

Запропоновано інноваційні проектні та конструктивно-технологічні рішення з підвищення енергетичної ефективності будівель і споруд, які почали експлуатуватися до 90-х років минулого століття. Ці рішення передбачають введення до складу існуючої системи термомодернізації нових транзитних трубопроводів системи водяного опалення вкупі з еквівалентною фасадною теплоізоляцією. Показано, що розроблені рішення приводять до суттєвого зменшення енергоспоживання існуючих будівель і споруд та сприяють підтриманню комфортних умов для життєдіяльності

Ключові слова: термомодернізація будівель і споруд, фасад, енергоефективність, теплоізоляція, система водяного опалення

Предложены инновационные проектные и конструктивно-технологические решения по повышению энергетической эффективности зданий и сооружений, которые начали эксплуатироваться до 90-х годов прошлого века. Эти решения предусматривают введение в состав существующей системы термомодернизации новых транзитных трубопроводов системы водяного отопления вместе с эквивалентной фасадной теплоизоляцией. Показано, что разработанные решения приводят к существенному уменьшению энергопотребления существующих зданий и сооружений и способствуют поддержанию комфортных условий для жизнедеятельности

Ключевые слова: термомодернизация зданий и сооружений, фасад, энергоэффективность, теплоизоляция, система водяного отопления

MODELING OF ENERGY EFFICIENT SOLUTIONS REGARDING THE HEATING SYSTEM AND THE FACADE HEAT INSULATION IN THE IMPLEMENTATION OF THERMOMODERNIZATION

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1. Introduction

Paper [1] outlines prospects for modernization. It takes into consideration an analysis of existing information on the features of thermomodernization of residential buildings and constructions. It considers modernization as part of a system of central water heating and facade heat insulation. It notes, specifically, that such a modernization should take into consideration many factors, including geometrical, physical and heat engineering parameters of facade walls, location of window openings, the existence of decorative elements and gutters, designed temperature mode of operation. Optimal design parameters and material for both transit pipelines and facade heat insulation are equally important for practical application.

The study substantiates the developed technical solutions for improving energy efficiency. Underlying it is a series of experimental-numerical and calculation studies. It provides effective structural parameters and material for the examined elements of a thermomodernization (thermal sanitation) system of residential buildings and structures whose operation started before the 90-ies of the last century.

Estimates by international experts on thermomodernization confirm the relevance of the research conducted. According to the calculations, it is necessary to spend about UAH 300 billion for heat insulation of individual houses in Ukraine. And the amount is not less than UAH 400 billion for multi-apartment buildings [2]. That is, the cost of energy-efficient solutions that are to be made based on the research results is too high, therefore, such solutions require thorough investigation, in particular, preliminary modeling.

2. Literature review and problem statement

We should note that the confirmation of any hypotheses or developed technical solutions for improvement of energy efficiency of residential buildings and structures is typically performed experimentally. It also takes into consideration the existing normative and technical documentation and results of research into this topic.

Article [1] states that the modernization of a heating system together with an insulation of a facade wall (equivalent to facade insulation), in particular, based on determining a

thermal resistance index of building structure R , is one of the defining stages of thermomodernization. It is advisable to carry out numerical modeling taking into consideration many factors, including design modes of operation of buildings and structures, as well as structural and heat engineering indicators to significantly reduce a number of field experiments.

Papers [3–5] represent regulatory and technical basis for the implementation of thermomodernization of Ukrainian buildings and structures. Study [3] considers guidelines for the implementation of thermomodernization of residential buildings in the form of DSTU B V.3.2-3: 2014. DBN (State Construction Standards) B.2.6-31: 2016 relate to the thermal insulation of buildings [4]. Brochure [5] outlines a number of technical aspects for the implementation of thermomodernization in the form of project documentation.

Authors of paper [6] applied model approaches. They proposed using a polyoptimal method based on the theory of fuzzy sets to determine effective schemes of thermomodernization of buildings and structures. There are numerical evaluation and experimental verification of a frequency of natural fluctuations of buildings before and after their thermomodernization in article [7]. Study [8] investigates various aspects of thermomodernization of a building and how it affects an internal microclimate of premises. Paper [9] describes the effect of thermomodernization of buildings and structures on the energy-efficient use of energy carriers.

Authors of article [10] analyze influence of the proposed technical solutions on thermomodernization of a residential building on the achievement of energy efficiency indicators. Paper [11] proposes a mathematical model that describes the dynamics of behavior of a centralized heating system during maintenance of buildings and structures. Work [12] is part of the above-mentioned integrated approach. It describes the expediency of using structural-parametric models to study complex structures and technologies using a specific example. Such models make it possible to illustrate and analyze relationships between structural elements of the examined system or a technology in general.

Paper [13] proposes simpler technical solutions for thermomodernization, in particular, using another insulation material, which provides air diffusion. It states that such material will contribute to an increase in energy efficiency of facade insulation of buildings and structures. Work [14] describes an analysis of results of modeling of energy efficiency parameters for facades of buildings and structures based on the obtained thermographic 3D models and orthogonal images. Paper [15] states that it is necessary to combine an external insulation system with any type of insulation to achieve the best result on energy efficiency for all climatic zones of location of buildings and structures. Article [16] suggests a procedure for the estimation of an external thermal insulation composition system used for the insulation of buildings and structures taking into consideration various factors.

Study [17] describes mathematical modeling of thermal characteristics in buildings of different types. The modeling involves calculation of thermal energy taking into consideration a loss of convection from an external facade of a building, the energy of the Sun, and operating internal loads due to mass-dimensional characteristics of a constructed structure. Article [18] reports a study into non-traditional system of house heating constructed in the form of a radiating panel. Heating by the radiation of panels regulates the temperature mode of a house.

