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Analysis of the Influence of the Internal Heat Capacity of a Public Building on the Thermal Comfort Parameters of the Premises During the Operation of the Heating System in Alternating Mode

Abstract. In the climatic conditions of Ukraine, which are characterised by a long heating period, considerable energy requirements for heating lead to an increase in energy efficiency requirements. A substantial reduction in the energy consumption of buildings while ensuring comfort conditions will be facilitated by the inclusion of a model of human thermal comfort in the complex “heat source – fencing” system. The purpose of this study was to find the factors affecting the internal heat capacity and, accordingly, the thermal inertia of the building and further take these factors into account upon assessing the thermal condition and parameters of thermal comfort of building rooms. The object of this study was the educational and administrative building of the National University of Life and Environmental Sciences of Ukraine. Many studies were carried out, namely full-scale measurements of heat flows and temperatures on the surfaces of samples of the building’s wall structure were carried out in a special climate complex that allows artificially creating external and internal thermal conditions of premises. It was found that the insulation of the structure with a layer of expanded polystyrene PSB-15, 100 mm thick, reduces heat losses through the wall panel by almost half. An algorithm for controlling the heat release process was developed, considering the internal heat capacity of the building. Compared to the “linear” dependence, this allows more accurately adjusting the schedule of heat carrier release to the heating system of a public building during the introduction of the alternating mode of its operation. The temperature deviation range is reduced by 4-6 °C, which allowed saving up to 10-12% of the consumed heat energy for the heating needs of the research object, provided that the normalised values of the internal temperature of the premises are maintained. Intermittent operation of the heating system of public buildings, the expediency of which is justified in this study, can be recommended for implementation in the structures of higher educational institutions of Ukraine

Keywords: thermal energy, energy requirements, energy efficiency, heating period, thermal inertia, control algorithm, heating system

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INTRODUCTION

Buildings are one of the main consumers of primary energy carriers in the world [1]. Climatic conditions in Ukraine are characterised by a long heating period, which causes 85% of the energy demand for heating [2]. Therefore, energy efficiency requirements are increasing, which is reflected in the standards [3-5]. Most of the buildings in Ukraine belong to the buildings of mass development of the 1980s, during the construction of which the emphasis was placed on minimising capital costs during construction, while operating costs faded into the background, and therefore 80% of buildings do not meet modern energy efficiency requirements [6; 7]. The period from the 1990s to the present day is characterised by a constant increase in energy prices, which means

that during the construction of buildings, considerable attention is already paid to operating costs, which is a late response to similar trends in Europe and the world.

According to the European Union Directive on the energy efficiency of buildings [8], a requirement has been introduced that all new public buildings put into operation from 2019 must meet the requirements presented for houses with almost zero energy consumption, which leads to an increase in energy efficiency and the use of renewable energy sources. Attention is being paid to the growth of thermal resistance of building fences, the relevance of economic assessment and assessment of its life cycle. This is conditioned upon the fact that in the EU, 1/3 of energy resources are

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spent on buildings, namely 60% of the energy consumed by the building is associated with operating costs [9].

Considering global trends in optimising energy demand and ensuring comfortable working conditions, the calculation of specific energy demand should be determined based on operating air temperature, or while observing the comfort indicator in various climatic conditions [10]. The global community pays special attention to thermal comfort issues, especially in the context of the need to reduce energy consumption. There are sections of the population that are particularly sensitive to thermal comfort requirements – these are children and the elderly; women and men feel differently under the same conditions. Therewith, special attention is paid to individual requirements for thermal comfort issues related to gender, age, etc. Hence, the transition from the paradigm of centralised microclimate quality assurance to personalised systems [11].

In Ukraine, thermal comfort is defined by several standards [12; 13]. The inclusion of the human thermal comfort model in the complex “heat source – fencing” system [14; 15] is an essential step towards reducing the energy consumption of buildings and ensuring a suitable level of thermal comfort, especially during the introduction of the alternating heating mode, which is an important step towards sustainable development. Therefore, the purpose of this study was to assess the impact of the level of thermal protection (heat capacity of the building) on the feeling of thermal comfort upon implementing the alternating heating mode. Such studies are important and relevant both in the context of improving the level of energy efficiency and increasing the quality of the microclimate.

LITERATURE REVIEW

Literature analysis has shown that the feasibility of introducing an intermittent (alternating) mode of operation of the heating system of a public building has been understudied. The available research results cover only a few isolated cases and do not provide an exhaustive answer to this question. The results of the study of the influence of thermal inertia of a room are presented in the paper [16], where consideration of the indicator of the internal heat capacity of a building, on the example of the educational and administrative building of the National University of Life and Environmental Sciences of Ukraine (NULES of Ukraine), avoids energy overspending at the level of about 10–12%. Therewith, it is also important to determine the operating time of the system in alternating mode and the depth of adjustment, provided that the parameters of room comfort are preserved. In this area, the authors V. Deshko, I. Bilous, N. Buyak, O. Golubenko, M. Gureev investigated the change in the comfort conditions of premises from the inertia of external enclosing structures of a building during the operation of the heating system in energy-saving modes [17], as well as the dependence of the comfort conditions of public buildings with different degrees of thermal protection of external enclosing structures in the operating conditions of the heating system of the structure in alternating mode [18],

