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Analysis of the unsteady temperature condition of a building during non-working hours when heating load is decreased

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Abstract. This paper examines the issue of fuel and energy resources conservation through the non-working hours heating load decrease. The paper`s objective is the determination of savings when non-working hours heating load is decreased, considering the unsteadiness of the heat transfer processes through the enclosing structures, heating modes determination, which ensure the required microclimate parameters in the building during working hours. The analysis of the unsteady temperature condition has been conducted using systems of differential equations, the heating load decrease method has been suggested with further calculation for the existing building and technical-and-economic evaluation of the suggested energy conservation measure. To solve this problem the mathematical model was constructed, which considers the unsteadiness of weather conditions and temperature conditions of the building when the heating load is decreased. The method of heating load decrease was suggested with further savings calculation for the High School №4 in Belgorod city. The modeling helped to establish that to ensure steady microclimate parameters in the building after period of heating load decrease to 12°C ends, it is necessary to conduct short-duration overheating of the building by increasing inside temperature to 21°C for the period from 5:00 till 9:00, to prevent loss of heat by the enclosing structures. When the room temperature during non-working hours is decreased to 12°C the calculated economy is 10%.

1. Introduction

One of the main problems in budget expenses control in the Belgorod region is constantly rising prices for the energy resources, costs for transportation to the consumer and its ineffective end use [1]. At present, most of the budget institutions have heat losses, which are results of the following factors [2]:

- poor condition of the building`s thermal envelope (doorways and window openings);
- insufficient maintenance of the supply and exhaust ventilation;
- out of adjustment heat load, which leads to substantial temperature overshoot in buildings against the normative, and as the result – overconsumption of the thermal energy for heating.

Building`s energy consumption forecast is necessary for planning, control, and conservation of energy. The data-based models provide a practical approach for the energy consumption forecast [3]. Forecast is very important for the control issues of heating system, ventilation, and air conditioning. On a practical level, there is a significant reduction of energy consumption in the building`s heating after the automated domestic heating plant (DHP) is installed, which controls the heating load depending on the weather conditions [4].

Energy consumption for the buildings is around 35% of the world`s total energy production. The educational institutions consume 20-40% of heat energy [5]. Therefore, they contribute significantly to the expenses of the municipal governments. A high level of energy consumption is caused, mostly, by the low building`s characteristics, modes of operation, etc.

One of the alternatives that give energy consumption reduction in buildings is an energy service contracting for energy efficiency improvement [6]. The energy service contract allows to reduce the operating costs. The heating load control automation, which is based on the energy service contract, ensures energy conservation with minimal expenses on the consumer`s side.

Evaluation of the heat energy savings value depends on the efficiency level of the reconstructed heating system and requires detailed information about the heat energy consumption value in relation to the weather parameters [7]. The scientific literature estimates savings value in the range from 3 to 30%.

2. Materials and Methods

In the budget institutions, which are in use mostly during working hours, the heating load can be adjusted, which results in a reduction of heat energy consumption. The calculation should be done under comparable conditions. The objective of the comparable conditions use in calculations is a recalculation of the values for the possibility of energy consumption of different buildings and conditions comparison.

The comparable conditions – combination of technical, climatic and mode factors, which have numeric values, that influence fuel-and-energy resources consumption in physical terms, but don`t influence the savings after implementation of measures for energy conservation and energy resources conservation, which are for recalculation of the energy consumption during the reporting period for value that could have been in conditions of base (standard, specified) period factors value.

Below presented the factors (comparable conditions) which influence the volume of TER consumption [8]:

- weather conditions change (average outside air temperature over a period, average duration of the daylight over a period, duration of the heating period);
- an institution`s working hours change (rate of working days and/or working hours in a period, number of employees and/or customers);
- institution`s room (rooms) purpose change (average temperature inside the room);
- change of the set-up, number and heated rooms (heated rooms area or heated volume);
- set-up, number or capacity of the energy-consuming equipment.