Work [19] describes a new model for studying thermophysical properties of switching insulation, so-called U-element. The U-element model structurally contains a double-glass unit. Glass has a form of a semi-transparent insulating panel installed inside. In paper [20], authors propose effective natural heat-insulating materials, which are used for facade insulation made of hemp fiber biomass. Such materials have a relatively low density compared to other heat-insulating materials, and, in addition, a porous structure.

Paper [21] analyzes a model proposed by authors for a building with a ventilated facade, based on which it is possible to make calculations concerning the energy demand of a building's facade, taking into consideration values of temperatures in the outer layer of a facade and inside its cavity.

Low-frequency ultrasonic processing of liquid polymeric raw materials used in the formation of porous facade composite insulation materials is an effective method that increases productivity of such a formation [22]. It is mainly executed at the stage of extrusion of thermoplastics in the manufacture of heat-insulating composite materials [23]. Paper [24] describes features of calculation and experimental verification of structural and technological parameters of an ultrasonic cavitation device based on a rectangular radiating plate, which performs bending vibrations along and across a radiating plate. It is advisable to use such a technique and a device in the production of innovative thermal insulation elements made of polymer composite materials.

However, we should note that the above analysis of the scientific literature reveals a relatively small number of publications devoted to this problem, despite its relevance. It is also worth noting that universal energy-efficient solutions, scientifically based on results of experimental numerical calculations, are limited. Thus, the scientific substantiation of the designed project construction and technical solutions developed to improve energy efficiency of existing buildings and structures is an important present-day task. It is promising both for enterprises in construction industry and for utilities companies in the communal economy.

3. The aim and objectives of the study

The aim of present study is to perform numerical and experimental-and-calculation modeling of the developed innovative design and constructional and technological solutions concerning significant reduction of energy consumption of existing buildings and structures of the facilities in operation longer than 30 years while conducting thermomodernization of Ukrainian buildings and structures. This is supposed to be done based on the improvement of a heating system and facade insulation, taking into consideration international experience.

It is necessary to solve the following tasks to accomplish the objective:

- development of innovative design and constructional and technological solutions for a significant reduction of energy consumption of existing buildings and structures of the Ukrainian housing stock;
- modeling of the proposed design solutions based on numerical calculations with the subsequent confirmation of the obtained results of calculations by field experiments;

– scientific substantiation of effective design parameters and material of elements of a heating system and facade insulation.

4. The examined design and constructional-and-technological solutions for thermomodernization

Fig. 1–9 show the examined design and constructional-and-technological solutions for thermomodernization of buildings and structures.

We accepted the following designations for Fig. 1–7: 1 – existing external (facade) wall of a thermomodernized building (hereinafter – a wall); 2 – a layer of equivalent facade insulation (hereinafter – facade insulation); 3 – an adhesive layer intended for fastening of facade thermal insulation to the existing external wall; 4 – a liquid heat-transfer agent; 5 – a layer of equivalent pipe heater; 6 – new transit pipelines of two-pipe system of central water heating (hereinafter – pipelines); 7 – a heating device with a side connection; 7' – a heating device with a lower connection; 8 – a distribution overhead comb; 9 – a new indent made in the existing wall 1 or in facade heat insulation 2 (hereinafter – an indent); 10 – a through hole in the existing wall 1; 11 – windows or translucent constructions; 12 – radiator fittings; 13 – an external protective layer that protects facade heat insulation 2 from atmospheric precipitation and/or ultraviolet radiation; D – an outer diameter of pipelines, mm; B_D – depth (height) of an indent, mm; B_W – width of an indent, mm; B_{min} – thickness of a facade heat insulation layer 2, mm; $B_{min,UA}$ – thickness of a layer of equivalent facade insulation in accordance with the climatic zones of Ukraine, mm; δ_T – thickness of an equivalent layer of thermal insulation, mm.

Fig. 1 shows the general scheme of a system of complex thermomodernization of buildings and structures [25]. We investigate its individual elements and its method of implementation [26] in the present paper. Roman numerals (II–XVII) mark individual elements (design solutions) of the thermomodernization system in Fig. 1. Fig. 2–5 present them separately, and they are marked accordingly in the upper part of these figures.

Fig. 2 shows the design solutions (II–V) for the location of heating devices with a lower connection (Fig. 2, a, c) and a side connection (Fig. 2, b, d) of thermostatic valve 12 to pipelines 6, which are located in indents made in the wall 1 at the side of its attachment to facade heat insulation 2.

Fig. 3 shows the fragments (VI–IX) of wall section 1. It presents two pipelines 6 in indents of rectangular (Fig. 3, a), triangular (Fig. 3, b) and arched (Fig. 3, c) forms. It also shows location of one pipeline 6 in rectangular indents (Fig. 3, d).

Fig. 4 shows the fragments (X–XIII) of wall section 1. It presents one pipeline 6 located in indents of the rectangular (Fig. 4, a) or arched (Fig. 4, b) forms, as well as the arrangement of two pipelines 6 in rectangular indents (Fig. 4, c) or triangular indents (Fig. 4, d) forms made in the layer of facade heat insulation 2.

Fig. 5 shows the fragments (XIV–XVII) of wall section 1. It presents two pipes 6 in indents of arch (Fig. 5, a) form and location of one pipe 6 in indents of rectangular (Fig. 5, b), triangular (Fig. 5, c) and arched (Fig. 5, d)

forms, which are made in the layer of facade heat insulation 2.