its influence on the dynamics of energy demand. Equally important was the assessment of the impact of ventilation on the overall energy consumption of the building. Thus, the authors of [19] studied the thermal environment in the room, the rate of air exchange, and the concentration of carbon dioxide before and after the energy modernisation of apartment buildings in Finland and Lithuania. The authors of the study [20] conducted a survey on the requirements and barriers in the implementation of ventilation systems in residential buildings with low energy consumption, as well as an assessment of operational problems from seven European countries that may arise in this case. The authors of the studies: [21] – conducted long-term measurements in recently built schools with low energy consumption in Sweden, [22] – characterised the design features of residential buildings in China, [23] – substantiated the feasibility of using adaptive thermal comfort methods for Iranian schoolchildren, [24] – investigated the parameters of residential adaptive comfort in a humid continental climate – Tianjin, China. Furthermore, the authors of [25] introduced the concept of controlling the thermal comfort of a building. The authors V. Nalyvaiko, I. Radko, A. Zhylytsov, O. Okushko, A. Mishchenko, I. Antypov studied the thermal comfort of the building after its thermal modernisation using renewable energy [26] and considering the provisions of the relevant standards [12; 13; 27]. However, the results of research in the studies listed above do not fully solve the problem of assessing the impact of the level of thermal protection (heat capacity of the building) on the feeling of thermal comfort when implementing an alternating heating mode, especially in terms of optimising the algorithm for controlling the heat release process considering the indicator of the internal heat capacity of the building and, accordingly, its thermal inertia, which is what this research is aimed at.

MATERIALS AND METHODS

The object of this study was the educational and administrative building of the National University of Life and Environmental Sciences of Ukraine. More detailed information about the thermophysical characteristics of enclosing structures and the operating mode of the building is given in the source [16].

To fulfil the purpose of this study, the influence of heat transfer resistance of external opaque enclosing structures (walls) of the structure on the efficiency indicators of the building’s heating system was evaluated, considering the parameters of the external environment and the parameters of the microclimate of premises in dynamic mode. For this, two types of wall panels were manufactured and investigated – “with” and “without” insulation on its outer part, which were carried out in different years: before the introduction of standards [7], in 2011-2012, and after – in 2018-2020.

Thermophysical studies of the sample of the building’s wall structure were performed in a special climate complex, which allows artificially creating external and internal thermal conditions of premises and comprises three compartments:

1. External, which simulates external climatic conditions (Fig. 1). 2. Internal, which simulates the microclimate

of the premises. 3. Operator’s room, which allows placing control and measuring equipment.

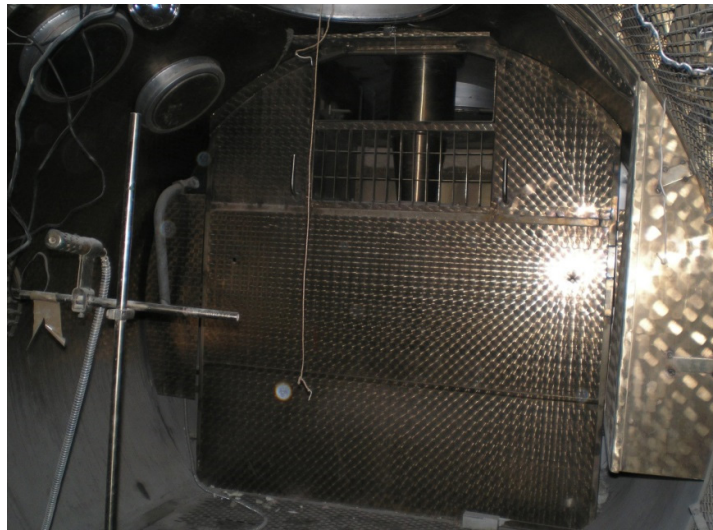


Figure 1. Appearance of the “cold” compartment of the climate chamber

The outer compartment was created based on the KTBV-8000/2 thermobaroclave, which has a powerful refrigerating unit, thanks to which the calculated values of the outdoor air temperature in the winter mode (-24 °C) were provided.

In stationary mode, the air temperature in the outer compartment was maintained by an automatic adjustment system with an accuracy of ±1.5 °C, in the inner compartment – up to ±1 °C. Humidity in the warm compartment of the camera was maintained in automatic mode with an accuracy of ±5%.

The given stationary thermal regime in the internal compartment was maintained using the EOS-2.00/220 electric convector and the BK-1500 air conditioner, which were turned on and off by the PTR-P semiconductor thermostat and the automatic temperature control system mounted in a separate unit.

The process of measuring heat flows and temperatures was controlled using the BS-2 Communication Unit, which has 300 input channels. Between the working compartments – external and internal – the tested product was located, mounted in a special cassette (Fig. 2a).

