

ЕНЕРГЕТИКА ТА ЕНЕРГОЗБЕРЕЖЕННЯ

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Assessment of the window replacement influence on building energy consumption and human thermal comfort on the basis of dynamic modeling

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The dynamic modeling of the energy characteristics of building structures with the help of energy-saving double-glazed windows was carried out in the work. The influence of different variants of windows replacement on the heat energy state of a typical mass building for various glazing coefficients in dynamic grid models created on the basis of the Energy Plus software product was analyzed. It is found that argon-filled glass, selective-coated glass on the outer and inner glass can reduce the energy requirement for the building by 8-10% compared to the double-glazed glass without selectively coating and filling the chambers with air. The load on the heating system is significantly different for the orientations North and South. It is assumed that the coefficient of glassy glass in the orientation of the South during the off-season (autumn / spring), less heating (switched on / off later). For North and South orientations, energy-saving windows with selective coating and / or filled up with inert gas cells have a different effect, which is explained by the coefficients of solar heat transmission, which was obtained on the basis of the simulation model. In addition, current standards in Ukraine do not provide all variants of the coefficients of optical transmittance characteristics of solar heat gains. In this work, a dynamic hourly simulation of the building energy demand in heated space for representative rooms N and S oriented for different glazing coefficients and window types has been carried out. Range of PMV change, average radiating temperature and air temperature in the room for the heating period were estimated. It was established that changing windows glazing can affect the PMV to change almost two times, which indicates the need for an integrated approach to the assessment of thermal comfort. Namely, the importance of taking into account the dynamic changes in the environment parameters and possible thermo-modernization were detected.

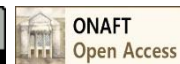
Key words: Energy need; Energy saving windows; Thermal comfort; PMV; Mean radiant temperature; Operating temperature

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1. Introduction

Most buildings in Ukraine relate to high-rise buildings of the 80's, the development of which focuses on the cost of the construction, what means, minimization of capital expenditures and almost did not take into account operating costs, so 80% of buildings

do not meet the current requirements of energy efficiency [1, 2]. The period from the 90s to the present, is characterized by a steady increase in prices of energy sources, what is a delayed response to similar trends in the world. Due to the gas crisis in Ukraine since 2014, which has become urgent in the winter of 2017-2018, the issue of energy efficiency is one of the

main directions of the country's development now.

2. Literature Review

Reducing the cost of energy for heating buildings can be achieved in different ways. The one which is the most common in Ukraine is using of modern heat-insulating materials and technologies. The main reference point while implementing a complex of energy-saving measures is to reduce energy consumption while maintaining the normative internal temperature of the air. Taking into account the world trends in optimization of energy demand and providing comfortable working conditions, the calculation of specific energy need should be based on the operating temperature of the air, or if the $PMV = 0$ is reached. These conditions of optimizing energy efficiency are the next promising step to be used in Ukraine.

Thermal comfort is set by a number of standards in Ukraine [3, 4]. The quality of thermal comfort is determined from the numbers of PMV (predicted average human heat perceptibility) and PPD (predicted percentage of dissatisfied with the thermal environment). The detailed calculations of both are presented in the relevant state and international standards [3]. According to PMV, the category of building to provide comfortable conditions is determined [4]. The basis of these standards is a model of human thermal comfort, built based on the energy balance between the surface of the human body and surrounding objects, developed by Fanger [5]. Involving a model of a human into complex system "heat source – building envelope" [6, 7, 8] is a significant step towards reducing energy consumption in buildings and ensuring an adequate thermal comfort level. Estimation of thermal comfort indicators provided in a dynamic change of the environmental parameters will show the possibility of adjusting the heating system with the aim to provide an adequate thermal comfort level and possible reduction of energy consumption.

