

Distribution of temperature is defined in the form of:

$$T(\tau,\xi) = a(\tau)e^{-\xi} + b(\tau)e^{-2\xi} \tag{3}$$

The time-temperature transformation follows the sine theorem:

$$\theta(\tau) = a\sin 2\pi\tau, \tag{4}$$

Then we receive such solution of the differential equation and final expression for definition wall temperature in any part of enclosure structure at any moment:

$$T(\xi,\tau)=\left\{2a\sin 2\pi\tau-\frac{3}{2}\pi a\cos 2\pi\tau\right\}e^{-\xi}+\left\{\frac{3}{2}\cdot\pi a\cos 2\pi\tau-a\sin 2\pi\tau\right\}e^{-2\xi}. \qquad (5)$$

Schedules of dependence of temperature from time for different points of a wall are submitted in Figures 3–4.

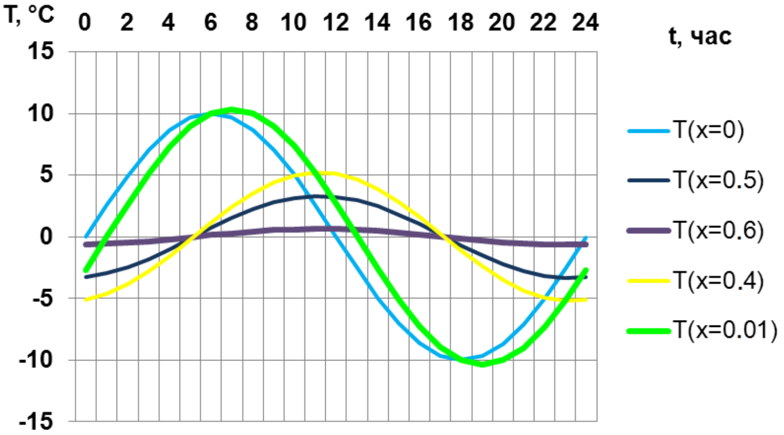

Figure 3. Distribution of temperature in a wall in time for a wall No. 1

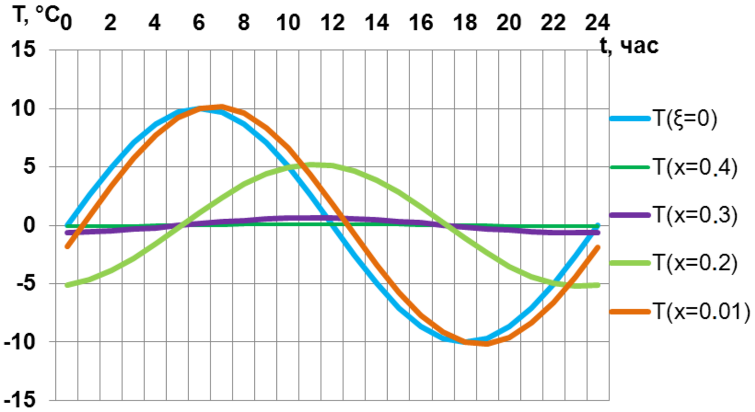

Figure 4. Distribution of temperature in a wall in time for a wall No. 2

From this schedules it is known that the temperature amplitude of oscillations decay in the thickness of structure. There is a phase shift of temperature oscillations in a structure, or in other words the delay of these oscillations in time.

Graphically it can be presented so in a Figures 5–6.