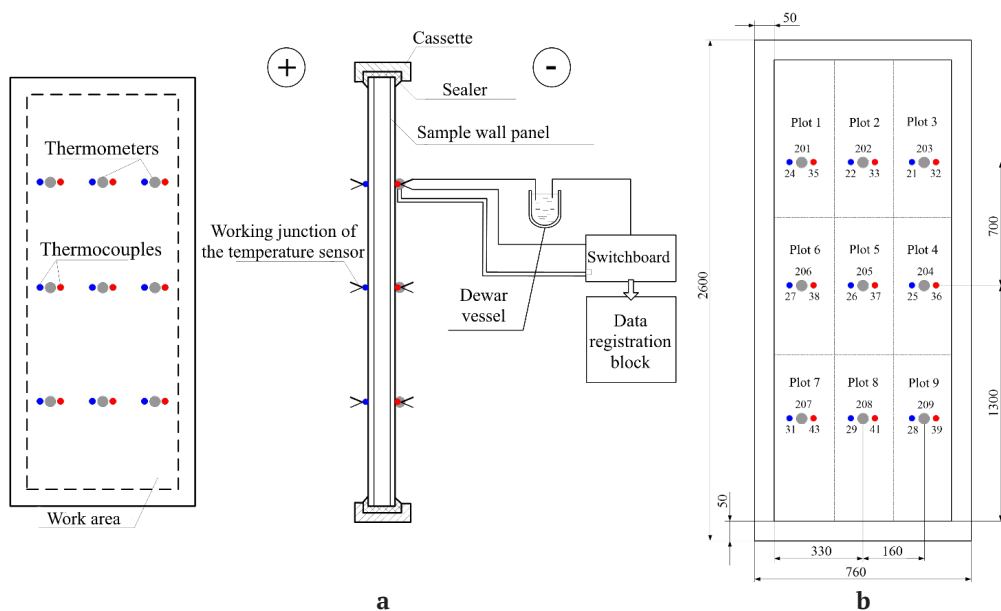


Figure 2. Installation diagram of the tested wall structure sample and placement of temperature and heat flow sensors on it (a) and placement diagram of primary temperature and heat flow converters on the surface of the wall panel sample tested (b): ● – heat flow sensors; ● – temperature sensors on the inner (“warm”) side of the wall panel; ● – temperature on the outer (“cold”) side of the wall panel

The readings of the measuring devices were taken remotely in the operator's compartment using the F70-78 measuring signal switch.

Chromel-Copel thermocouples with a relative measurement error of $\pm 5\%$ were used as temperature sensors. Primary temperature converters were tightly attached to the outer and inner surfaces of products at selected points. Plasticine with an application thickness of no more than 2 mm was used for fastening thermocouples. Therewith, the thermometric wire is led from the place of attachment of the sensitive element along the surface of the enclosing structure towards isotherms or the minimum temperature gradient for a length of at least 50 wire diameters. The free ends of the thermocouples were placed in a thermostat or Dewar vessel, while the latter must contain ice and water at the same time.

Thermobattery sensor PTP-1B.11.2.1.P.001.1.16.00.0 is a working tool for measuring surface heat flux density [28]. Since the thermal resistance of the sensor is negligible compared to the thermal resistance of the wall panel, it was not considered. For the same reason, the dimensions of the sensor ($10 \times 12 \times 1.2$ mm) in the wall plane also do not affect its temperature field.

The universal voltmeter B7-21A was used as a meter of the DC output signal. The voltmeter is designed to measure DC voltage in the range up to 10 MV. The accuracy class of the device is 0.2.

Experimental studies of energy-efficient fencing construction. For experiment No. 1, an experimental light hinged wall panel with overall dimensions of 760×2600 mm was manufactured. Panel thickness $\delta = 100$ mm.

The experimental panel was a three-layer panel with differentiation of layers by functions performed. Facing layers – external and internal – had the functions of weather protection and protection of insulation from mechanical damage. They were made of plywood sheets with a thickness $\delta = 5$ mm.

When choosing the insulation material, good thermal insulation was the decisive factor. Mineral wool [6] with a thickness $\delta = 100$ mm was used as insulation.

There was no monolithic connection between the plywood sheets and the heat insulator, which caused contact thermal resistances.

For experiment No. 2, polystyrene foam plates PSB-15, $\delta = 100$ mm thick, which repeated the dimensions of the wall panel, were attached to the previous wall panel from the side of the cold compartment of the climatic chamber using DRAGON polymer glue.

The conditions of experiment No. 1 and experiment No. 2 were the same: the temperature of the cold compartment of the camera was -24 °C, the temperature of the warm compartment was $+16$ °C.

The method of determining the heat transfer resistance is based on the creation of stationary heat exchange conditions in the enclosing structure and the measurement of the air temperature in two compartments of the climate chamber, the heat flow density and the temperature of the surfaces of the structure under study, which were used to calculate the heat transfer resistance of the sample.

Since the wall panel was thermally relatively homogeneous (without substantial “cold bridges”), nine areas were selected for the experimental study, which were least affected by marginal outflows or inflows of heat in the chamber. 9 sections comprised the working zone (Fig. 2b), the boundaries of which were located at a distance of 50 mm from the edges of the sample under study. The locations of the sensors were marked on the sections with dots.

The test product was installed in the slot between the warm and cold compartments of the climate chamber. The contact surfaces with external fences were insulated with an effective heat-insulating material.

After checking the readiness of the equipment, the warm and cold compartments were isolated from the outside air by closing the airtight doors. The air temperatures in the warm and cold compartments were set on the regulating equipment, including refrigerating, heating, and air humidifying equipment.

