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CLIMATIZATION AND DECARBONIZATION MEASURES OF A RESIDENTIAL BUILDING BASED ON MINIMALLY INVASIVE SOLUTIONS FOR RECONSTRUCTION

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Abstract
A significant portion of buildings in European cities require climatization measures and a transition to decarbonized heating sources. Based on the MIX – Mixed approach scenario developed in the EU for the reconstruction of buildings, an algorithm for climatization measures and decarbonization of buildings built in the 1930s and 1940s has been developed. Criteria for assessing indoor comfort and decarbonization have been defined. An integrated BIM model of the building and adjacent structures that influence the thermodynamic and energy parameters of the building under study has been developed. Using the BIM model of the building, an assessment was made of the influence of solar radiation on the thermal regime of the premises in the building, considering adjacent buildings. The required minimally invasive solutions for building reconstruction for warm and cold periods of the year have been identified. A heat pump with underground-mounted vertical collectors operating in bivalent mode was selected as a heat source (instead of apartment gas heat generators). The integrated use of minimally invasive reconstruction solutions allows us to achieve target indoor comfort indicators (PMV = 0.5 ÷ 0.6) and reduce carbon emissions (73% compared to emissions before reconstruction). The developed model of climatization measures and decarbonization a building can be extended to similar objects.

Keywords: climatization and decarbonization of buildings, minimally invasive solutions for building reconstruction, climate-neutral buildings

INTRODUCTION

A significant proportion of buildings in European cities require work to improve their energy efficiency and switch to decarbonized heat sources (heat pumps, heating networks or the use of «green gas»).

According to the requirements of the European Commission, the reduction of greenhouse gas emissions in 2030 relative to 2015 for residential buildings should reach from 47 to 65% (depending on the chosen building reconstruction scenario) [1].

The implementation of this task in the construction sector requires large-scale modernization of the existing real estate fund and the attraction of significant financing [2].

The development of most cities in the European Union is characterized by quarters with historic buildings that, as a rule, have the status of "worthy of preservation", which limits the possibilities for global modernization of the building (e.g. insulation of facades, ceilings, etc.).

In most cases, these buildings use gas heat generators as a heat source, and during operation, CO_2 emissions significantly pollute the environment.

Additionally, existing buildings must remain usable during extended heat waves

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without creating new peak electrical loads through traditional cooling systems.

These limitations require a search for compromise solutions for both decarbonizing the building and improving indoor comfort during cold and warm periods of the year, considering actual operating conditions.

In the European Union, a number of scenarios have been developed for the climatization measures and decarbonization of buildings [1]. One of the possible reconstruction scenarios is called MIX – Mixed approach [1], it involves incentives for renewable energy sources in heating/cooling, support for heat pumps and renovation policies. Furthermore, the MIX scenario involves implementing technical measures in the building that significantly reduce greenhouse gas emissions.

A residential building with a typical architectural and structural layout characteristic of the 1930-1940s and located in an existing residential development was selected as the object of reconstruction (Fig. 1). The building was built in 1936 according to the design of the architect Franz Gessner (1879-1975) [3].



Fig. 1. *BIM model of the building with adjacent structures*

The decarbonization and climatization measures of the building was developed using BIM (building information modeling) modeling, which allows linking the construction area and climate parameters with the geometric dimensions of the building, data on energy consumption, materials, engineering systems and the cost of measures [4].

EXPOSITION

At the first stage of the work, an analysis of existing technical solutions was carried out that allow achieving the target indicators of the MIX scenario.

The main technical measures include:

1) improving the building's thermal insulation;

2) reducing outdoor air infiltration;

3) reducing building overheating during warm periods;

4) switching heating systems to low-temperature operation;

5) replacing gas-fired heat generators with heat pumps.

At the next stage of the work, the structural features of the building (location in a residential development, space for equipment placement, building orientation in relation to the cardinal points, the state of thermal protection, apartment layout) and the state of engineering systems (heating and ventilation) were analyzed.