Adequate evaluation of buildings energy efficiency level and detalization of the energy status indicators, mostly, depend on the use of the building's mathematical models, the complexity of which is determined by the problems must be solved. Trends in the development of mathematical models for determining the building energy state are aimed at reducing the time intervals and determining the localization of the system characteristics and other influential factors [9–11]. Modern computer methods and tools of the building energy modelling based on BEM models

(Building Energy Modeling) is a versatile, multipurpose tool that allows you to manage energy consumption in real-time. BEM is used in a deep analysis of the building energy efficiency and the development of strategies (energy efficiency policies). The main aspect of BEM-modelling is the determination of energy requirements, taking into account the internal environmental indicators (thermal and visual comfort, indoor air quality, etc.) [12-14]. The models take into account hourly weather data of the terrain, geometry and thermophysical properties of the building, internal heat emissions caused by lighting, people, equipment, specifications of the heating system, ventilation and cooling, operating schedules, etc. The most powerful software products implemented on the basis of BEM modelling are BLAST, DOE-2, ESP-r, HVACSIM +, TRNSYS, EnergyPlus, etc [15-21].

BEM modelling allows us to consider the building as an energy system what is similar to the standards of Europe that are vastly being implemented in our country. Therefore, the building as a complex energy system is considered as a set of external climate, engineering systems, shell, human, as an indicator of the comfort conditions, and energy processes in the rooms of the building.

The methodology of the systematic approach in a detailed analysis of the building dynamic energy characteristics allows us to consider not the building, but to analyse individual zones and obtain a general picture of the energy characteristics for the object as a whole [22-26].

The energy characteristics of the building is influenced by a number of parameters: thermophysical properties of building envelope, geometric sizes, additional internal and solar heat transfer, air exchange, operating modes, and others. Dynamic modelling of buildings allows us both measure changes and the level of influential parameters (window replacement, insulation of building envelope, change in solar heat gains, glazing coefficient, change in external temperature, etc.), while analysing energy modernization, switch between the temperature of the internal air and generalized comfort parameters.

3. Object, subject and methods of research

The object of the research is a process of the assessment of energy efficiency in the conditions of dynamic change of environmental characteristics with taking into account parameters of human thermal comfort.

Subject of research – methods of energy efficiency indicators estimation in public buildings using mathematical models.

Methodological basis of this scientific research were the following methods: analysis and synthesis methods of mathematical and simulation modelling, the fundamental provisions of the heat and mass transfer theory, dynamic computer methods of building energy modelling (BEM) as a complex system.

The purpose of the work is to analyse the application of dynamic BEM simulation in determining the energy characteristics of the replacement of windows for a different glazing coefficient according to comfortable conditions. According to the goal, the following tasks should be solved:

1. Creation of room dynamic models in EnergyPlus programme with the most common thermophysical and geometric characteristics for the conditions of Ukraine,

2. Analysis of temporal changes in the energy characteristics of the building in the variants of windows replacement for typical thermophysical and geometric characteristics of the building envelope;

3. Analysis of changes in the parameters and indicators of thermal comfort during the heating period, provided that the windows have been replaced.

4. Research results

Output data and model description. To study the energy characteristics of the building, a room for thermophysical properties of the "Khrushchevka" type of building envelope was considered. The room size is 5.5x6.1 m, the height of the room is 3.2 m. The room has one outer wall (5.5 m) with a window. Window - double-glazed with filling: 1) air; 2) argon. The design of the window is considered with: 1) ordinary sheet glass; 2) selective coating on the inner glass; 3) selective coating on the outer glass; 4) selective coating on the inner and outer glass. The bearing part of the outer wall is made on the basis of masonry in one brick. The bearing part of the inner walls is made of half-brick masonry. Overlapping over the heating rooms is reinforced concrete – 20 cm. Ventilation is natural with multiplicity of air exchange 1 hour-1. The constant air temperature was maintained by an ideal thermostat.

To evaluate the parameters of thermal comfort, the subjective parameters of the microclimate are taken as follows: thermal resistance of the human clothes $I_{clo}=0,155 \text{ m}^2\text{C/W}$; human activity (metabolism) $M=70 \text{ W/m}^2$.

The hourly calculation is based on the simulation model of the room created in the EnergyPlus software, which allows you to get the relationship between temperature distribution in the room area, the level of heating and operating modes, inertial features of the building envelope. The geometry of representative rooms was created in the GoogleSketchup graphical editor that is synchronized through OpenStudio. The sample rate of the calculation which was chosen – 1 hour. The research was run for the climatic conditions of Kyiv, data have been taken from the international climatic file IWEC [27]. For the calculation of solar radiation influence on the room conditions, the detailed method "Full interior and exterior with reflection" was used.