The unsteady heat transfer through the walls of a building can be calculated in the following way [9]:

$$\rho c \frac{\partial T}{\partial \tau} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right), \tag{1}$$

where ρ – density kg/m^3; c – specific heat capacity, kJ/(kg·°C); τ – time, s.; T – temperature, °C, x – grid step, m; λ – heat transfer coefficient, kW/(m·°C).

A solution of the differential heat transfer equation lies in its discretization, i.e. substitution of the value, which is given by the differential function, for several values in certain points – nodes of a spatial grid [10]. Determination of the temperature values in the nodes of a grid is done by sequential calculation of temperature in every node using temperature value in the preceding node. To increase calculation precision, it is possible to use different discretization methods, i.e. substitution of the differential for increment (finite difference method, balance method, etc.). The disadvantage of the mentioned above methods is in low accuracy, therefore, mainly the two-point boundary problem is considered in the heat transfer modeling when the heat transfer conditions are given in right and left boundaries [11].

To solve the differential heat transfer equation of the enclosing structure the spatial grid should be divided into 10 points (0-9) (see Figure 1). When a building is insulated 6 points are used (0-5) to determine the temperature field through the wall and 3 points (7-9) to determine the temperature field through insulation.

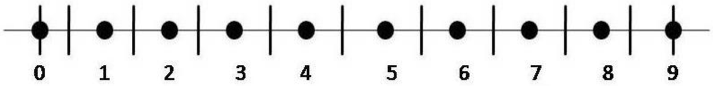

Figure 1. Spatial grid

For the endpoints of the spatial grid the boundary conditions of the third kind were given [12]:
for the left boundary:

$$q = \alpha_{in}\left(T_0^1 - T_{in}^1\right), \tag{2}$$

where α_{in} – heat transfer coefficient of the enclosing structure's inner surface, W/(m^2·K), T_0^1 – temperature in a corresponding point at the current time, °C; T_{in}^1 – temperature inside the building in a corresponding point at the time of preceding iteration, °C.
for the right boundary:

$$q = \alpha_{out}\left(T_{out} - T_n^1\right), \tag{3}$$

where α_{out} – heat transfer coefficient of the enclosing structure's outer surface, W/(m^2·K); T_{out} – outside temperature, °C; T_n^1 – temperature in a corresponding point at the current time, °C.

As a result of the equation (1) discretization on the grid, presented in Figure 1, the equations are obtained for zero point, *i-th* point and *n-th* point.

Heat transfer equation for zero point, T_0:

$$\frac{\rho c}{\Delta\tau}\cdot\left(T_0^1 - T_0^0\right) = \frac{\lambda}{\Delta x}\cdot\left(T_1^1 - T_0^1\right) - \alpha_{in}\cdot\left(T_0^1 - T_{in}^1\right), \tag{4}$$

where ρ – material density, kg/m^3; c – specific heat capacity of a material, kJ/(kg·K); Δτ – time step, s; λ – heat transfer coefficient of a material, W/(m·K); Δx – grid step, m; α_{in} – heat transfer coefficient of the enclosing structure's inner surface, W/(m^2·K); T^1 – temperature in a corresponding point at the current time, °C; T^0 – temperature in a corresponding point at the time of preceding iteration, °C.

Heat transfer equation for *i-th* (i=1-8) point, T_i:

$$\frac{\rho c}{\Delta\tau}\cdot\left(T_i^1 - T_i^0\right) = \frac{\lambda}{\Delta x}\cdot\left(T_{i+1}^1 - T_i^1\right) - \frac{\lambda}{\Delta x}\cdot\left(T_i^1 - T_{i-1}^1\right). \tag{5}$$

Heat transfer equation for *n-th* point, T_n:

$$\frac{\rho c}{\Delta\tau}\cdot\left(T_n^1 - T_n^0\right) = \alpha_{out}\cdot\left(T_{out} - T_n^1\right) - \frac{\lambda}{\Delta x}\cdot\left(T_n^1 - T_{n-1}^1\right), \tag{6}$$

where ρ – material density, kg/m^3; c – specific heat capacity of a material, kJ/(kg·K); Δτ – time step, s; λ – heat transfer coefficient of a material, W/(m·K); Δx – grid step, m; α_{out} – heat transfer coefficient of the enclosing structure's outer surface, W/(m^2·K).