The tested panel belongs to the non-inertial class, its exit to the stationary mode took place within three to four hours. The onset of stationary mode was recorded by stable indicators of thermocouples and heat meters. The sampling of experimental data in stationary mode for their further processing was made from the last six measurements (on six cycles), during which the temperature and heat fluxes remained practically constant.

Experimental studies of the parameters of thermal comfort of premises were carried out for five consecutive days, including Saturday and Sunday. Air temperature and humidity parameters were recorded by portable data loggers – Trotec BL30. Therewith, the measurement error was as follows: ± 2 °C – in the temperature range from 1 °C to 50 °C and ± 3 °C – in the range from -18 °C to -1 °C.

Evaluation of the influence of the resistance of the opaque enclosing structures of the building on the parameters of the thermal comfort of the premises and the energy consumption of the building using a numerical method. The total heat transfer and heat input were calculated according to [29], where dynamic impacts are considered by introducing the coefficient of use of heating inputs (accepted in the study) and the coefficient of use of cooling losses. The effect of inertia in the case of intermittent heating or its shutdown was considered separately.

The dimensionless coefficient of use of heating inputs $\eta_{h,gn}$ is calculated for each month according to [29] based on the ratio of heat inputs and losses and the numerical parameter a_H , which depends on the inertia of the building:

$$a_H = a_{H,O} + \frac{\tau}{\tau_{H,O}} \quad (1)$$

where $a_{H,O}$ is the reference dimensionless numeric parameter, $a_{H,O} = 1.0$; τ is the time constant of the building zone, h; $\tau_{H,O}$ is the reference time constant, which is taken as 15 h.

The time constant of the building zone τ , h, characterises the internal thermal inertia of the conditioned zone of the building, both for the heating period and for the cooling period:

$$\tau = \frac{C_m}{H_{tr,adj} + H_{ve,adj} + H_{ve,extra,adj}}, \quad (2)$$

where C_m is the internal heat capacity of the building or building zone, W·h/K; $H_{tr,adj}$ is the representative value of the overall heat transfer coefficient of the transmission, W/K; $H_{ve,adj}$ is the representative value of the general coefficient of heat transfer by ventilation, W/K; $H_{ve,extra,adj}$ is the representative value of the overall heat transfer coefficient due to additional ventilation from night and/or natural cooling, W/K (for heating mode $H_{ve,extra,adj}=0$):

$$H_{ve,extra,adj} = \frac{\sum_{i=1}^n (\sum_{j=1}^{24} f_{ve,extra,j,k} H_{ve,extra,j,k})}{t}, \quad (3)$$

where t is the total heat transfer coefficient due to added ventilation (night ventilation and/or natural cooling) from the k -th element, W/K, and the share of work for a specific j -th hour of the day of the i -th day of the month from the k -th element of added ventilation (if night ventilation and/or natural cooling works = 1, otherwise 0.5); j is the calculation step in hours, from 1 to 24 h; $i=1$ to n is the calculation step in days ($n=31$ for January).

The building of the object under study belongs to the class of "massive" buildings – brickwork in two bricks with a reinforced concrete floor. In this case, the internal heat capacity of the building is calculated according to [29]:

$$C_m = CA_f \quad (4)$$

where C is the internal heat capacity of the building per unit area, taken according to the Table 15 [29], W·h/(m²·K); A_f is the conditioned area of the building, m².

In the case under study, for intermittent (alternating) heating mode, the energy consumption for heating $Q_{H,nd,interm}$, W·h, was found as follows:

$$Q_{H,nd,interm} = a_{H,red} Q_{H,nd,cont} \quad (5)$$

where $Q_{H,nd,cont}$ is the energy demand for continuous heating, W·h; $a_{H,red}$ is the dimensionless reduction coefficient for intermittent heating mode, with a minimum value $a_{H,red} = f_{H,hr}$ and a maximum value $a_{H,red} = 1$:

$$a_{H,red} = 1 - b_{H,red} (\tau_{H,0}/\tau) \gamma_H (1 - f_{H,hr}), \quad (6)$$

where $f_{H,hr}$ is the share of the number of hours per week with a normal (permanent) set heating mode (not set on alternating or switched off); $b_{H,red}$ is the empirical correlation coefficient, $b_{H,red} = 3$; τ is the time constant of the building zone, h; $\tau_{H,0}$ is the reference time constant for the heating mode, h; γ_H is the ratio of heat input and loss for the heating mode.

Adjustments for the non-use period. According to the data [16], it was found that in the building under study, periods of non-use during the heating period (on weekends

and holidays) lead to a reduction in energy consumption during heating.

Energy consumption for heating was calculated, considering the period of non-use, $Q_{H,nd}$, W·h:

- for the period of use (normal heating settings);
- for setting the non-use period.