Fig. 6, 7 show calculation-and-experimental results of design solutions when placing pipes 6 in two variants (A) and (B), each of which includes three calculation-and-experimental cases. Thus, for the variant (A), we placed new pipelines 6 into indent 9 made in wall 1 at the side of its attachment to facade insulation 2 (calculation-and-experimental cases number 4, number 5, number 6). For the variant (B), we placed 6 pipes into indent 9, which was made in facade insulation 2 at the side of its attachment to existing wall 1 (calculation-and-experimental cases Nos. 1, 2, 3).

Fig. 7 also shows graphical dependences of the temperature fall of heat carrier 4 over time in pipelines 6 in two operating modes when the thickness of a layer of the facade insulation B_{min} varies. Estimated (normative) temperature is $T=+80^\circ\text{C}$.

Fig. 8, 9 represent results of experimental-and-numerical studies on the distribution of temperature T in the investigated elements of the thermomodernization system. The estimated temperature inside a room is $T=+20^\circ\text{C}$.

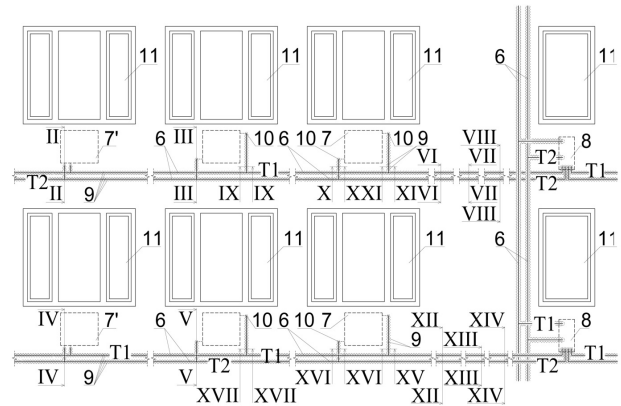


Fig. 1. General scheme of the examined system of complex thermomodernization of a building

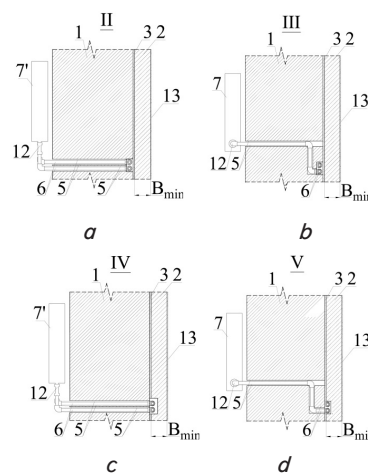


Fig. 2. Examined design solutions (II–V) for the location of heating devices with the connection of thermostatic valve 12 to pipelines 6, which are located in the indents executed in wall 1 at the side of its attachment to facade insulation 2: a, c – bottom connection; b, d – side connection

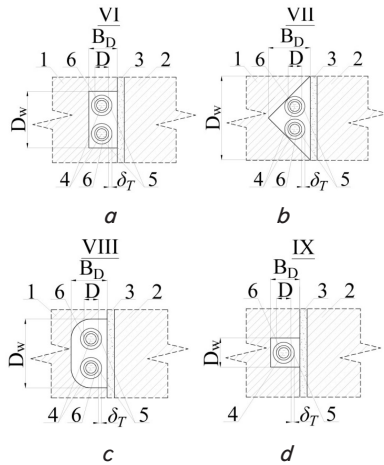


Fig. 3. Fragments (VI–IX) of wall section 1 where there are one or two pipelines 6 in the indents of different geometrical forms: *a* – location of two pipelines 6 in rectangular indents; *b* – location of two pipelines 6 in triangular indents; *c* – location of two pipelines 6 in arched indents; *d* – location of one pipeline 6 in rectangular indents

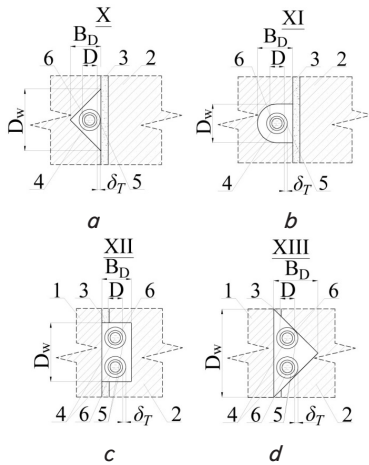


Fig. 4. Fragments (X–XIII) of wall section 1 or the layer of facade heat insulation 2 where there are one or two pipelines 6 in the indents of different geometrical forms: *a* – location of one pipeline 6 in the indent of rectangle form with identical catheti executed in wall 1; *b* – location of one pipeline 6 in an arched indent made in wall 1; *c* – location of two pipelines 6 in rectangular indents made in the layer of facade heat insulation 2; *d* – location of two pipelines 6 in triangular indents made in the layer of facade heat insulation 2

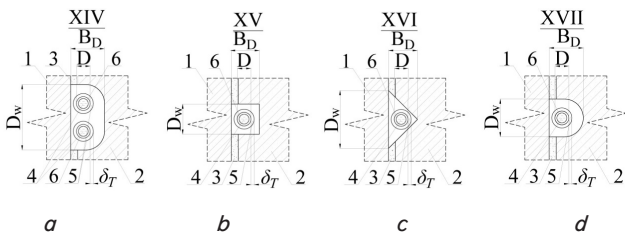


Fig. 5. Fragments (XIV–XVII) of wall section 1 where there are one or two pipelines 6 in indents of various geometrical shapes made in the layer of facade insulation 2: *a* – location of two pipelines 6 in arched indents; *b* – location of one pipeline 6 in rectangular indents; *c* – location of one pipeline 6 in triangular indents; *d* – location of one pipeline 6 in arched indents

