Methods of evaluating the effectiveness of the insulation from the internal air temperature control

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Abstract. In this paper, the technique of definition of economic efficiency of energy-saving activities of the internal air temperature regulation during the daily period by means of individual regulators. Proposed analytical method assessment of the effectiveness of this method of energy saving in the long-term operation of the system.

1 Introduction

Implementation of measures aimed at saving energy in heating systems for buildings, should correlates with the possible economic benefits from the effect of [1–4]. One way to reduce the annual heat consumption is to reduce the internal air temperature relative to the calculated value in certain hours of the day: night and nonworking time [5]. However, the implementation of this decision raises the need to install additional regulatory systems (often automated) that increases the cost of heating systems [6]. So the economic effect of the implementation of this method does not completely obvious and requires an appropriate analysis.
2 Materials and methods

In the present work, it is proposed to analyse the effectiveness of heat consumption reduction technique in heating systems from the internal air temperature regulation when using automated tools to regulate the heating of heat transfer appliances. The method is based on the use of analytical expressions and mathematical models of system parameters and associated elements that define a comprehensive evaluation of the effectiveness of the method.

3 Results

Heat consumption for heating buildings heat-consuming defines $W_p$ per heating period $P$:

$$W_p = \sum_{i=1}^{P} W_i,$$

where is $W_i$ – heat consumption for $i$ day of the heating season, W * day.

The daily thermal consumption $W_i$, can be expressed through the hour $W_j$:

$$W_i = \sum_{j=1}^{24} W_j,$$

Hourly energy consumption for heating the building volume $V$, where the internal air temperature is maintained at $t_B$ determined from the expression:

$$W_j = V q_0 \left( t_B - t_{hj} \right) j,$$

where is $q_0$ – specific heat characteristics of building $W/m^3 \cdot ^\circ C$.

$t_{hj}$ - the temperature of external air in/h, $^\circ C$; $j$ - period of time, 1h.

From the expression (1) that alter the heat consumption of the heating system in the process of building operation, you can regulate the internal air temperature.

The internal air temperature reduction compared with the calculated value possible out of hours days $Z_1$, on holidays and weekends $Z_2$. Duration period $Z_1$ define operating premises (buildings). Provided that in the building after hours days may reduce the temperature of internal air to the amount of $\Delta t_B$ the daily thermal consumption will be defined with the following expression:

$$W_i = W_{z1i} + W_{z2i}$$

$$= \sum_{j=1}^{Z_1} V q_0 (t_B - \Delta t_B - t_{hj}) + \sum_{j=1}^{Z_2} V q_0 (t_B - t_{hj}),$$

(4)
where is $W_{z1i} \text{ and } W_{z2i}$ - heat consumption respectively in non-working and working periods $i$ days, $W$ = day.

The internal air temperature is determined by convective heating appliances and heating systems due to the heat of enclosing constructions, equipment and furniture the dynamics of this change corresponds to the interim period. But given that the internal air temperature $\Delta t_B$ and subsequent recovery values (before $t_B$) is regular, then you can think of this process as a discrete function (see Figure 1).

**Figure 1.** the scheme of distribution of internal and external air temperatures in the daily period.

The temperature of external air is usually too is changed regularly and during the daily period of her stroke corresponds to the trigonometric law:

$$t_{ij} = t_{Hi} + A_{ti} \cos \left( \frac{2\pi j - \sigma}{24} \right),$$  \hspace{1cm} (5)

where $t_{Hi}$ – the average temperature of external air, °C;
$A_{ti}$ - the amplitude of the diurnal fluctuations of temperature of external air, °C;
$j$ - h, respectively, the current and minimum external air temperature, h.

Then the expression (2) can be represented as follows:

$$W_i = W_{z1.1i} + W_{z1.2i} + W_{z2i} = \sum_{j=1}^{Z1.1} Vq_0(t_B - \Delta t_B - t_{ij}) +$$
\[
+ \sum_{j=Z_{1.1}+1}^{Z_{1.2}} V q_0(t_B - \Delta t_B - t_{ij}) + \sum_{j=Z_{1.1}+1}^{Z_{2.2}} V q_0(t_B - t_{ij}) = \\
= \sum_{j=1}^{Z_{1.1}} V q_0(t_B) + \sum_{j=Z_{2.1}+1}^{Z_{1.2}} V q_0(t_B) + \sum_{j=Z_{1.1}+1}^{Z_{2.2}} V q_0(t_B) - \sum_{j=1}^{Z_{1.1}} V q_0(\Delta t_B) - \\
- \sum_{j=Z_{2.1}+1}^{Z_{2.2}} V q_0(\Delta t_B) - \sum_{j=Z_{1.1}+1}^{Z_{2.2}} V q_0(t_{ij}) - \\
\sum_{j=Z_{1.1}+1}^{Z_{2.2}} V q_0(t_{ij}) = -V q_0 \left \{ t_B (Z_{1.1} + Z_{1.2} + Z_2) - \Delta t_B (Z_{1.1} + Z_{1.2}) - \\
\sum_{j=1}^{Z_{1.1}} t_{Hi} + A_{ti} \cos 2\pi \frac{j}{24} \right \} - \sum_{j=Z_{2.1}+1}^{Z_{2.2}} \left \{ t_{Hi} + A_{ti} \cos 2\pi \frac{j}{24} \right \} - \\
\sum_{j=Z_{1.1}+1}^{Z_{2.2}} \left \{ t_{Hi} + A_{ti} \cos 2\pi \frac{j}{24} \right \} + \sum_{j=Z_{2.2}+1}^{Z_{1.1}} \left \{ \cos 2\pi \frac{j}{24} \right \} = \] 

where is \( Z_{\Delta t} = Z_{1.1} + Z_{1.2} \) – the duration of the internal air temperature during the daily period.

The sum of the cosines for full circadian period will be equal to zero. Therefore, the expression (3) takes the form:

\[
W_l = V q_0 (24 t_B - \Delta t_B Z_{\Delta t} - 24 t_{Hi}) = 24 V q_0 (t_B - t_{Hi} - \Delta t_B Z_{\Delta t} Z_{\Delta t}),
\]

Where is \( Z_{\Delta t} = \frac{Z_{\Delta t}}{24} \) – the relative duration of the internal air temperature during the day.

Thermal energy consumption is determined by the following formula:

\[
W_p = \sum_{l=1}^{P} W_l = 24 V q_0 \sum_{l=1}^{P} (t_B - t_{Hi} - \Delta t_B Z_{\Delta t}) = 24 V q_0 \left \{ P t_B - \sum_{l=1}^{P} t_{Hi} - \sum_{l=1}^{P} \Delta t_B Z_{\Delta t} \right \},
\]

where is \( P \) – the duration of the heating period, days;

The index in \( Z_{\Delta t} \) due to the fact that on some days the allowable periods of internal air temperature during the day can not match duration. In holidays (weekends and holidays) temperature reduction can be a full day. Then the expression (4) can be written as:

\[
W_p = \sum_{l=1}^{P} W_l = 24 V q_0 \left \{ P t_B - \sum_{l=1}^{P} t_{Hi} - \sum_{l=1}^{P} \Delta t_B Z_{\Delta t} \right \},
\]

where is \( - I_{K1} \) - the number of working days in the heating period (with decreasing internal air temperature during part of the day \( Z_{\Delta t} \));

\( (P - I_{K1}) \) - the number of days in the heating period (with decreasing internal air temperature for full days \( Z_{\Delta t} = 24 h \).
Given that one of the meteorological characteristics of the climate of the district is the average temperature for the heating season \(t_{HP}\) [7], defined by the formula:

\[
t_{HP} = \frac{\sum_{i=1}^{P} (t_{Hi})}{P}
\]

then, it follows that:

\[
\sum_{i=1}^{P} t_{Hi} = t_{HP} P
\]

and, accordingly:

\[
W_{K} = \sum_{i=1}^{I} W_{i} = 24 V \ q_{0} \left\{ P_{t_{B}} - t_{HP} P - \sum_{i=1}^{I_{K1}} \Delta t_{B} Z_{\Delta t_{i}} - \sum_{i=I_{K1}+1}^{P} \Delta t_{B} \right\} = 24 V \ q_{0} \left\{ P_{t_{B}} - t_{HP} P - I_{K1} \Delta t_{B} Z_{\Delta t_{i}} - (P - I_{K1}) \Delta t_{B} \right\}
\]

\[
= 24 V \ q_{0} P (t_{B} - t_{HP} - I_{K1} \Delta t_{B} Z_{\Delta t_{i}} - (1 - I_{K1}) \Delta t_{B})
\]

\[
= 24 V \ q_{0} P (t_{B} - t_{HP} - \Delta t_{B} \left[ I_{K1} Z_{\Delta t_{i}} + (1 - I_{K1}) \right])
\]

or in final form have:

\[
W_{P} = 24 V \ q_{0} P (t_{B} - t_{HP} - \Delta t_{B} \left[ I_{K1} Z_{\Delta t_{i}} + (1 - I_{K1}) \right]).
\]