As a result, the system is obtained, which contains (n+1) equation:

$$\begin{cases} \frac{\rho c}{\Delta\tau}\cdot\left(T_0^1 - T_0^0\right) = \frac{\lambda}{\Delta x}\cdot\left(T_1^1 - T_0^1\right) - \alpha_{in}\cdot\left(T_0^1 - T_{in}^1\right) \\ \dots \quad \dots \; \dots \quad \dots \; \dots \\ \frac{\rho c}{\Delta\tau}\cdot\left(T_i^1 - T_i^0\right) = \frac{\lambda}{\Delta x}\cdot\left(T_{i+1}^1 - T_i^1\right) - \frac{\lambda}{\Delta x}\cdot\left(T_i^1 - T_{i-1}^1\right) \\ \dots \quad \dots \; \dots \quad \dots \; \dots \\ \frac{\rho c}{\Delta\tau}\cdot\left(T_n^1 - T_n^0\right) = \alpha_{out}\cdot\left(T_{out} - T_n^1\right) - \frac{\lambda}{\Delta x}\cdot\left(T_n^1 - T_{n-1}^1\right) \end{cases} \tag{7}$$

To find the solution using the sweep method [13] the system is presented in the standard way:

$$\begin{cases} a_0\cdot T_1^1 + b_0\cdot T_0^1 + d_0 = 0 \\ \dots \quad \dots \quad \dots \quad \dots \quad \dots \\ a_i\cdot T_2^1 + b_i\cdot T_1^1 + c_i\cdot T_0^1 + d_i = 0 \\ \dots \quad \dots \quad \dots \quad \dots \quad \dots \\ b_n\cdot T_n^1 + c_n\cdot T_{n-1}^1 + d_n = 0 \end{cases} \tag{8}$$

where $a_0 = \frac{\lambda}{\Delta x}$; $b_0 = \frac{\rho c}{\Delta\tau} + \alpha_{in} + \frac{\lambda}{\Delta x}$; $d_0 = \left(-\frac{\rho c}{\Delta\tau}\cdot T_0^0 + \alpha_{in}\cdot T_{in}^1\right)$;
$a_i = \left(-\frac{\lambda}{\Delta x}\right)$; $b_i = \left(\frac{\rho c}{\Delta\tau} + 2\cdot\frac{\lambda}{\Delta x}\right)$; $c_i = \left(-\frac{\lambda}{\Delta x}\right)$; $d_i = \left(-\frac{\rho c}{\Delta\tau}\cdot T_1^0\right)$;
$b_n = \left(\frac{\rho c}{\Delta\tau} + \alpha_{out} + \frac{\lambda}{\Delta x}\right)$; $c_n = \left(-\frac{\lambda}{\Delta x}\right)$; $d_n = \left(-\frac{\rho c}{\Delta\tau}\cdot T_n^0 - \alpha_{out}\cdot T_{out}\right)$

The temperature field through the insulation layer is calculated by a similar method.
Heat transfer equation for zero point, T_0:

$$\frac{\rho_1 c_1}{\Delta\tau}\cdot\left(T_0^1 - T_0^0\right) = \frac{\lambda_1}{\Delta x_1}\cdot\left(T_1^1 - T_0^1\right) - \alpha_{\mathrm{in}}\cdot\left(T_0^1 - T_{\mathrm{in}}^1\right) \tag{9}$$

Heat transfer equation for *i-th* (i=7-9) point, T_i:

$$\frac{\rho_1 c_1}{\Delta\tau}\cdot\left(T_i^1 - T_i^0\right) = \frac{\lambda_1}{\Delta x_1}\cdot\left(T_{i+1}^1 - T_i^1\right) - \frac{\lambda_1}{\Delta x_1}\cdot\left(T_i^1 - T_{i-1}^1\right) \tag{10}$$