A study of the building's thermal envelope revealed that the thermal transmittance values of the walls, roof, and windows correspond to those typical for the building's construction period. The thermal transmittance values of the windows and balcony doors provide the required U-value, preventing condensation on the interior surface of the building envelope and providing minimal thermal insulation. Replacement of windows and balcony doors is limited by the need to ensure significant air permeability, which is necessary to maintain the operability of gas heat generators that have natural exhaust gas removal.

A significant improvement in the thermal insulation properties of enclosing structures based on modern thermal insulation (for example, using the technology proposed in [5]) is currently impossible for architectural and financial reasons.

As an alternative to a complete reconstruction of the building, the development of a set of minimally invasive measures was considered that would allow for the simultaneous solution of two

problems: a significant reduction in greenhouse gas emissions and ensuring the required comfort in the premises (without installing air conditioning systems).

The following criteria were selected to evaluate the improvement of indoor comfort and decarbonization of the building:

- *PMV* – Predicted Mean Vote (expected average sensation), is a value that describes the degree of comfort or discomfort

- CO_{2eq} – carbon dioxide emission equivalent, g/kWh.

The criteria equations can be written as:

$$\begin{cases} PMV \rightarrow \pm 0{,}5 \div 0{,}6 \\ CO_{2eq} \rightarrow min \end{cases} \quad (1)$$

If the condition $PMV \rightarrow \pm 0{,}5 \div 0{,}6$ is met, it is possible to calculate Δt_p – the deviation of the room temperature from the optimum using the formula [6]:

$$\Delta t_p = |PVM| \frac{0{,}35+0{,}65\text{clo}}{0{,}468-0{,}148M} \quad (2)$$

Here, clo – is the thermal resistance of clothing in arbitrary units [6].

M – is the metabolic heat, *met* [6].

Calculations performed using formula (2) with *PMV* = 0,5 showed that Δt_p is no more than 1 °C.

One of the main factors influencing the thermal comfort of premises is solar radiation [7]. Using a BIM model of the building, an assessment of the influence of solar radiation on the thermal regime in residential premises of the building was conducted (Fig. 2).

Modeling of periods of day with intense (direct and diffuse) solar radiation was conducted for the longest day of the warm season (Fig. 2) in cloudless weather from 5:00 a.m. to 9:00 p.m. The modeling was conducted considering adjacent buildings that exert a sun protection effect on the building in question.

Analysis of the modeling results showed that north-facing windows and balcony doors do not require additional sun protection. Field measurements and calculations of the indoor microclimate parameters for residential spaces facing the north (using the Fanger comfort model [8]) show that comfort parameters in most spaces correspond to a *PMV* ≈ 1,2. The degree of *PPD* dissatisfaction is no more than 30%, and the deviation of the room temperature from the optimum is no more than 2,5 °C (for the hottest period). Improvement of comfort conditions in these spaces to target *PMV* ≈ 0,5 ÷ 0,6 can be achieved through passive, minimally invasive measures, including: ventilation of the spaces, use of local fans, and operation of radiators in "cold" mode (utilizing the capabilities of a heat pump, as suggested in [9]).

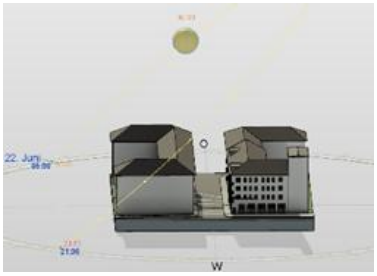


Fig. 2. *Solar radiation intensity model*

East-facing windows and balcony doors can be effectively protected by using internal thick curtains and ventilation (which does not require significant modifications).

Comfort parameters *PMV* ≈ 0,5÷0,6 in these rooms can be achieved by using local fans and operating radiators in the “cold” mode (as suggested in [9]).

Modeling results showed that approximately 20% of the windows on the building's southern façade are in the most unfavorable position (in the zone of prolonged, intense direct solar radiation). In these spaces, excess heat input from solar radiation leads to internal microclimate parameters corresponding to a comfort level of *PMV* ≈ 1,4 ÷ 1,5.

To improve comfort in these rooms, sun protection blinds can be installed in the windows and balcony doors on the balconies (Fig. 3) and in some windows (Fig. 4) (area 22,7 m^2).