Linear interpolation was performed depending on the time fraction of the non-use mode compared to the maintenance mode:

$$Q_{H,nd} = (1 - f_{H,nocc}) Q_{H,nd,occ} + f_{H,nocc} Q_{H,nd,nocc} \quad (7)$$

where $Q_{H,nd,occ}$ is the energy demand for heating, W·h, (either $Q_{H,nd,cont}$ or $Q_{H,nd,interm}$), assuming that on all days of the month, the adjustment and setting of the automatic air temperature controller in the room (e.g., the thermostat on the heating device) correspond to the settings of the period of use; $Q_{H,nd,nocc}$ is the energy demand for heating, W·h, (either $Q_{H,nd,cont}$ or $Q_{H,nd,interm}$), assuming that on all days of the month, the regulation and settings of the thermostat correspond to the settings of the period of non-use; $f_{H,nocc}$ is the fraction of a month with a period of non-use of heating (e.g., 10/31).

Additionally, according to the method [29], the influence of automatic control systems installed at the district heating point was investigated:

$$Q_{gen,out} = Q_{dis,in}/\eta_{ac}, \quad (8)$$

where $Q_{gen,out}$ is the produced/generated energy (output energy) from the generation (accumulation) subsystem, specifically based on phase-transition heat accumulators [30]; $Q_{dis,in}$ is the energy input to the distribution subsystem; η_{ac} is the efficiency of automatic adjustment.

RESULTS AND DISCUSSION

Figure 3 demonstrates the nature of changes in heat flows through the wall panel. Visual analysis shows that for experiment No. 1, the surface heat fluxes were 1.8 times greater than for experiment No. 2, at almost the same temperatures on the panel surface in the warm and cold compartments of the chamber.

The practical value of the obtained results, in terms of thermophysical studies of samples of the wall structure of the building, allows estimating the factual heat loss through the wall panel with an effective heat-insulating material [6] and bring the reference values to the operational values of its coefficient of thermal conductivity, considering the specific features of the real operating conditions of the structure. It was found that the insulation of the structure under study with a layer of expanded polystyrene PSB-15, 100 mm thick, reduces heat losses through the wall panel by almost half.

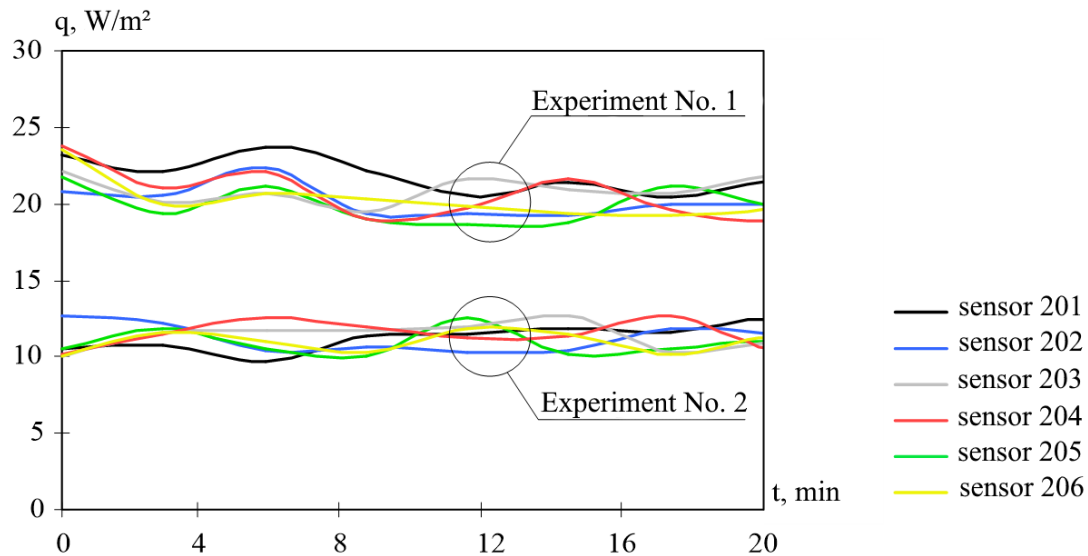


Figure 3. Graphs of changes in heat flows through the wall panel under study for experiment No. 1 – study of heat-insulating properties of a wall panel without insulation and for experiment No. 2 – study of heat-insulating properties of a wall panel with insulation – expanded polystyrene PSB-15.

Evaluating the influence of the resistance of the opaque enclosing structures of the building on the thermal comfort parameters of the premises using the numerical method according to [31], it was established that the used

model considers the dynamic change of heat flows through the wall panels under study (Fig. 3), which were made of different structural materials. The results of calculations for [31] are presented in Figure 4.