Heat transfer equation for *n-th* point, T_n:

$$\frac{\rho_1 c_1}{\Delta\tau}\cdot\left(T_n^1 - T_n^0\right) = \alpha_{out}\cdot\left(T_{out} - T_n^1\right) - \frac{\lambda_1}{\Delta x_1}\cdot\left(T_n^1 - T_{n-1}^1\right) \tag{11}$$

As the result the system of equations was obtained:

$$\begin{cases} \frac{\rho_1 c_1}{\Delta\tau}\cdot\left(T_0^1 - T_0^0\right) = \frac{\lambda_1}{\Delta x_1}\cdot\left(T_1^1 - T_0^1\right) - \alpha_{\text{in}}\cdot\left(T_0^1 - T_{\text{in}}^1\right) \\ \dots \quad \dots \dots \quad \dots \dots \\ \frac{\rho_1 c_1}{\Delta\tau}\cdot\left(T_i^1 - T_i^0\right) = \frac{\lambda_1}{\Delta x_1}\cdot\left(T_{i+1}^1 - T_i^1\right) - \frac{\lambda_1}{\Delta x_1}\cdot\left(T_i^1 - T_{i-1}^1\right) \\ \dots \quad \dots \dots \quad \dots \dots \\ \frac{\rho_1 c_1}{\Delta\tau}\cdot\left(T_n^1 - T_n^0\right) = \alpha_{out}\cdot\left(T_{out} - T_n^1\right) - \frac{\lambda_1}{\Delta x_1}\cdot\left(T_n^1 - T_{n-1}^1\right) \end{cases} \tag{12}$$

or

$$\begin{cases} a_0\cdot T_1^1 + b_0\cdot T_0^1 + d_0 = 0 \\ \dots \quad \dots \quad \dots \quad \dots \quad \dots \\ a_i\cdot T_2^1 + b_i\cdot T_1^1 + c_i\cdot T_0^1 + d_i = 0 \\ \dots \quad \dots \quad \dots \quad \dots \quad \dots \\ b_n\cdot T_n^1 + c_n\cdot T_{n-1}^1 + d_n = 0 \end{cases} \tag{13}$$

where $a_0 = \frac{\lambda_1}{\Delta x_1}$; $b_0 = \frac{\rho_1 c_1}{\Delta\tau} + \alpha_{\text{in}} + \frac{\lambda_1}{\Delta x_1}$; $d_0 = \left(-\frac{\rho_1 c_1}{\Delta\tau}\cdot T_0^0 + \alpha_{\text{in}}\cdot T_{\text{in}}^1\right)$;

$a = \left(-\frac{\lambda_1}{\Delta x_1}\right)$; $b = \left(\frac{\rho_1 c_1}{\Delta\tau} + 2\cdot\frac{\lambda_1}{\Delta x_1}\right)$; $c = \left(-\frac{\lambda_1}{\Delta x_1}\right)$; $d = \left(-\frac{\rho_1 c_1}{\Delta\tau}\cdot T_1^0\right)$;

$b_n = \left(\frac{\rho_1 c_1}{\Delta\tau} + \alpha_{out} + \frac{\lambda_1}{\Delta x_1}\right)$; $c_n = \left(-\frac{\lambda_1}{\Delta x_1}\right)$; $d_n = \left(-\frac{\rho_1 c_1}{\Delta\tau}\cdot T_n^0 - \alpha_{out}\cdot T_{out}\right)$

The discrete analog of the heat transfer equation [16] on the border of layers (point 6) can be described as follows:

$$a_i\cdot T_{i+1}^1 + b_i\cdot T_i^1 + c_i\cdot T_{i-1}^1 + d_i = 0, \tag{14}$$

where $a = \left(-\frac{\lambda_1}{\Delta x_1}\right)$; $b = \left(0{,}5\cdot\frac{\rho c\Delta x}{2\Delta\tau} + 0{,}5\cdot\frac{\rho_1 c_1\Delta x_1}{2\Delta\tau} + 2\cdot(0{,}5\cdot\frac{\lambda}{\Delta x} + 0{,}5\cdot\frac{\lambda_1}{\Delta x_1})\right)$;