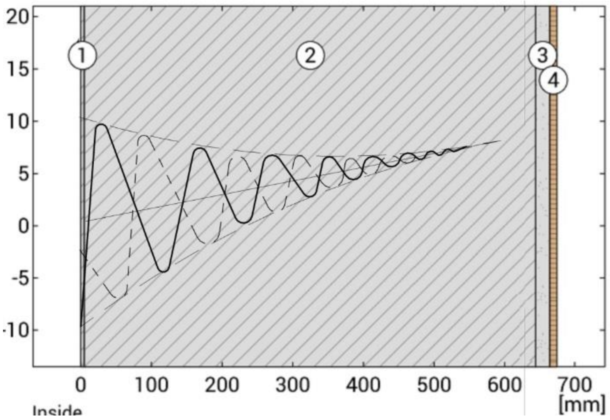

Figure 5. The schedule of temperature fluctuations in a wall No. 1

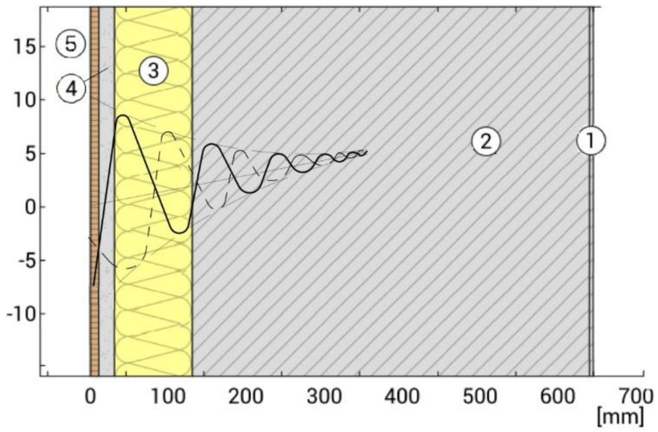

Figure 6. The schedule of temperature fluctuations in a wall No. 2

In the structure with a low heat transfer resistance the temperature fluctuations penetrate through the walls, but in energy efficient structure the temperature fluctuations are localized at a cold side of a wall.

Assessment of thermal stability of a design

We determined the average stationary temperature for each type of wall by the formula:

$$T_\infty = \frac{\alpha_c \cdot T_c + \alpha_h \cdot T_h \cdot \left(1 + \alpha_c \cdot \int_0^\delta \frac{dx}{\lambda(x)}\right)}{\alpha_c + \alpha_h \cdot \left(1 + \alpha_c \cdot \int_0^\delta \frac{dx}{\lambda(x)}\right)} + \frac{\alpha_c \cdot \alpha_h \cdot (T_h - T_c)}{\alpha_c + \alpha_h \cdot \left(1 + \alpha_c \cdot \int_0^\delta \frac{dx}{\lambda(x)}\right)} \cdot \frac{1}{\delta} \cdot \int_0^\delta \frac{(\delta - \xi) d\xi}{\lambda(\xi)} \qquad (6)$$

where α_c = 23 W/(m²·˚C) – outer surface heat transfer coefficient of the building envelope;

α_h = 8.7 W/(m²·˚C) – inner surface heat transfer coefficient of the building envelope;

T_h – the internal air temperature in the premises of a residential building in St. Petersburg, taken in accordance with Russian State Standard GOST 30494 at 20 °C;

T_c – the average monthly outdoor air temperature in January, taken in accordance with Russian Building Norms and Regulations SNIP 23-01-99* [15] at -8.7 ° C;

δ – thickness of the wall, m;

λ – thermal conductivity, W/(m·°C).

Now we determine the instantaneous average temperature of the wall:

$$\overline{T} = (T_h - T_\infty) \cdot \theta + T_\infty. \qquad (7)$$

where $\theta = \exp\left(-\frac{t}{t_h} - \frac{t}{t_c}\right)$; $t_h = \frac{\rho \cdot c_p \cdot \delta}{\alpha_h}$; $t_c = \frac{\rho \cdot c_p \cdot \delta}{\alpha_c}$.

Then time on which it is possible to turn off heating can be defined as time $\overline{T}(\tau)$ for which will approach average value of temperature of a wall in the stationary mode $\overline{T}_\infty$. Mathematically it can be written down so:

$$t_c = \frac{\overline{T} - \overline{T_\infty}}{v} \qquad (8)$$

Results of calculation of instant temperature of a wall are presented in the table of the application. Schedules of instant temperature of a wall, or cooling, are submitted in Figure 7.

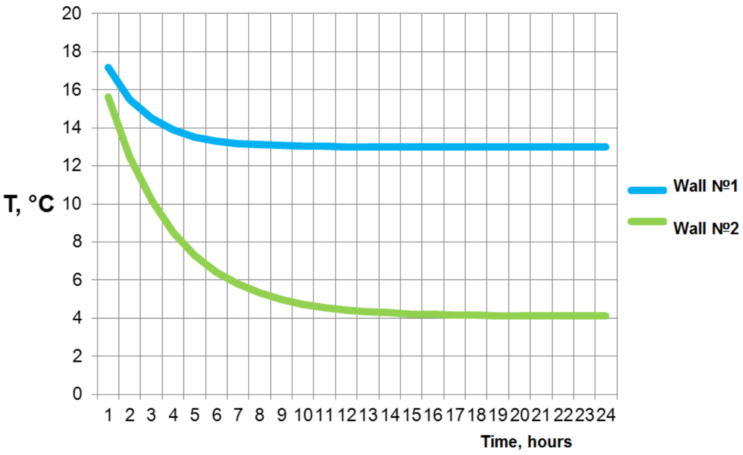

Figure 7. The schedule of cooling of a design of walls at a temperature of external air of -10 °C

The heating shutdown time is about 4 hours/day. We can provide the periodic heating duty.