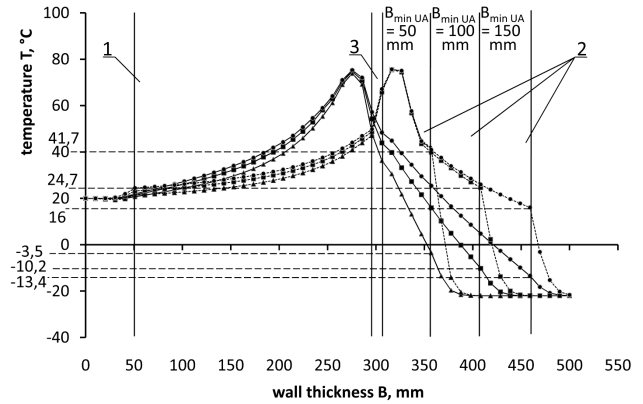


Fig. 6. Temperature change in elements of the building structure depending on thickness of the facade insulation $B_{min,UA}$ for calculation-and-experimental cases No. 1 – No. 3 at the location of pipelines 6 in the wall, and for calculation-and-experimental cases No. 4 – No. 6 at the location of pipelines 6 in the layer of facade heat insulation 2, with constant thickness of adhesive layer 3:
 ---▲--- calculation-and-experimental case No. 1, $B_{min,UA}=50$ mm; ---■--- calculation-and-experimental case No. 2, $B_{min,UA}=100$ mm; — calculation-and-experimental case No. 3, $B_{min,UA}=150$ mm; —▲— calculation-and-experimental case No. 4, $B_{min,UA}=50$ mm; —■— calculation-and-experimental case No. 5, $B_{min,UA}=100$ mm; —●— calculation-and-experimental case No. 6, $B_{min,UA}=150$ mm

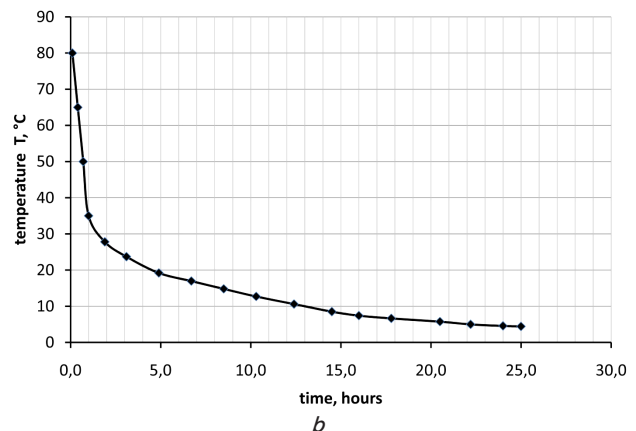
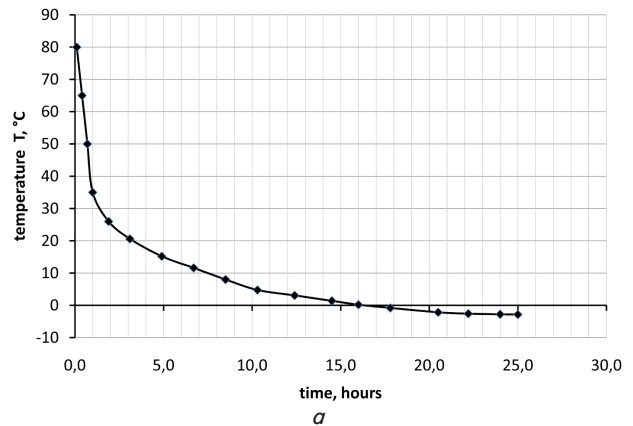


Fig. 7. Changes in the temperature of heat-transfer agent 4 over time in pipelines 6 due to the design temperature of a heat-transfer agent $T=+80$ °C to $T=0$ °C: *a* – at $B_{min}=50$ mm; *b* – at the complete cessation of a movement of a heat-transfer agent at $B_{min}=100$ mm

Fig. 8. *a–c* shows temperature distribution in the elements of the thermomodernization system with a different thickness of B_{min} of the facade heat insulation 2.

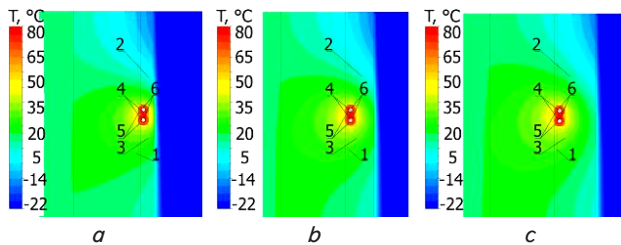


Fig. 8. Temperature distribution in elements of the thermomodernization system with variable thickness of the facade insulation B_{min} for calculation-and-experimental cases Nos. 1–3 of the indents in wall 1:

- a* – calculation-and-experimental case No. 1, $B_{min}=50$ mm;
- b* – calculation-and-experimental case No. 2, $B_{min}=100$ mm;
- c* – calculation-and-experimental case No. 3, $B_{min}=150$ mm

Fig. 9. *a–c*, shows temperature distribution in the elements of the thermomodernization system with a variable thickness B_{min} of the facade heat insulation 2.