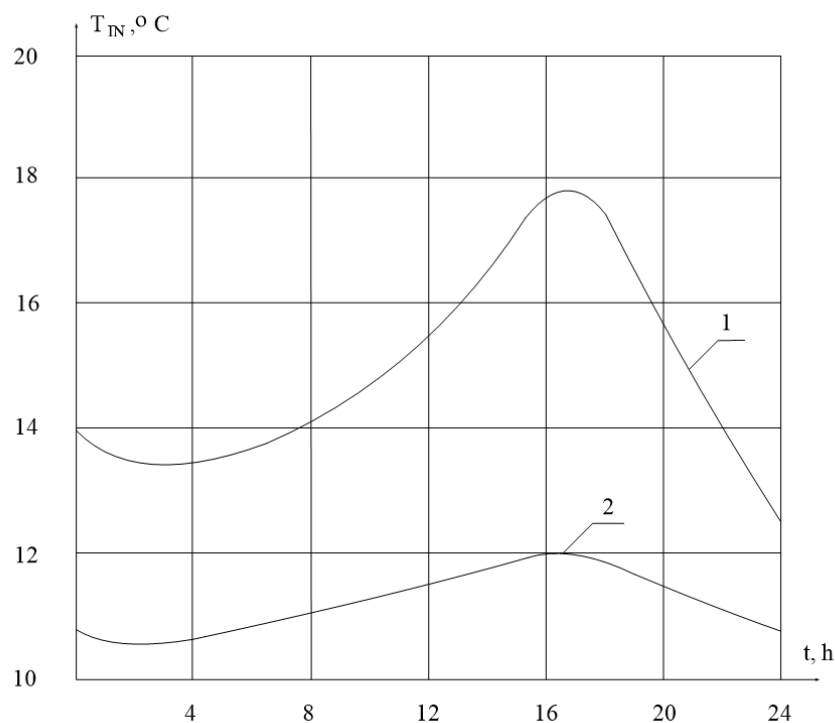


Figure 4. Temperature change on the inner surface of the wall of the room during the day: 1 – the enclosing structures made of multi-layered wall structures with insulation; 2 – the enclosing structures made of brickwork without insulation

Analysis of Figure 4 shows that when the operating mode of the heating system of a public building is introduced in the alternating mode, a substantial temperature change is observed on the inner surface of the enclosing structure. In the case of external walls made of multi-layer wall structures with insulation, the temperature drop reaches $\pm 5^\circ\text{C}$, which meets the requirements [7], in contrast to the

building's enclosing structures made of brickwork without insulation. The latter indicates a substantially lower indicator of the internal heat capacity of such a building.

The above (Fig. 3), in contrast to the results of research given in papers [17; 18], wherein, upon assessing the change in the comfort conditions of the premises from the inertia of the external enclosing structures of the building

during the operation of the heating system in energy-saving modes [17], as well as the dependence of the comfort conditions of public buildings with different degrees of thermal protection of the external enclosing structures in the operating conditions of the building heating system in the regular mode [18], calculated (standardised) and not experimental (operational) values of the thermal conductivity coefficient were accepted. The results obtained in this study allow more accurately determining the factual temperature values on the inner surface of external enclosing structures (Fig. 4) and compare them with the minimum permissible ones [7] upon assessing the comfort conditions of the premises, which complements the results of the study [19], considering national standards [7; 12; 13].

Quasi-stable heating. For the object under study, the mode of intermittent (alternating) heating, as constant heating considering the set temperature value, in mode A and mode B was considered and investigated.

Mode A: the set temperature for calculation is the time average of the set temperature values for periods of constant heating and periods of alternating heating, since the time constant of the building is less than 0.2 of the duration of the shortest period with the alternating heating mode.

Thus, it was experimentally confirmed that an essential factor in the implementation of the regular heating mode

is the thermal inertia of the building, which determines the time interval and the depth of adjustment [16] under the condition of maintaining the comfort parameters of the premises. When switching from constant mode to alternating mode, the average decrease in the temperature of the coolant and indoor air (from 18:00 to 4:00) was 8-10°C and >16°C (at the allowed 12°C), respectively. The recorded outdoor temperature was -3°C. Considering the structure of the external walls of the object under study, the “warm-up” time of the building, the heating system of which has been working for a long time in regular mode, with the achievement of the parameters of thermal comfort of the premises, was established. Thus, the duration of the heating of the “A” type building, when the heating system was operating in the “forced” mode, was 6.5 hours [16]. Savings in the consumed heat energy during the operation of the building’s heating system in alternating mode amounted to 6-8%, the air temperature during this period was maintained at 12°C. An algorithm for controlling the heat release process was developed, considering the internal heat capacity of the building. Compared to the conventional “linear” dependence (inherent in type A buildings), this allows more accurately adjusting the schedule of heat carrier release (Fig. 5) to the heating system of a public building during the introduction of the alternating mode of its operation.

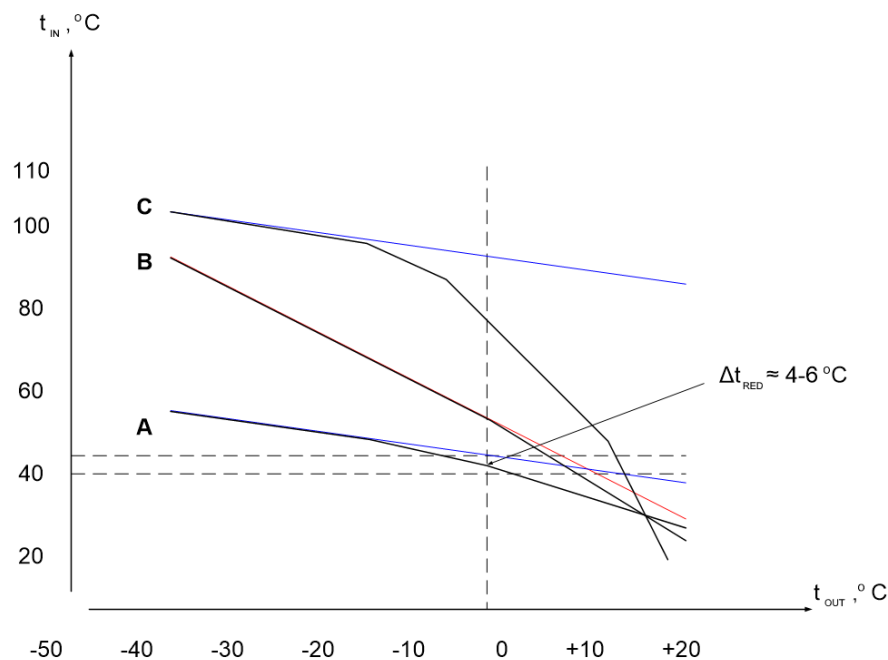


Figure 5. Temperature schedule of heat carrier release to the building’s heating system, considering the outdoor air temperature and the internal heat capacity of the structure