Economic efficiency of decisions

The heattechnical calculation has been made and thermal losses of the building are defined (Fig. 8).

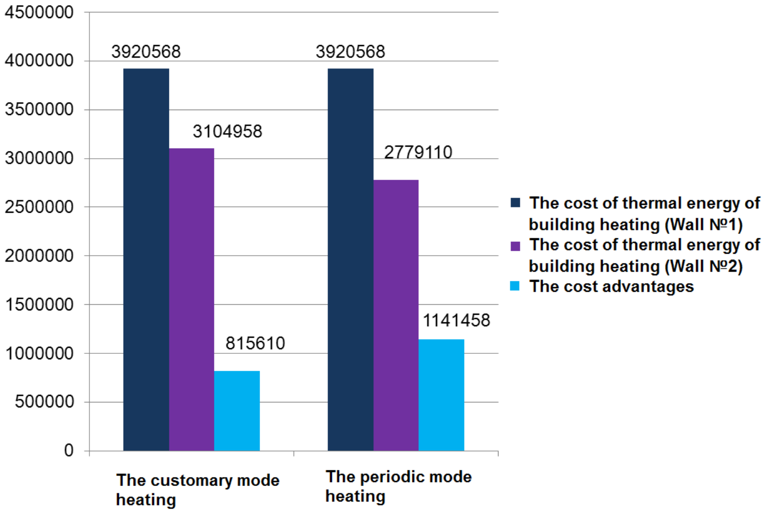

Figure 8. The schedule of cost of thermal energy on heating of the building

At increase in thermal resistance of a design of Gidrokorpus-2 the economy of thermal energy is about 800 thousand rub/year.

At advent of automated control station and periodic heating duty to the building the economy of the thermal energy for heating of the building is about 900 thousand rubles/year.

Results and Discussion

As a part of the research the following results have been received:

1. The fluctuation of temperature in energy efficient enclosure structure are localized at a cold side of a wall, and in construction with a low thermal resistance temperature fluctuations "penetrate" a wall.
2. High-frequency (daily, week) fluctuations of temperature are localized in a thin layer of fluctuations and do not cause noticeable change of average temperature of a wall on big times.
3. The velocity of cooling of a hot penetration conduit is less than the velocity of cooling in a structure with a large-scale thermal resistance.
4. The measure of energy efficiency of a wall protection is inversely proportional λ, and heat assimilation and thermal stability $\lambda^{1/2}$ is proportional; therefore, increase in energy efficiency reduces thermal stability and vice versa.

5. At increase in thermal resistance of a buildings construction the economy of thermal energy is about 800 thousand rub/year. At implementation of domestic heating plant to the building and providing the periodic mode of heating of the building the economy of the thermal energy for heating is about 900 thousand rubles/year. Increase the energy efficiency of a wall and use of accumulative ability from the economic point of view are equivalent.
6. The measure of energy efficiency of a wall protection is inversely proportional λ, and heat assimilation and thermal stability $\lambda^{1/2}$ is proportional; therefore, increase in energy efficiency reduces thermal stability and vice versa.

Authors [1–10] propose the constructive solutions of external walls providing their high thermal stability. Authors [11–22] cconsider the factors influencing the thermal mode of the room after shutdown of heat supply of the building. On rate of cooling the greatest influence is exerted by the size of warm losses through the enclosure structure at the expense of a heat transfer and on heating of infiltration air. The big areas of a glazing of the room are a factor of increase in heatlosses and, therefore, quickly cooling of the building after heating shutdown [23].

Conclusions

The typical building construction absorbs the temperature wave caused temperature fluctuations of external air. It means this building construction has a thermal stability. Therefore, there is a reserve for warmth accumulation which can be used for decreasing of thermal losses.

The measure of energy efficiency of a wall protection is inversely proportional to coefficient of heat conductivity, and heat assimilation and thermal stability is inversely proportional to coefficient of heat conductivity; therefore, increase in energy efficiency reduces thermal stability and vice versa.

Therefore, in future researches it would be possible to define conditions and resistance of a heat transfer of the protecting designs under which two concepts "energy efficiency" and "thermal stability" are crossed in one point.

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