In the Window [28] calculation program, synchronized with EnergyPlus [16], different types of double-glazed windows with selective coating and filling with inert gas were created and investigated. In the work, the coefficient of glazing varies from 20 to 60%. The filling of window chambers with air and argon is considered.

To estimate the level of thermal comfort, the method presented in ISO Standard 7730, based on the human heat balance equations [5], is used:

$$PMV = (0,303 \cdot e^{-2,1 \cdot M} + 0,028) \cdot \left[\frac{(M - W) - H - E_c}{-C_{res} - E_{res}} \right];$$

$$PPD = 100 - 95 \cdot e^{-(0,03353 \cdot PMV^4 + 0,2179 \cdot PMV^2)}, \quad (1)$$

where M – degree of metabolism, W/m^2 ; W – effective mechanical work, W/m^2 ; H – sensitive heat losses, (W/m^2) ; E_c – heat exchange by evaporation from the skin, W/m^2 ; C_{res} – heat transfer by convection during breathing, W/m^2 ; E_{res} – heat exchange by evaporation during breathing, W/m^2 .

$$H = 3,96 \cdot 10^8 \cdot f_{cl} \cdot \left[(t_{cl} + 273)^4 - (t_r + 273)^4 \right] - f_{cl} \cdot h_{cl} \cdot (t_{cl} - t_a), \quad (2)$$

$$E_c = 3,05 \cdot 10^{-3} \cdot [5733 - 6,99 \cdot (M - W) - p_a] - 0,42 \cdot [(M - W) - 58,15], \quad (3)$$

$$C_{res} = 0,0014 \cdot M \cdot (34 - t_a), \quad (4)$$

$$E_{res} = 1,7 \cdot 10^5 \cdot M \cdot (5867 - p_a), \quad (5)$$

where f_{cl} – factor taking into account the surface area of the clothes; t_a – air temperature, $^{\circ}\text{C}$; t_r – average radiant temperature, $^{\circ}\text{C}$; t_{cl} – temperature of the clothes surface, $^{\circ}\text{C}$; p_a – Partial steam pressure in the air, Pa; I_{cl} – thermal resistance of clothing, $\text{m}^2\text{C/W}$; h_{cl} – coefficient of convective heat transfer, $\text{W/m}^2\text{C}$.

Data on the importance of metabolism, depending on the type of human activity and the thermal re-

sistance of clothing, are described in detail in [5].

5. Analysis of the energy characteristics of the building

Figure 1, shows the annual energy demand of rooms for different glazing coefficients and thermo-physical characteristics of translucent elements for

South orientation. The paper deals with the most common coefficients of glazing. The effect of the glazing coefficient is different for rooms oriented to South (*S*) and to North (*N*). The given results can be used in optimization of energy consumption while realization of energy-saving measures for considered geometrical and thermophysical properties of building envelope.