$c_i = \left(-\frac{\lambda}{\Delta x}\right)$; $d = \left(-(0{,}5\cdot\frac{\lambda}{\Delta x} + 0{,}5\cdot\frac{\rho_1 c_1\Delta x_1}{\Delta\tau})\cdot T_i^0\right)$

2.1. Method of savings determination

The inside room temperature calculation uses dependences between air heat capacity, heated space, time interval under consideration, dynamically changing incoming and outgoing heat energy quantities [14]. Dynamics of the air temperature change inside the building under consideration can be examined with the help of the following formula:

$$t_{i+1} = \frac{c_{air}\cdot V_{heat}\cdot t_i - \Delta\tau\cdot\left(Q_{vent} + Q_{attic} + Q_{basem} + Q_{wind} + Q_{wall} - Q_{inc}\right)}{c_{air}\cdot V_{heat}}, \tag{15}$$

where t_{i+1} – inside room temperature in the next point of time, °C; c_{air} – air specific heat capacity, kJ/(m^3·K); V_{heat} – heated space in a building, m^3; t_i – inside room temperature in the preceding point of time, °C; $\Delta\tau$ – time step, s.; Q_{vent}– heat losses through the ventilation, kW; Q_{attic}– heat losses through the attic floor, kW; Q_{basem}– heat losses through the basement, kW; Q_{wind}– heat losses through the windows, kW; Q_{wall} – heat losses through the walls, kW; Q_{inc}– incoming heat from the building`s heat supply system, kW.

It is also necessary to monitor the inner surface of the wall when the heating load is reduced because excessive temperature reduction can lead to condensation on the wall`s surface [15]. The inner wall`s surface temperature is calculated as follows:

$$t_{in.wall} = \frac{t_{in}-(t_{in}-t_{out})}{\alpha_{in}\cdot R_{wall}}, \tag{16}$$

where $t_{in.wall}$ – inner temperature of a wall, °C; t_{in} – inside room temperature, °C; t_{out} – outside temperature of the atmosphere, °C; α_{in}– heat transfer coefficient of the enclosing structure`s inner surface, W/(m^2·°C); R_{wall} – thermal resistance of a wall, (m^2·°C)/W.

Outer surface temperature of the wall is calculated as follows:

$$t_{out.wall.} = \frac{t_{out}-(t_{in}-t_{out})}{\alpha_{out}\cdot R_{wall}}, \tag{17}$$

The idea behind heat energy conservation is in heating load reduction. It is realized in the calculations by the heating load coefficient:

$$K = \frac{Q_{heat}}{Q_{heat\ init}}, \tag{18}$$

where K – heating load coefficient; Q_{heat} – current consumed heat energy amount for heating of the rooms, kW; $Q_{\mathrm{heat\ init}}$ – initial consumed amount of heat for building heating, kW.

The mathematical model allows observing the building`s parameters change as the result of a reduction or increase of the heating load and search of the optimal choice of the heating mode when savings are maximum [16].

3. Results

The heating load adjustment during 1 week has been studied, which allows conducting a more accurate analysis of temperatures. The studies were carried out at several actual buildings. The calculation results presented here are from the High School № 4 in Belgorod city.

The obtained room air temperature changes and average wall`s temperature is presented in Figure 2.