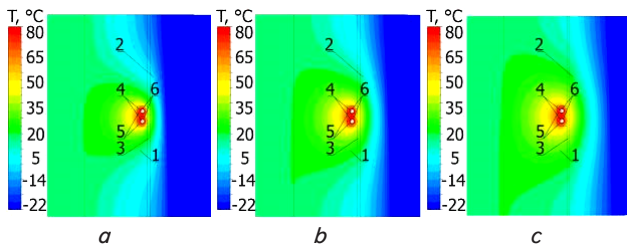


Fig. 9. Temperature distribution in the elements of the system of thermomodernization with variable thickness of the facade insulation B_{min} for calculation-and-experimental cases Nos. 4–6 of the indents in facade heat insulation 2:

- a* – calculation-and-experimental case No. 4, $B_{min}=50$ mm;
- b* – calculation-and-experimental case No. 5, $B_{min}=100$ mm;
- c* – calculation-and-experimental case No. 6, $B_{min}=150$ mm

We should determine optimal parameters and effective materials for the creation of structural elements of the system, including the optimal thickness of B_{min} layer of facade heat insulation 2 and geometrical parameters of pipelines 6 both experimentally and in the experiment-and-calculation procedure. Heat cuts (Fig. 9) can be simulated graphically using the software and computational capabilities in the environment of the universal programming system of a finite element analysis.

We used the following parameters and characteristics, as well as operating conditions, for calculation-and-experimental cases (Nos. 1–6). The ambient temperature was $T=-22$ °C; the design temperature of the heat-transfer agent 4 was $T=+80$ °C.

We used the following materials. Wall material 1 – foam concrete, wall thickness – 250 mm. Characteristics of foam concrete in the dry state: density – 1,000 kg/m³; specific heat capacity – 0.84 kJ/(kg·°C); coefficient of thermal conductivity – 0.29 W/(m²·°C); calculation coefficient of thermal conductivity – 0.47 W/(m²·°C).

Facade thermal insulation 2 – PSB-S-25 foam plastic with the following characteristics: density – 25 kg/m³; specific heat capacity – 1.26 kJ/(kg·°C); coefficient of thermal

conductivity – 0.039 W/(m²·°C); calculation thermal conductivity – 0.042 W/(m²·°C).

Material of pipelines 6 – polypropylene with the following characteristics: density – 900 kg/m³; specific heat capacity – 1.93 kJ/(kg·°C); coefficient of thermal conductivity – 0.22 W/(m²·°C); calculated thermal conductivity coefficient – 0.22 W/(m²·°C). The diameter of pipelines 6 was $D=20$ mm, thickness of the wall of the pipelines was 6–2.8 mm.

Equivalent pipe insulation 5 – the foamed polyethylene, which is mounted above pipelines 6, with the following characteristics: density – 40 kg/m³; specific heat capacity – 1.8 kJ/(kg·°C); coefficient of thermal conductivity – 0.37 W/(m²·°C); calculated thermal conductivity coefficient – 0.037 W/(m²·°C). Thickness of the insulation of pipelines 6 was $\delta_T=13$ mm.

Adhesive seam. We added an adhesive seam between the existing wall 1 and the facade insulation. The properties of the adhesive seam are as follows: density $\rho=1,800$ kg/m³; specific heat capacity $c=0.84$ kJ/(kg·°C); coefficient of thermal conductivity for conditions “B” $\lambda(B)$: 0.93 W/(m²·°C).

The study also took into consideration (designed or estimated) the coefficient of resistance of external enclosing structure R_s , m²·K/W, which determines the ratio of a temperature difference on both sides of heat-insulating material to a value of the heat flow, which passes through the heat-insulating material. The coefficient depends on the applied temperature zone of Ukraine according to DBN (State Construction Standards) [4].

5. Distribution of a temperature field inside a building structure

We investigated the distribution of temperature field T inside the building structure of a thermomodernized building experimentally and by calculation. In this case, pipelines 6 are located in indent 9 made in wall 1 at the side of its attachment to the facade heat insulation 2 of the thermomodernized building.

We found that an average temperature inside the building structure increases with an increase in thickness of B_{min} of the layer of facade heat insulation 2. For example, there is an increase in the average temperature inside the building structure from $T=40$ °C up to $T=42$ °C with an increase in thickness of B_{min} of the layer of facade insulation 2 from 50 mm to 100 mm. Fig. 6 illustrates a given case.

There is an increase in the average temperature inside the building structure from $T=40$ °C to $T=44$ °C with an increase in thickness of B_{min} of the layer of facade heat insulation 2 from 50 mm to 150 mm. It also contributes to the additional drainage of the building structure, which increases the efficiency of the system of integrated thermomodernization indirectly, and, in turn, leads to an improvement in thermal characteristics of the thermomodernized building.

We calculated the time required for heat-transfer agent 4 to reach the limiting temperature $T=0$ °C at the complete cessation of heat-transfer agent 4 movement in the calculation-and-experimental cases No. 4–6. This can occur, for example, in the case of a pump failure or temporary interruptions of electricity supply.

In this case, we considered three values of thickness of the facade heat insulation 2: $B_{min}=50$ mm, $B_{min}=100$ mm, $B_{min}=150$ mm. We found that the cooling of heat-transfer

agent 4 from $T=+80\text{ }^{\circ}\text{C}$ to $T=0\text{ }^{\circ}\text{C}$ occurs at $B_{\min}=50\text{ mm}$ in 16 hours (Fig. 7, *a*). Sometimes, such cooling can lead to a violation of the integrity of pipelines 6.