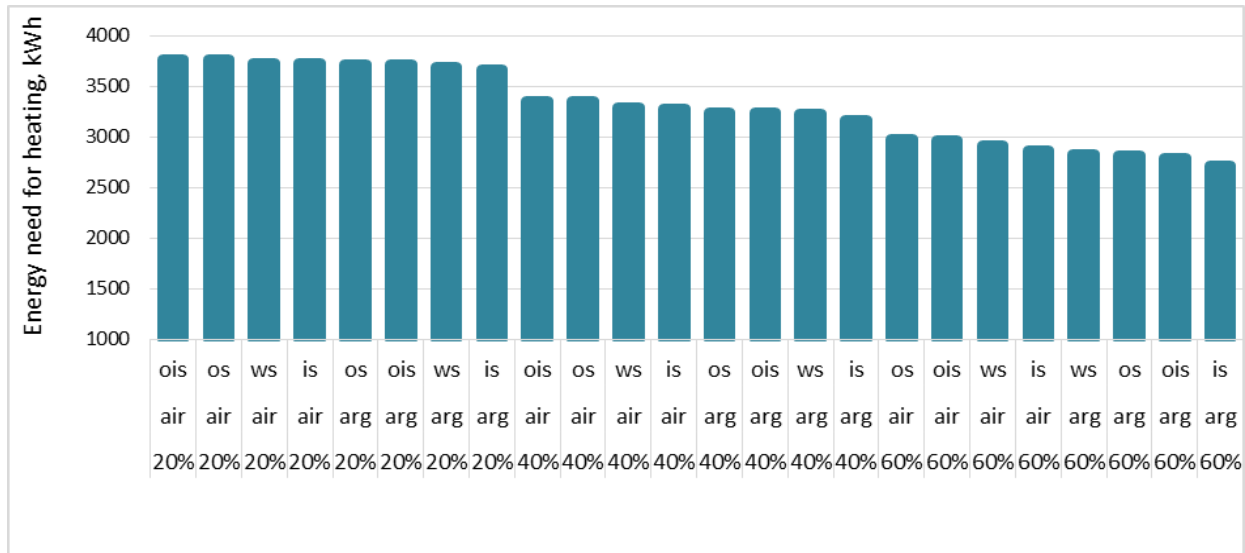


Figure 1 – Annual energy consumption in the heated area, depending on the glazing area, %, fill in the inert gas of the chambers and availability and type of selective coating for the South oriented premises: *air* – box with air filling; *arg* – with argon filling; *os* – selective coating on the inner surface of the outer glass; *is* – selective coating on the outer surface of the inner glass; *ois* – selective coating on the inner and outer glass; *ws* – without selective coating

For considered energy-efficient double glazed windows for *S*, the maximum savings can be achieved by using windows with argon filling, selective coating on the inner glass and a glazing coefficient of 0.6, and the minimum energy requirement – with air-filled coatings, selective coating on the inner and outer glass and the coefficient of glazing 0.2. In this case, the energy demand will be changed by 27% (fig. 1).

For *N* the most effective option among the considered is the use of windows with argon filler, with a selective coating on both sides and a coefficient of glazing 0.6, the worst – with air-filled without a selective coating and a coefficient of glazing 0.2. The annual difference between the best and worst options is about 13%.

For existing buildings, the coefficient of glazing in thermo-modernization is often not a variable parameter, therefore, as a result of the analysis, it was found that argon filling improves the energy performance of the glass pane in comparison with air filling by 3-4%. Double-panelled argon-filled glass with a

selective coating on the outer and inner glass can reduce the energy consumption of the building, for the orientation of *S* and *N*, on average, by 8-10%, on the outer glass – by 5%, on the internal – by 8% compared with Argon double-chamber double-glazed windows without selective coatings for a 40% glazing coefficient. With an increase in the coefficient of glazing from 40% to 60%, the energy demand of the building's rooms will increase by an average of 5%.

It should be noted that double-glazed windows were simulated in EnergyPlus and Window, the heat transfer coefficients of the windows are different from those given in the standard of Ukraine [29]. Figure 2, shows the values of the coefficients of heat transfer K and the relative transmittance of solar radiation ζ of different types of double-glazed windows, calculated in EnergyPlus and Window [16], in comparison with the data given in the standard DNB B.2.6-31 [29].

The heat transfer coefficients from EnergyPlus [16] are somewhat lower (5-15%) from the values given in the standard [29], which makes a difference

in the results of determining the energy demand of the building. The difference is the smallest (2-5%) for windows with a selective coating on the inner and outer glass (fig. 2).

It should be noted that the transmission coefficients of solar radiation by translucent structural elements in the standard [29] are not given for all types of windows.