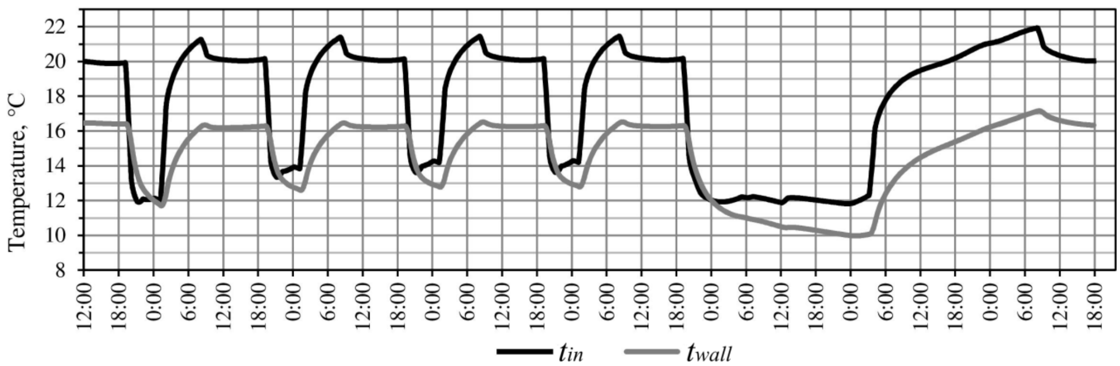

Figure 2. Dependence diagram of the air temperature in the High School №4 with temperature reduction to 12°C and average wall`s temperature within one week on the heating load adjustment.

The heating load reduction starts at 20:00 and then gradually increases until 2:00. From 2:00 the heating load increases until the heating load coefficient reach 1.2, so the initial air temperature parameters in the building are back at the beginning of the working day at 9:00. Therefore, the diagram shows short-duration overheating of the building until 9:00, however, at the beginning of the working day the temperature will be the same as the day before. The temperature changes are presented in Figure 3.

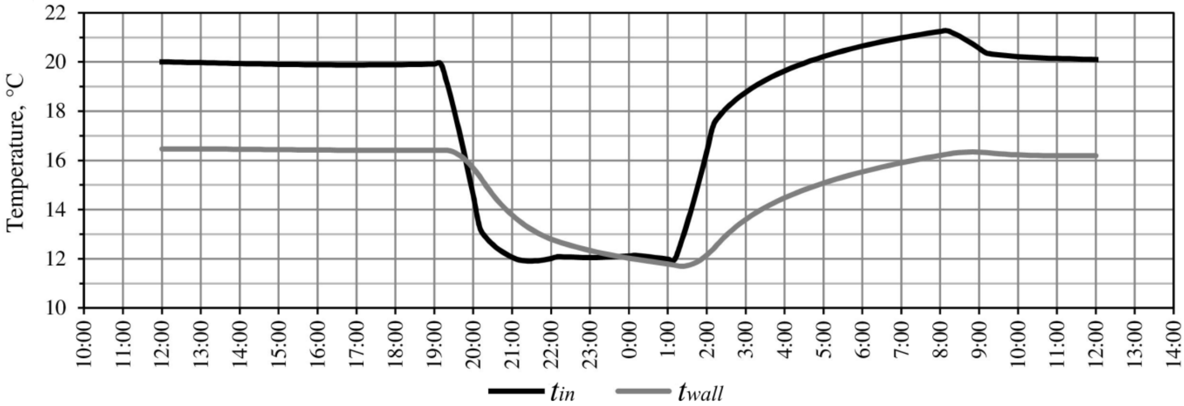

Figure 3. Dependence diagram of the air temperature in the High School №4 with temperature reduction to 12°C and average wall`s temperature during the working day on heating load adjustment.

Short-duration overheating of the building before the beginning of the next working day is necessary to prevent enclosing structure cooling, which afterward can lead to condensation forming on the inside surface of the walls. The average temperature of the outer enclosing structures change during the week without short-duration overheating is presented in Figure 4.