The cooling of heat-transfer agent 4 from $T=+80\text{ }^{\circ}\text{C}$ to $T=+8\text{ }^{\circ}\text{C}$ occurs at $B_{\min}=100\text{ mm}$ in 16 hours (Fig. 7, *b*). The temperature of heat-transfer agent 4 becomes stable after 23 hours at the level $T=+5\text{ }^{\circ}\text{C}$ and stays the same for 48 hours. We did not carry out calculations for the thickness of equivalent facade insulation 2, which is $B_{\min}=150\text{ mm}$, because at a thickness of $B_{\min}=100\text{ mm}$, even after 48 hours, there is no freezing of heat-transfer agent 4, which indicates that freezing of heat-transfer agent 4 will not happen either at $B_{\min}=150\text{ mm}$.

Based on the above analysis, we determined experimentally that the minimum thickness of B_{\min} for facade insulation 2 should be $B_{\min}=100\text{ mm}$ for the investigated temperature regime and operating conditions (temperature zone). The same value of B_{\min} correlates with characteristics of the materials used, the geometry of pipelines and facade heat insulation 2. Such a thickness of the equivalent facade insulation layer 2 prevents destruction of pipelines 6 under the mode of intensive operation.

It follows from the above calculation-and-experimental cases that the optimal placement of pipelines 6 is the location in indents 9 made in wall 1, and covered further by a layer of the equivalent thermal insulation 2 with a thickness of $B_{\min}=100\text{ mm}$.

The developed technical solution also improves the hydraulic mode of heat-transfer agent 4 movement and possibility of using both high- and low-temperature heat-transfer agent 4. This is due to the fact that modern heat sources have a maximum efficiency when working under a low temperature mode.

Fig. 7, *a* shows a change in the temperature of heat-transfer agent 4, which flows in pipelines 6, with time $t_{50}=16\text{ hours}$ at the complete cessation of its motion and thickness of the layer of facade insulation 2 $B_{\min}=50\text{ mm}$ (the subscript at t_{50}). Fig. 7, *b* shows a change in the temperature of heat-transfer agent 4, which flows in pipelines 6, with time $t_{100}=16\text{ hours}$ at the complete cessation of its motion and thickness of the layer of facade insulation 2 $B_{\min}=100\text{ mm}$ (the subscript at t_{100}).

Thus, we established that the time of the heat-transfer agent 4 cooling depends on the diameter D of pipelines 6 and it changes proportionally at the complete cessation of its flow through pipelines 6. However, after a certain time, the freezing of heat-transfer agent 4 occurs. This means that thickness $B_{\min}=50\text{ mm}$ of facade insulation 2 is not applicable in those heating systems where a heat-transfer agent movement can be completely stopped. The value of parameter t_{50} varies from 8 hours to 19 hours, which is generally inappropriate, because heat-transfer agent 4 may technologically freeze during this time. At the same time, an increase in the thickness of facade insulation 2 to $B_{\min}=100\text{ mm}$ (Fig. 7, *b*) leads to a 100 % protection against freezing of pipelines 6 even at the complete stop of the heat-transfer agent 4 movement.

6. Investigation of temperature values on the surface of a facade insulation

In the calculation-experimental case No. 1 (Fig. 8, *a*), pipelines 6 are located in indent 9 made in the layer of fa-

cade insulation 2 at the side of its attachment to wall 1; the temperature on the surface of facade heat insulation 2 at a thickness $B_{\min}=50\text{ mm}$ is $T=+41.7\text{ }^{\circ}\text{C}$.

In the calculation-experimental case No. 4 (Fig. 9, *a*), pipelines 6 are located in indent 9 made in wall 1 at the side of its attachment to facade insulation 2; the temperature on the surface of facade heat insulation 2 at thickness $B_{\min}=50\text{ mm}$ is $T=-3.5\text{ }^{\circ}\text{C}$.

For calculation-experimental cases No. 1 and No. 4 with the same thickness of facade insulation 2, which is $B_{\min}=50\text{ mm}$, thermal losses in the surrounding space are significantly reduced. The temperature on the surface of facade insulation 2 in case No. 1 is $\Delta T=+41.7\text{ }^{\circ}\text{C}$, and in case No. 4 is $T=-3.5\text{ }^{\circ}\text{C}$, which makes the absolute difference in $\Delta T=45.2\text{ }^{\circ}\text{C}$ between these calculation-and-experimental cases. This, in turn, leads to a reduction in thermal losses in the surrounding space, affects the cooling of heat-transfer agent 4, and leads to heat losses at the calculation temperature of the outside air, which is $T=-22\text{ }^{\circ}\text{C}$ directly proportionally.

It also follows from the above that the location of pipelines 6 in indents 9 made in walls 1 at the side of its attachment to facade insulation 2, the calculation-and-experimental case No. 1 (Fig. 8, *a*), reduces thermal losses substantially (by 92 %) in comparison with the calculation and experimental case No. 4 (Fig. 9, *a*) when pipelines 6 are placed in indents 9 made in facade heat insulation 2 at the side of its attachment to wall 1.

In the calculation-and-experimental case No. 2 (Fig. 8, *b*), pipelines 6 are located in indent 9 made in the layer of facade heat insulation 2 at the side of its attachment to wall 1; the temperature on the surface of facade heat insulation 2 at thickness $B_{\min}=100\text{ mm}$ is $T=+24.7\text{ }^{\circ}\text{C}$.

In the calculation-and-experimental case No. 5 (Fig. 9, *b*), pipelines 6 are located in indent 9 made in wall 1 at the side of its attachment to facade insulation 2; the temperature on the surface of facade heat insulation 2 at a thickness $B_{\min}=100\text{ mm}$ is $T=-10.2\text{ }^{\circ}\text{C}$.