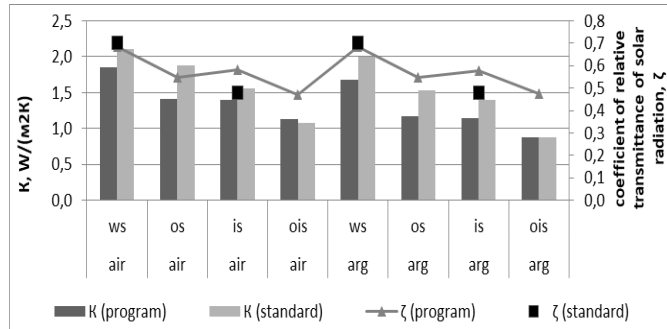


Figure 2 – Heat transfer coefficient and relative transmittance of solar heat supply for different types of windows

For windows without a selective coating, the coefficients are the same, for windows with a selective coating on the inner glass are different by 20%. The standard does not show the transmission coefficients for windows with selective coating on the outer glass.

An analysis of the monthly energy data for heating needs allows take into account the influence of the off-season periods. Given that the solar heat transfer into the zone of the room comes through translucent structural elements, this element of the structures can affect the energy characteristics of the building in different ways. For example, for S orienteering of the room during the off-season with a large glazing area can work as a passive heating system. For rooms with windows focused on the N effect of the selective coating is less noticeable for the cold period of the year.

For premises oriented on S, it is noticed that when the coefficient of glazing equal 0,6, heating can be switched off in April, in the winter months the solar component is lower (for January, December). The climate data of the IWEC weather file for February is characterized by the lowest external air temperature and the highest solar activity for the winter months, which explains the progress for S orientation (fig. 3,b). N orientation of the room is not so sensitive to the wobble of solar radiation (fig. 3,a). The coefficient of glazing has small effect on the energy demand for N, therefore an external wall with low thermal resistance (1 m²K/W – typical for mass building) and an energy efficient window with a thermal resistance of 0,7 m²·K/W (fig. 2) was adopted in the analysis.

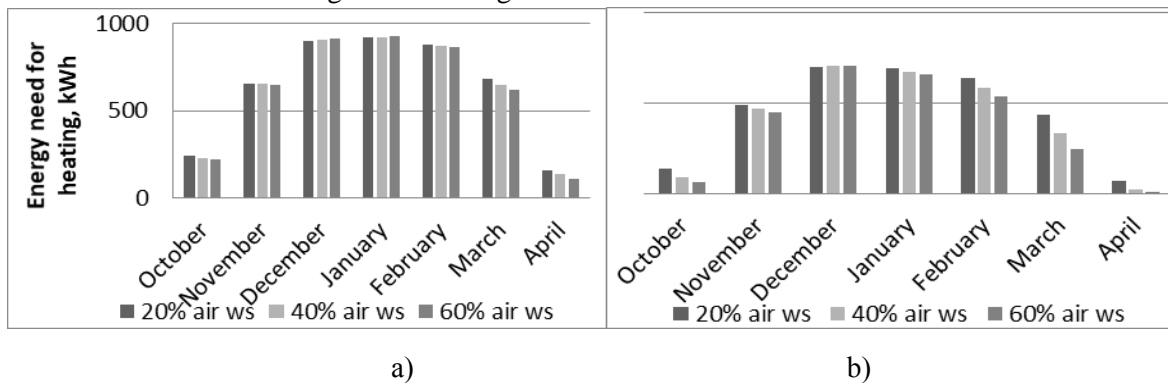


Figure 3 – Monthly energy consumption in the heated space for the premises is directed to N (a) and S (b) for the different glazing area with metal-plastic two-chamber plastic windows with air filling