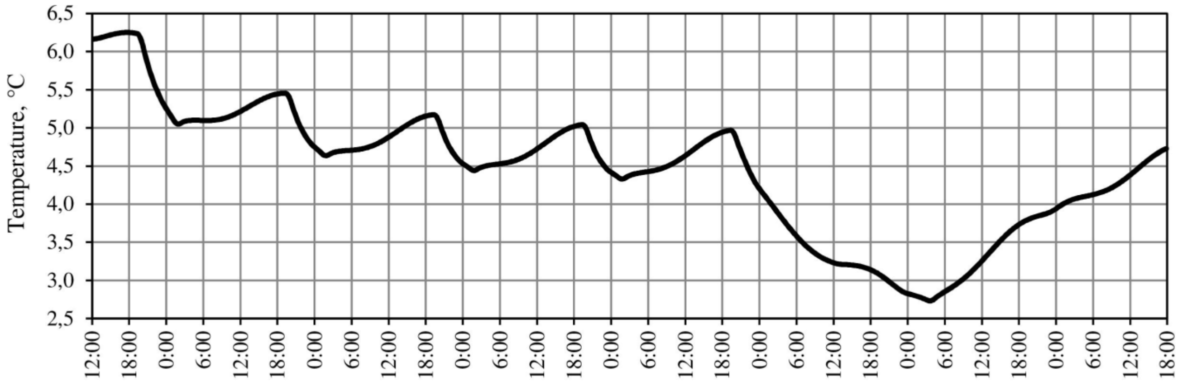

Figure 4. Change of the average outer wall temperature in the High School №4 without short-duration overheating.

This problem can be solved by the slight temperature increase from 20 to 21°C for the period from 5:00 to 9:00. The result of the adjustment is presented in Figure 5.

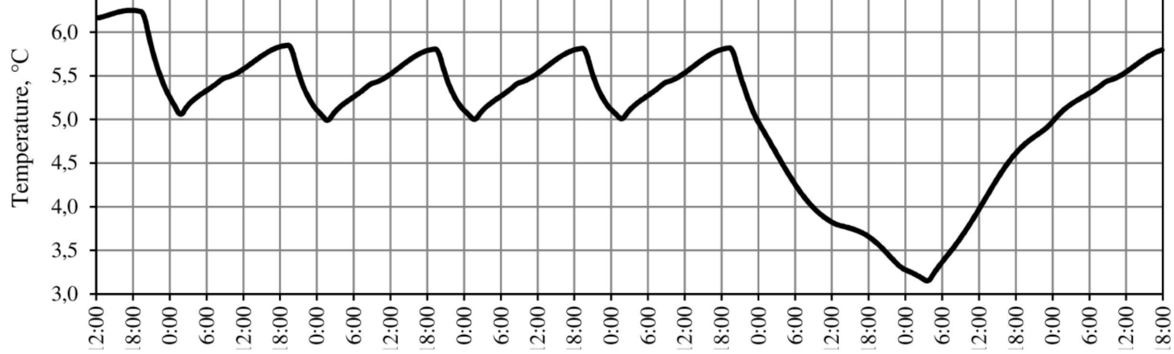

Figure 5. Change of the average outer wall temperature in the High School №4 with short-duration

overheating.

At the end of Friday, the temperature diagram shows a long-duration temperature reduction to 12°C. Since the budget institutions, for the most part, are not open during the mentioned time period, the load can be reduced for the whole weekend. The reduction starts on Friday from 20:00 with a constant temperature of 12°C by a gradual increase in the coefficient (Figure 6).