For calculation-and-experimental cases No. 2 and No. 5 with the same thickness of facade thermal insulation 2, which is $B_{\min}=100\text{ mm}$, the thermal losses in the surrounding space are substantially reduced. Indeed, the temperature on the surface of facade heat insulation 2 in the case No. 2 is $T=+24.7\text{ }^{\circ}\text{C}$, and in the case of No. 5, is $T=-10.2\text{ }^{\circ}\text{C}$, which makes the absolute difference in $\Delta T=34.9\text{ }^{\circ}\text{C}$ between two calculation-and-experimental cases No. 2 and No. 5. This, in turn, leads to a decrease in thermal losses in the surrounding space, directly proportional to the cooling of heat-transfer agent 4 and to heat losses at the designed temperature of the outside air, which is $T=-22\text{ }^{\circ}\text{C}$.

It also follows that the location of pipelines 6 in indents 9 made in walls 1 at the side of attachment to facade insulation 2, the calculation-and-experimental case No. 2 (Fig. 8, *c*), reduces thermal losses substantially (by 70 %) in comparison with the calculation-and-experimental case No. 5 (Fig. 9, *b*) with the placement of pipelines 6 in indents 9 made in facade heat insulation 2 at the side of its attachment to wall 1.

In the calculation-experimental case No. 3 (Fig. 8, *c*), pipelines 6 are located in indent 9 made in the layer of facade heat insulation 2 at the side of its attachment to wall 1; the temperature on the surface of facade heat insulation 2 at thickness $B_{\min}=150\text{ mm}$ is $T=+16\text{ }^{\circ}\text{C}$.

In the calculation-experimental case No. 6 (Fig. 9, *c*), pipelines 6 are located in indent 9 made in wall 1 at the side of the attachment of facade heat insulation 2 to it; the tem-

perature on the surface of facade insulation 2 at thickness $B_{\min}=150$ mm is $T=-13.4$ °C.

We determined that in the case of the location of pipelines 6 in indents 9 made in wall 1, the temperature on the surface of facade heat insulation 2 is: for the calculation-and-experimental case No. 4 (Fig. 8, *a*) at $B_{\min}=50$ mm, $T=-3.5$ °C. For the calculation-and-experimental case No. 5 (Fig. 8, *b*) at $B_{\min}=100$ mm, the temperature on the surface of facade thermal insulation 2 is $T=-10.2$ °C; for the calculation-and-experimental case No. 6 (Fig. 8, *c*) at $B_{\min}=150$ mm, $T=-13.4$ °C. We found that in the case of the location of pipelines 6 in indents 9 made in facade heat insulation 2 the temperature on facade heat insulation 2 is: for the calculation-and-experimental case No. 1 (Fig. 9, *a*) at $B_{\min}=50$ mm, $T=+40$ °C. For the calculation-and-experimental case No. 2 (Fig. 9, *b*) at $B_{\min}=100$ mm, the temperature on the surface of facade heat insulation 2 is: $T=+24.7$ °C; for the calculation case No. 3 (Fig. 9, *c*) at $B_{\min}=150$ mm, $T=+16$ °C.

The above results regarding the temperature values on the surface of facade heat insulation 2 optimize its thickness B_{\min} indirectly.

7. Optimization of thickness of the facade insulation

For calculation-and-experimental cases No. 3 and No. 6 at the same thickness of facade insulation 2, which is $B_{\min}=150$ mm, thermal losses in the surrounding space are substantially reduced. After all, the temperature on the surface of the equivalent facade heat insulation 2 in case No. 3 is $T=+16$ °C, and in the case of No. 6 is $T=-13.4$ °C. This makes the absolute difference $\Delta T=29.4$ °C between these calculation-and-experimental cases.

In turn, this leads to a decrease in thermal losses in the surrounding space, affects the cooling of heat-transfer agent 4 and thermal losses directly proportionally at the calculation temperature of the outside air, which is $T=-22$ °C.

In the absence of a technological possibility for the placement of pipelines 6 in indents 9 made in wall 1 at the side of the attachment to the facade insulation, the minimum thickness of B_{\min} of heater 2 should be not less than 150 mm. This is due to the fact that for this thickness of facade heat insulation 2 temperature on its surface is $T=+16$ °C. This is an acceptable value for the permissible thermal losses of pipelines 6 that are used for external laying.

At thickness of equivalent facade insulation 2, which is less than 150 mm, the temperature on the surface of the equivalent facade heat insulation 2 raises to $T=+40$ °C. This is unacceptable for the permissible thermal losses of pipelines 6 that are used for external laying.

In the calculation-and-experimental cases No. 4, No. 5 and No. 6, the pipelines 6 are located in indents 9 made in wall 1 at the side of its attachment to facade heat insulation 2, and covered with a layer of facade insulation 2 of thickness B_{\min} . With an increase in thickness of B_{\min} of facade insulation 2 from 50 mm to 150 mm there is a decrease in the temperature on the surface of facade heat insulation 2 from $T=-3.5$ °C to $T=-13.4$ °C.

The results of these calculations also determine the optimal range of thickness of facade heat insulation 2, which is (50–150) mm for Ukraine.

8. Effective forms of making indents for pipelines laying

With regard to the shape of indents 9 execution, they can be made in rectangular, triangular, or arched form, or in the form of two sections of rectangles, or in the form of any combination of the above-mentioned forms (Fig. 2) in the existing wall 1 or in the layer of the facade insulation (Fig. 3–5).