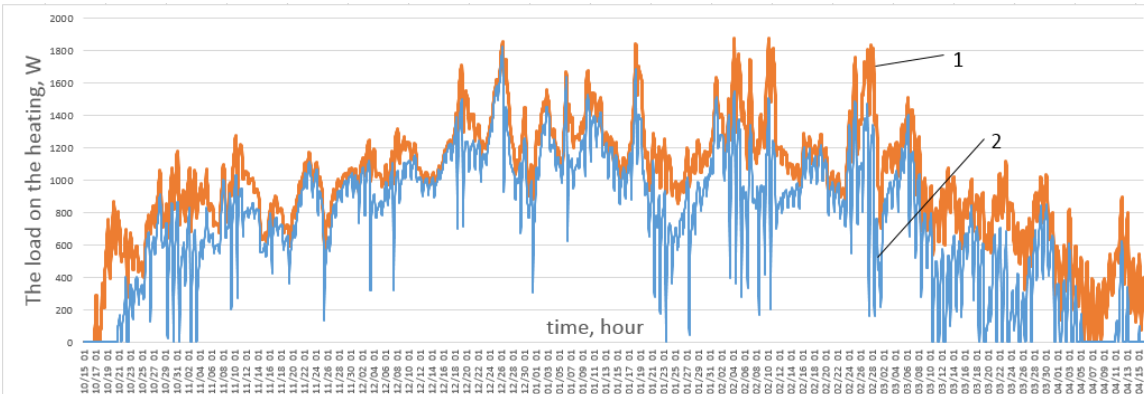


Figure 4 – Load on the heating system of the room oriented on N (1) and S (2) for various indoor temperature graphs

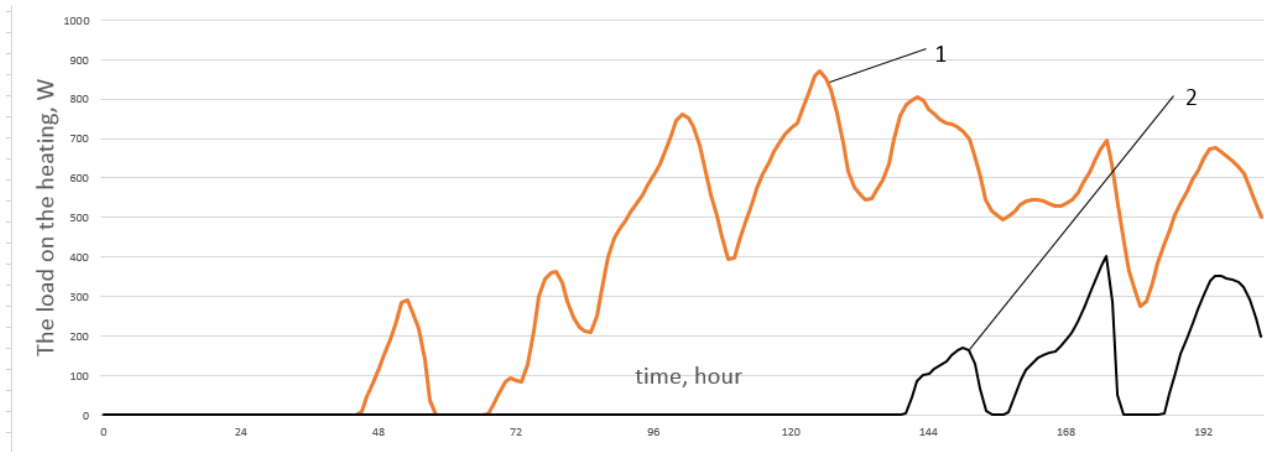


Figure 5 – The load on the heating system of the room oriented N (1) and S (2)

Similar calculations are made for double-glazed windows with different combinations of selective coating applications, as well as filling with inert gas. For S the orientation of the energy demand is lower for the off-season compared to similar premises where windows without spray are installed, which is explained by the passage of solar radiation.

An hourly analysis of changes in the load on the heating system for various glazing coefficients and types of translucent structures has been driven. In fig.4, gives an hourly load on the heating system for the S (1) and N (2) orientation for a building with a coefficient of glazing of 0,4. For other glazing variants, the load shifting trend is similar.