Source: compiled by the author based on [16]

The temperature deviation range is reduced by 4-6°C, which allowed saving up to 10-12% of the consumed thermal energy for the heating needs of the educational and administrative building of NULES of Ukraine under the condition of supporting the normalised (for the alternating regime) values of the internal temperature of the premises.

Mode B: the set temperature for the calculation is

the set temperature for the normal (continuous) heating mode, since the time constant of the building is more than three times the duration of the longest period with the alternating heating mode.

Comparing the data of the factual consumption by the educational and administrative building of the NULES of Ukraine with the calculated reduced to the factual

number of degree-days of the heating period (for March 2019, Table 4 [16]) and the parameters of the comfort of the premises (temperature and air humidity), it was established that with an insignificant ($+1.3^{\circ}\text{C}$) deviations of the indicators of the factual values of the internal air temperature in the premises of the building from the normalised values ($18\pm 2^{\circ}\text{C}$), an excess of the level of factual consumption of thermal energy was observed compared to the calculated value adjusted to the factual number of degree-days by 3.73 Gcal [16]. Thus, during the operation of the heating system of a public building in constant mode (Fig. 6a), there

was an overspend of consumed thermal energy by 7.4% for the heating period of 2018-2019.

Given the structure of the enclosing structures of the object, the influence of heat transfer resistance on the performance indicators of the building heating system was investigated considering the parameters of the external environment and the microclimate of the premises in dynamic mode, a comparison was made of the specific energy consumption indicators of the building “before” the implementation of the heat release process management algorithm considering the indicator of its internal heat capacity (Fig. 6a) and “after” (Fig. 6b).

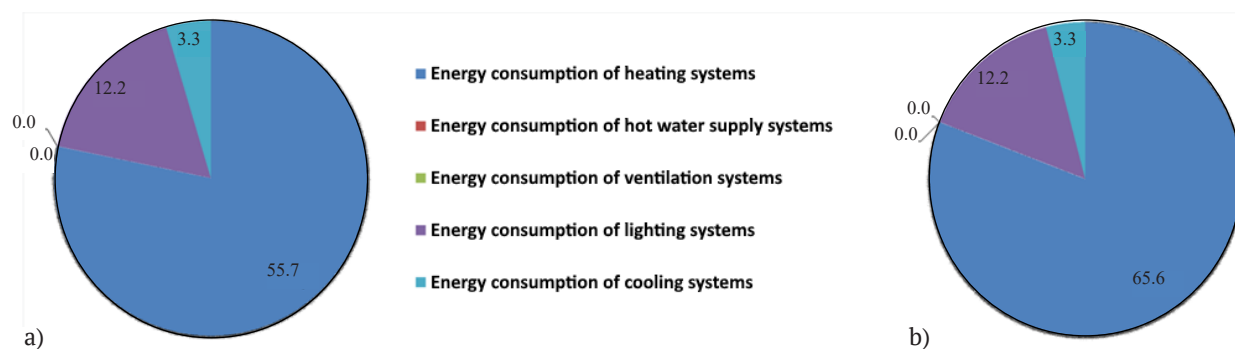


Figure 6. Specific indicators of the building’s energy consumption “after” (a) and “before” (b) the implementation of the heat release process control algorithm, considering the indicator of its internal heat capacity, $\text{kW}\cdot\text{h}/\text{m}^2$.

Therewith, the inclusion of the human thermal comfort model in the complex “heat source – fencing” system [14; 15] is an essential step towards reducing the energy consumption of buildings and ensuring a suitable level of thermal comfort, especially during the introduction of the alternating heating mode. The results obtained in this study regarding the assessment of the influence of the level of thermal protection (heat capacity of the building) on the feeling of thermal comfort of a person during the implementation of a regular heating mode, in contrast to the results of studies given in the papers [23-25], where the feasibility of using adaptive methods of thermal comfort is substantiated [23], and not the algorithms for its achievement, also consider the influence of the thermal inertia of the building, which determines the time interval and the depth of regulation, provided that the comfort parameters of the premises are observed and preserved, and not only their control [25]. This allows adjusting the coolant release schedule more accurately, according to the developed algorithm (Fig. 5) into the heating system of a public building during the introduction of the alternating mode of its operation, considering the outdoor air temperature and national standards [2; 29].