Structural features of wall 1 of thermomodernized building in place of its connection to heating devices 7, 7' determine a choice of a specific shape of making an indent 9. The above design features in wall 1 include the presence of crossings with existing engineering networks (air conditioning systems, drains, low-current and power wiring, connection of lighting equipment), structural elements of the building's facade. It is also necessary to take into consideration restrictions on the depth B_D of possible indent 9 to avoid breaking the bearing capacity of the thermomodernized building (with insufficient width of existing walls).

9. Discussion of the results of modeling the energy-efficient solutions for the implementation of thermomodernization

In the course of the study, we used the modeling method for the proposed design and constructive-and-technological energy-efficient solutions for the implementation of thermomodernization of Ukrainian buildings and structures. This method is the most expedient, since the cost of energy-efficient solutions to be made based on the results of the research conducted is too high given the number of thousands of buildings that require thermomodernization. That is why these solutions require thorough studying, in particular, preliminary numerical and calculation and-experimental modeling.

By implementing solutions, which are protected by the Ukrainian patents for inventions (the method and the system), it is proposed, in particular, to introduce new elements in the form of new transit pipelines of a two-pipe system of central water heating with the use of equivalent facade insulation into an integrated thermomodernization system.

As a result of the research conducted, we determined optimal geometric parameters, material of execution and a mutual placement of new elements of a thermomodernization system. The obtained results show the prospects of the proposed design and construction-and-technological solutions for the thermomodernization of the Ukrainian housing stock, which has been in operation for longer than 30 years. Their implementation will contribute to maintaining comfortable living conditions and gradual reduction of household heating payments within 2–3 years from the time of implementation. It is also necessary to emphasize the simplicity of the technical procedure for the implementation of the developed solutions for thermomodernization.

Directions for improving our original studies are to optimize the mutual placement of new transit pipelines with the attachment to locations of existing heating devices. Such an attachment should take into consideration a number of technical and physical factors, including geometrical, physical and heat engineering parameters of a facade wall, design temperature operation, and a climate zone. In this case, it is also advisable to take into consideration geometrical, physical and heat engineering parameters of the

transit pipelines, pipe thermal insulation, equivalent facade insulation, etc.

10. Conclusions

1. As a result of experimental and numerical research and calculation study, we confirmed the prospects of the proposed innovative design and construction-technology solutions for the thermomodernization of residential buildings and structures, which involves modernization of a central water heating system together with a facade insulation. The developed innovative design and construction-technological solutions lead to a significant reduction in the energy consumption of existing buildings and structures of the housing stock, which has been operated for longer than 30 years, and contribute to maintaining comfortable living conditions. Therefore, it is expedient to disseminate the results of present study among organizations that operate housing infrastructure over corresponding years of commissioning.

2. We investigated distribution of a temperature field inside a building structure, temperature on the surface of a facade thermal insulation at the variation of its thickness for different forms of execution of new indents, where new pipelines of a two-pipe system of central water heating are located. We established that the placement of pipelines in new indents made in existing external walls makes it possible to reduce the heat losses from these pipelines by 74 % compared with the placement in the layer of facade insulation at the side of a wall.

3. We investigated the dependence of time for cooling a heat-transfer agent at its complete cessation of movement through pipelines on the diameter of these pipelines. We obtained the optimal value of the layer of a facade insulation, which leads to a 100 % protection against freezing of pipelines, even at the complete stop of a heat-transfer agent movement under given operational modes. We established that an increase in the thickness of a facade thermal insulation contributes to additional drainage of a building structure. This indirectly increases the efficiency of a system of complex thermomodernization, and, in turn, leads to an improvement in the thermal characteristics of the thermomodernized building.

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Запропоновано метод формування температурних режимів мікроклімату в тваринницьких спорудах різного функціонального призначення з застосуванням багатошарової грійоючої підлоги. Розроблено структурну математичну модель, що дозволяє при заданому режимі роботи т-ярусних трубчастих нагрівачів з урахуванням теплопровідності кожного шару теплогенеруючих модулів визначати конструктивно-теплотехнічні параметри. Це дає можливість забезпечувати формування оптимального температурного поля на поверхні багатошарової структури грійоючої підлоги

Ключові слова: температурні поля, грійоюча підлога, теплогенеруючі модулі, трубчасті нагрівачі, шарувата структура

Предложен метод формирования температурных режимов микроклимата в животноводческих сооружениях различного функционального назначения с применением многоуровневого греющего пола. Разработана структурная математическая модель, которая позволяет в зависимости от режима работы т-ярусных трубчатых нагревателей с учетом теплопроводности каждого уровня теплогенерирующих модулей определять конструктивно-теплотехнические параметры. Это позволяет обеспечивать формирование оптимального температурного поля на поверхности многоуровневой структуры греющего пола

Ключевые слова: температурные поля, греющий пол, теплогенерирующие модули, трубчатые нагреватели, слоистая структура

1. Introduction

Food security of the country and the well-being of people are largely determined by the performance efficiency of agriculture, including livestock industry. High quality,

competitive livestock products, including pork, cannot be obtained without the development and implementation of modern resource-efficient technologies based on automated electrotechnical complexes. The functionality of the systems of these complexes must fully ensure veterinary-sanitary re-

UDC 631.2:631.171:65.011.56

DOI: 10.15587/1729-4061.2018.121827

EFFECT OF THERMAL FIELD DISTRIBUTION IN THE LAYERED STRUCTURE OF A HEATING FLOOR ON THE TEMPERATURE OF ITS SURFACE

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