Thermal energy savings from the reduction of indoor air temperature during heating period will be equal to:

\[
W_{P}^{\Delta} = W_{P} - \Delta W_{P} = 24 V \ q_{0} P (t_{B} - t_{HP} - \Delta t_{B} \left[ I_{K1} Z_{\Delta t_{i}} - 1 \right] + 1) = 24 V \ q_{0} P \Delta t_{B} \left[ I_{K1} Z_{\Delta t_{i}} - 1 \right] + 1,
\]

where \(W_{P}^{\Delta}\) - design heat consumption for heating period (without internal air temperature).

Thus, from (6) that potential savings of heat does not depend on internal and external air temperatures, and is defined only by the size of the internal air temperature and the duration of the periods of downturn. These figures depend on the purpose of the building, its mode of operation and are chosen individually [8-10]. But in General, public and industrial buildings, reducing the temperature of internal air logically attributed to holidays and non-working time.

The number of working days in the heating period \(I_{K1}\) depends on its duration and for an average year of this distribution is linear (fig. 2) and can be represented by the formula:

\[
I_{K1} = 0.68P.
\]

Then the expression (6) takes the form:

\[
\Delta W_{P} = 24 V \ q_{0} P \Delta t_{B} \left[ 0.68 \left( Z_{\Delta t_{i}} - 1 \right) + 1 \right].
\]
Figure 2. The dependence of the number of working days from the length of the heating season for an average year.

The relative reduction of heat consumption heating system will be:

\[ \Delta W_p = \frac{\Delta W_p^*}{W_p^*} = \frac{24 V q_0 P \Delta t_B [0,68 (\bar{Z}_{\Delta t_t} - 1) + 1]}{24 V q_0 (t_B - t_{HP})} = \frac{\Delta t_B [0,68 (\bar{Z}_{\Delta t_t} - 1) + 1]}{(t_B - t_{HP})}. \]

The economic effect of reducing heat consumption by regulating the temperature inside a building depends on the value of automation systems \( C_{GAP} \), implementing this mode:

\[ \bar{C}_t = \frac{\Delta C_W}{C_{GAP}} = \frac{\Delta C_W}{\sum_{i=1}^{T} \Delta C_{W,i}} = \frac{\sum_{i=1}^{T} \Delta W_{P,i} * c_{W,i}}{C_{GAP}} \]

where \( T \) - the period of operation of the regulatory system, year;
\( i \) - year of operation, the internal air temperature control mode;
\( c_{W,i} \) - the rate of thermal energy in \( i \) year of operation, rubles/Gcal.

4 Discussion

The current steady growth energy costs poses challenges for searching technological solutions aimed at the rational use and lower power systems. One such energy-intensive systems is the heating of buildings. Traditionally the heating system shall be designed to maintain the temperature of the air in the room throughout the heating season. However, this principle does not preclude the possibility of lowering the standard level to acceptable values,
without prejudice as to the strictest safety and structural elements of buildings in valid for the periods of days. Naturally, any reduction in the level of room temperature reduces the heat consumption of the heating system. Effective implementation of this method is possible only with the use of appropriate regulatory devices and systems, which unfortunately can significantly complicate and the rise of the heating system. It therefore seems relevant in development is justified.

5 Conclusion

Analyzing the obtained expressions to identify economic efficiency, it may be noted that the proposed methodology is fully taken into account the factors contributing to the reduction of heat consumption heating system from lower temperature level internal air and value systems or devices to enable this decrease. At the same time, the proposed dependencies are applicable for any purpose facility located in any geographical location and operated in random mode. In addition, the technique also allows you to identify the most effective climate control mode of the object (days, weeks, months), which provides the greatest efficiency from reporting activities already at the design stage of a building or when the choice of regulatory framework.

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