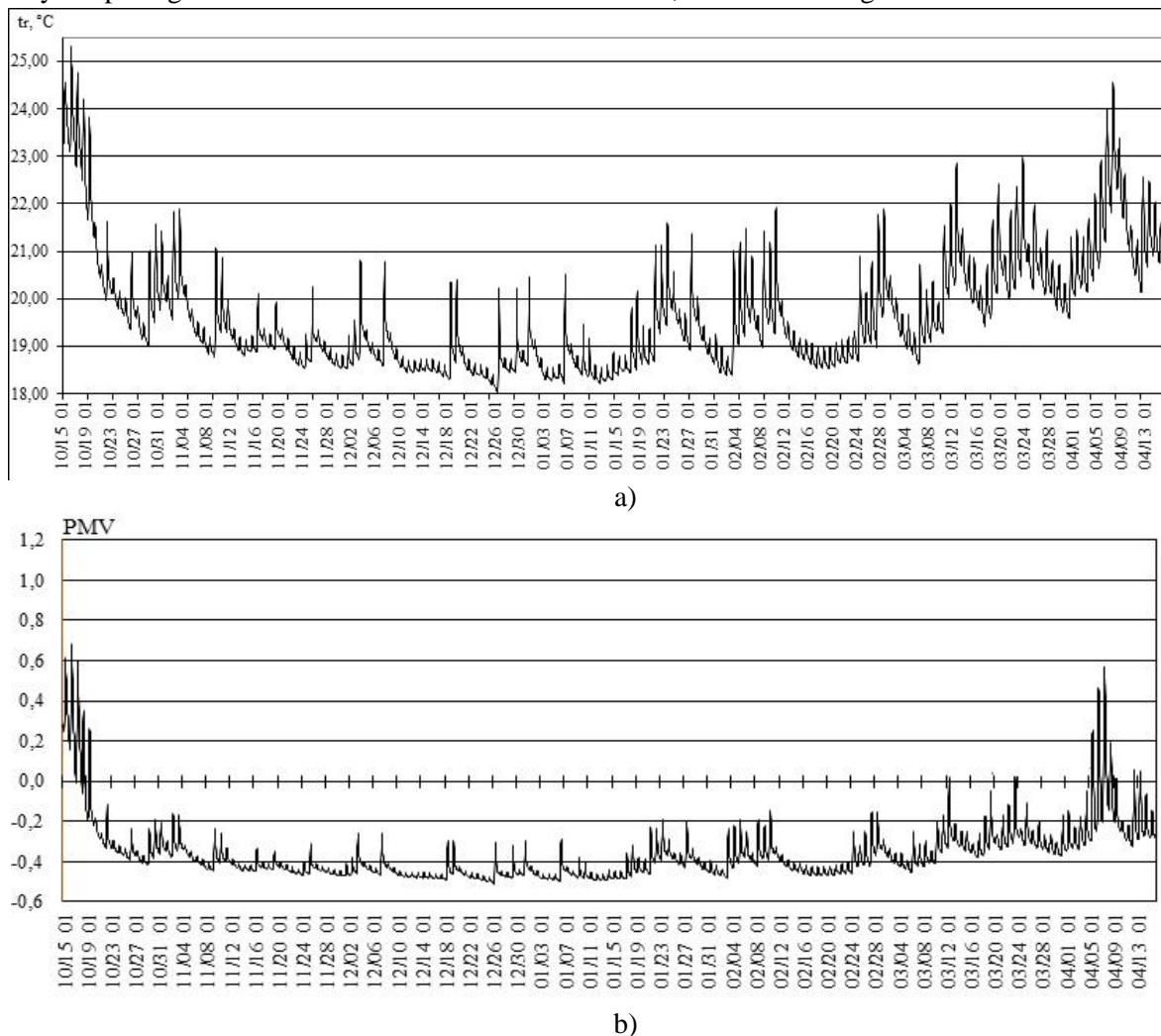


Figure 6 – Change in mean radiant temperature (a) and PMV (b) for the heating period

The range of daily oscillations for the controlled load on the heating system is slightly larger for S orientation than for N , which is associated with the solar heat transfer to the room area. For the period of the off-season during the hourly calculation there is a turns of heating during periods of peak solar activity. In fig. 5 the load on the heating system for 9 days of the beginning of the heating season (October 15-24) is given. With the increase of the glazing coefficient on the S orientation in the off-season period, the heating is switched off for even longer.

The above analysis that has been carried out under the condition of heating regulation with a constant temperature of the internal air in the room. The need for heating can be determined with taking into account the comfort conditions, also based on the mean radiant (or operating) temperature, which will reduce the load on the heating system in hours of solar activity.