Given the factual indicators of savings in consumed heat energy during the operation of the building’s heating system in alternating mode at the level of 6-8%, as well as the deviation of the factual values of the internal air temperature in the building from the normalised values, the total indicator of savings in consumed heat energy was 14-16% (Fig. 6), which complements the results of studies [14; 15; 32]. Considering the above, the intermittent (alternating) operation of the heating system of public buildings, the expediency of which is justified in this study, can be recommended for implementation in the structures of higher educational institutions of Ukraine.

CONCLUSIONS

When assessing the thermal state of the building and the thermal comfort parameters of the rooms, those factors that affect its internal heat capacity and, accordingly, thermal inertia, are determined and considered. Reasonable expediency of implementing an intermittent (alternating) mode of operation of the heating system of public buildings and facilities of higher education institutions, namely:

1. It was experimentally confirmed that an essential factor in the implementation of the regular heating mode is the thermal inertia of the building, which determines the time interval and the depth of adjustment under the condition of maintaining the comfort parameters of the premises. When switching from constant mode to alternating mode, the average decrease in the temperature of the coolant and indoor air (from 18:00 to 4:00) was $8-10^{\circ}\text{C}$ and $>16^{\circ}\text{C}$ (at the allowed 12°C), respectively. The recorded outdoor temperature was -3°C .

2. Considering the structure of the external walls of the object under study, the “warm-up” time of the building, the heating system of which has been working for a long time in regular mode, with the achievement of the parameters of thermal comfort of the premises, was established. Thus, the duration of the heating of the “A” type building, when the heating system was operating in the “forced” mode, was 6.5 hours. Savings in the consumed heat energy during the operation of the building’s heating system in alternating mode amounted to 6-8%, the air temperature during this period was maintained at 12°C .

3. Evaluating the influence of the resistance of the enclosing structures on the thermal comfort parameters of the premises using the numerical method, it was established that the used model considers the dynamic change

of heat flows through the wall panels under study, which were made of different materials, including in the alternating mode. Thus, in the case of external walls made of multi-layer wall structures with insulation, the temperature drop reaches $\pm 5^{\circ}\text{C}$, in contrast to the building's enclosing structures made of brickwork without insulation.

4. An algorithm for controlling the heat release process was developed, considering the internal heat capacity of the building. Compared to the conventional "linear" dependence, this allows more accurately adjusting the schedule of heat carrier release to the heating system of a public building during the introduction of the alternating mode of its operation. The temperature deviation range is reduced by $4-6^{\circ}\text{C}$, which allowed saving up to 10-12% of the consumed thermal energy for the heating needs of the educational and administrative building of NULES of Ukraine under the condition of supporting the normalised values of the internal temperature of the premises.

5. Given the factual indicators of savings in consumed heat energy during the operation of the building's heating system in alternating mode at the level of 6-8%, as well as the deviation of the factual values of the internal air temperature in the building from the normalised values, the total indicator of savings in consumed heat energy was 14-16%.

In summary, intermittent (alternating) operation of the heating system of public buildings, the expediency of which is justified in this study, can be recommended for implementation in the structures of higher educational institutions of Ukraine. Therewith, the issue of establishing the limit time for cooling and "warm-up" of the building in the "forced" mode, considering the factual value of its thermal inertia under the operating conditions of the controller of the individual thermal point according to the developed algorithm for controlling the process of releasing heat into the building's heating system, requires further research.

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Аналіз впливу внутрішньої теплоємності громадської будівлі на параметри теплового комфорту приміщень при роботі системи опалення в черговому режимі

Анотація. У кліматичних умовах України, які характеризуються довгим опалювальним періодом, значні енергопотребити на опалення призводять до зростання вимог щодо енергоефективності. Суттєвому зниженню енергоспоживання будівель при забезпеченні умов комфортності сприятиме включення моделі теплового комфорту людини до складної системи «джерело тепла – огородження». Мета цього дослідження – визначення чинників, які впливають на внутрішню теплоємність та, відповідно, теплову інерцію будівлі і подальше врахування цих факторів при оцінці теплового стану та параметрів теплового комфорту кімнат будівлі. Об'єкт дослідження – навчально-адміністративний корпус НУБіП України. Проведено ряд досліджень, зокрема натурні виміри теплових потоків і температур на поверхнях зразків стінової конструкції будівлі виконувались в спеціальному кліматичному комплексі, який дозволяє штучно створювати зовнішні та внутрішні теплові умови приміщень. Показано, що утеплення конструкції шаром пінополістиролу ПСБ-15, товщиною 100 мм, дозволяє знизити теплові втрати через стінову панель майже вдвічі. Розроблено алгоритм управління процесом відпуску теплоти з урахуванням показника внутрішньої теплоємності будівлі. Порівняно з «лінійною» залежністю це дозволяє більш точно коригувати графік відпуску теплоносія в систему опалення громадської будівлі під час впровадження чергового режиму її роботи. Діапазон відхилення температур знижується на 4–6 °С, що дозволило заощадити до 10–12 % спожитої теплової енергії на потреби опалення об'єкту дослідження при умові збереження нормованих значень внутрішньої температури приміщень. Переривчастий режим роботи системи опалення громадських будівель, доцільність якого обґрунтована в даному дослідженні, може бути рекомендований до впровадження у спорудах закладів вищої освіти України

Ключові слова: тепла енергія, енергопотребити, енергоефективність, опалювальний період, тепла інерція, алгоритм управління, система опалення