Installing sun protection devices in in windows will prevent overheating during the

warmer months and maintain normal indoor microclimate conditions (*PMV* ≈ 0,5 ÷ 0,6) during the warmer months, also using passive, minimally invasive measures (described above).



Fig. 3. *Model of sun protection devices on the balconies of the southern facade*



Fig. 4. *Model of sun protection devices on the windows of the southern facade*

The balconies and windows on the south side of the building face the inner courtyard, allowing for the installation of sun protection devices without significantly altering the building's external architectural appearance.

During the cold season, the building's heat loss is compensated for by apartment heating systems connected to individual gas-fired heat generators.

An analysis of comfort during the cold season showed that the average comfort index in the building's premises is *PMV* ≈ 1,1 ÷ 1,3, which is explained by the low level of thermal protection of the building's enclosing structures, high gas consumption for heating (which leads to forced savings due to the cost of gas), and, as a consequence, the inability of the heating system to provide the required comfort.

To analyze the operating modes of the apartment heating system, a thermal-hydraulic model was developed that made it possible to identify the actual thermal-hydraulic loads and the power reserve of the heating system.

A simulation of the heating system's operation under conditions of low coolant temperatures was conducted when the system was connected to a heat pump with parameters of 55-30 °C (instead of 80-60 °C). The simulation showed that the heating system is capable of providing comfortable conditions (*PMV* ≈ 0,5 ÷ 0,6) in the building's rooms when operating in low-temperature mode for 80% of the heating season (outside air temperature ≥ -3 °C) provided a number of minimally invasive energy-saving measures are applied.

To ensure comfortable conditions (*PMV* ≈ 0,5 ÷ 0,6) during most of the heating season (outside air temperature ≥ -3 °C), it is necessary to carry out a number of minimally invasive measures: cleaning the internal surfaces of heating devices, installing heat-reflecting screens behind heating devices, replacing windows and balcony doors in some rooms.

During the coldest days of the heating season (outside air temperature ≤ -3 °C), it is necessary to provide an additional heat source that allows for a temperature difference in the heating system of 80-60 °C. For this purpose, a heat pump with an additional (backup) heat source is required; i.e., the heat pump should be connected to the heating system using a bivalent circuit (Fig. 5).

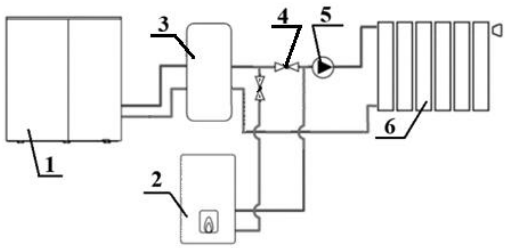


Fig. 5. *Heat pump in a bivalent circuit: 1 – heat pump; 2 – additional heat source; 3 – storage tank; 4 – two-way valve; 5 – pump; 6 – radiator.*

It is rational to lay the supply pipelines from the heat pump to the apartment distribution stations through the existing chimney openings from gas boilers.

Based on monitoring gas consumption and required thermal energy during the heating season, it was determined that 40 MWh of thermal energy is required to heat the building. Actual thermal energy consumption allows us to determine the required heating system capacity during this period, which is approximately 60 kW. Based on this capacity, the heat pump capacity is estimated.

A significant reduction in CO_2 emissions is achieved by using heat pumps [11], however, with minimally invasive reconstruction, the capacity of the heating system may be insufficient to ensure comfortable conditions throughout the entire heating season.

To increase the capacity of the heating system, the heat pump must be connected in a bivalent circuit with an additional heat source.

An analysis of the building's spaces showed that there is sufficient space in the building and in the surrounding area for installing a ground source heat pump, laying main pipelines through the courtyard (Fig. 6), and placing distribution units for connecting individual apartment heating systems.