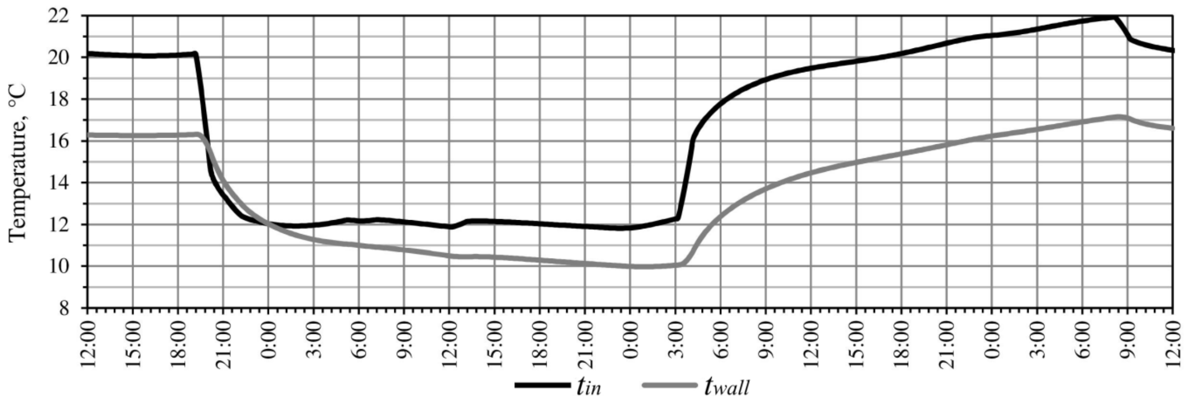

Figure 6. Dependence diagram of the air temperature in the High School №4 with temperature reduction to 12°C and average wall temperature during weekend day on heating load adjustment.

The calculation has shown that returning to the normal operating mode requires heating load increase starting on Sunday at 4:00 and the heating load coefficient should stay at 1.18 until Monday 9:00 of the next week. During this period the inside building temperature and temperature of the outer wall return to the initial values, which are comfortable for the employees and full functioning of the whole building.

4. Discussion

Let`s determine the economic feasibility of the heating load adjustment using the High School №4 in Belgorod city as an example.

The average price for the automated DHP in Belgorod city is around 400.000 Rub. The average annual cost of 1GCal of heat energy for the budget institutions in 2019 is 1882 Rub.

The calculations have shown that one week of the heating load adjustment with temperature reduction to 12°C gives savings in heat energy consumption on:

$$\mathrm{d}Q_{cons} = 19620940 \text{ J/week} = 19.621 \text{ GJ/week} = 4.686 \text{ GCal/week}$$

Financially the weekly savings can be calculated as follows:

$$E_{week} = \mathrm{d}Q_{cons} \cdot P_{heat} = 4.686 \cdot 1882 = 8819 \text{ Rub/week},$$

where $\mathrm{d}Q_{cons}$ – thermal energy for heating consumption reduction, GCal/week; P_{heat} – the tariff for thermal energy, Rub/GCal.

The heating period in a calendar year is 191 days, which is 27 full weeks of heating period. Annual savings are calculated as follows:

$$E_{year} = E_{week} \cdot n_{week} = 8819 \cdot 27 = 238113 \text{ Rub},$$

where E_{week} – thermal energy savings, Rub/week, n_{week} – number of heating period weeks, week.

The payback period of equipment is calculated as follows:

$$PP = C \,/\, E_{\text{year}} = 400000 \,/\, 238113 = 1.68 \text{ year},$$

where C – expenses for measures implementation, Rub; E_{week} – savings from measures implementation, Rub/year.

The obtained payback period indicates the satisfactory feasibility of the suggested system of adjustment implementation.

5. Conclusion

In the process of work the mathematical model was constructed with analysis purpose of the unsteady temperature condition of the building and savings determination from heating load reduction during non-working hours considering unsteady heat transfer processes through the enclosing structures, heating modes determination, which allow establishing required microclimate parameters during working hours. The model allows modeling of the unsteady processes of heating and cooling of the building during a change of weather conditions and heat energy consumption, that is supplied to the building, which allows determining the heat saving values when heating load is reduced during non-working hours.

The study has shown that the biggest savings can be achieved by air temperature reduction to 12°C. The modeling helped to establish that to provide stable microclimate parameters in the building after the end of heating load reduction period, it is necessary to carry out short-duration overheating of the building with inside temperature increase to 21°C for the period from 5:00 till 9:00, and after long-duration reduction (weekends or holidays) to 22°C for the period from 18:00 till 9:00.

The method of heating load reduction also has been suggested, with the following savings calculation for the High School № 4 in Belgorod city. When the room temperature during non-working hours is reduced to 12°C the calculated saving is 10%.

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