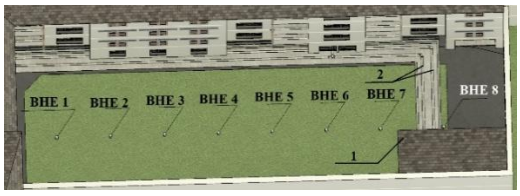


Fig. 6. *Placement of a heat pump in the local area: BHE-1 – BHE8 – borehole heat exchanger; 1 – location of the heat pump; 2 – pipelines*

The installation of a heat pump and main pipelines is also minimally invasive (it does not require expensive reconstruction or reinforcement of the building's load-bearing structures). The area for the location of a ground source heat pump (in the building's courtyard) is approximately 20 m^2, which occupies less than 10% of the building's courtyard area.

The reduction in CO_2 emissions is calculated based on the indicators given in [10] and is as follows (Fig. 7):

– baseline indicator (GH/Base): individual gas heating per residential unit. CO_2 emission factor: 249 g CO_2-eq/kWh;

– bivalent variant – Heat pump (HP_{bv}) + GH 80/20%: Central heating system with heat pump (COP 3,5), CO_2 emission factor: 152 g $CO_{2\text{-eq}}$/kWh + 249 g $CO_{2\text{-eq}}$/kWh (GH).

– HP variant – Heat pump (HP) - 100%: central heating system with heat pump (COP 3,5). CO_2 emission factor: 152 g CO_2 eq/kWh.

The change in the comfort index in the building before and after minimally invasive reconstruction (Fig. 8) confirms the effectiveness of the planned measures.

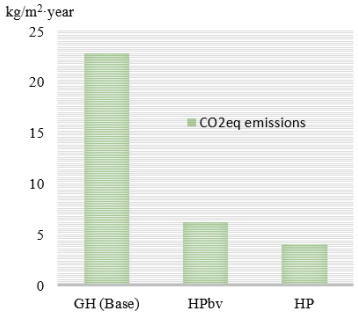


Fig. 7. *CO_2 emissions*

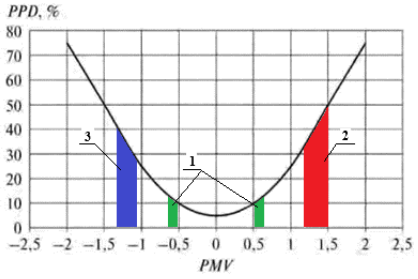


Fig.8. *The relationship between the expected number of people (PPN) dissatisfied with the thermal environment and the comfort index PMV for the building under study:*
1 – target values after modernization of the PMV ≈ 0,5 ÷ 0,6; 2 – values before modernization in the warm period of the PMV ≈ 1,4 ÷ 1,5; 3 – values before modernization in the cold period of the year PMV ≈ 1,1 ÷ 1,3.

CONCLUSION

The implementation of climatization and decarbonization measures for the building allowed us to develop a specific sequence of work that can be extended to similar facilities.

The implemented algorithm of measures for climatization and decarbonization of the building includes: selection of the scenario and goals of modernization → creation of a BIM model of the building (Fig. 1) → modeling of energy consumption, room comfort and carbon emissions → selection of minimally invasive measures → selection of a heat source → justification for improving comfort parameters and reducing CO_2 emissions.

To evaluate the effectiveness of climate control and decorating measures, criteria (*PMV* and CO_{2eq}) were selected. These criteria determined the impact of minimally invasive solutions on indoor comfort and the degree of building decarbonization.

Based on the developed minimally invasive measures, $PMV = 0{,}5 \div 0{,}6$ values of are achieved in the premises, and the reduction in CO_2 emissions amounts to 73% of the mass of emissions before reconstruction (Fig. 6).

Minimally invasive solutions include:

- for the warm season: using internal thick curtains, sun protection blinds installed on balconies and windows (Figs. 3, 4), ventilation of rooms, or the use of local fans;
- for the cold season: cleaning the interior surfaces of heating units, installing heat-reflecting screens behind heating units, and replacing windows and balcony doors in certain rooms.

A ground source heat pump with vertical ground collectors operating in a bivalent mode was selected as the heat source (to replace the apartment's gas heat generators).

Further reduction of CO_2 emissions is possible by implementing measures to improve the thermal insulation of the walls, foundation, and roof. A complete replacement of the apartment's heating and ventilation systems is also necessary. In this case, the heat pump can be used during the heating season and for cooling during the warm season.

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