Analysis of parameters and indicators of thermal comfort changing during the heating period

Since studies assume that the subjective parameters of thermal comfort, namely human activity and the type of clothing, are constant, the change in PMV (the basic parameter of thermal comfort) is due to the change in the mean radiant temperature of air t_r at a constant room air temperature. The change in t_r is due to changes in the temperature of the fences, the temperature of the outside air and the flow of solar radiation. The value of t_r in EnergyPlus [16] is calculated as the average weighted of the fences areas in the room, given that the person is in the centre of the room. In fig. 6, shows the change of t_r (a) and PMV during the heating period for the 0.4 glazing for the external orientation wall. The total range of t_r changes in the range of 18-25 °C, and PMV as the main index of thermal comfort from -0,5 to 0,7, were established. The increase in the mean room radiant temperature is due to the inflow of solar radiation, and fluctuations - the change in the temperature of the outside air.

For more detailed analysis of the effect of the glazing coefficient on t_r and PMV in fig. 7, the change of the given values for a system with a coefficient of glazing what was equal to 0,4, 0,5 and 0,6 during 202 observations from the beginning of the heating period is given. It has been established that for this observations, the difference between mean radiant temperatures in the room can reach 3 °C, while the PMV varies from 0,5 to 1,1. That indicates the significant influence of the glazing coefficient on the indicators of thermal comfort. In fig.7, for various glazing coefficients, the indoor air temperature change is displayed.

At the beginning of the heating period, the room temperature can reach 24 °C (for a glazing coefficient of 0,4) and 27 °C (for a glazing coefficient of 0,6) due to solar radiation and a lack of air conditioning. With further reduction of the environmental temperature after 92 hours, the room temperature for all variants of glazing with the help of a thermostat is maintained at 20 °C, but there is a daily increase of temperature under the influence of heat from solar radiation.

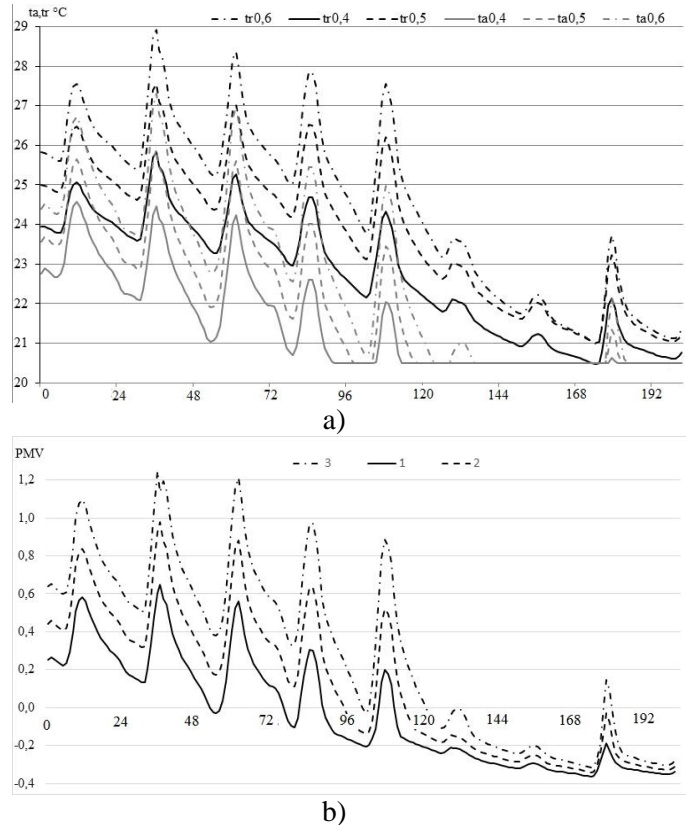


Figure 7 – The highest and lowest values of t_r (a) and PMV (b) during 9 days of the heating period: 1 – the coefficient of glazing 0,4; 2 – 0,5; 3 – 0,6

According to the standard [4], four recommended categories of buildings are distinguished, depending on the PMV value for the design of buildings with mechanical heating and cooling. The first category is for sensitive and sick people where $-0,2 < PMV < +0,2$; the second one corresponds to the normal level of expectations, should be used for new buildings and renovations and $-0,5 < PMV < +0,5$. So, analyzing the fig.7 for different variants of the glazing coefficient, the indoor air temperature can be reduced to provide $PMV = -0,5$, which in turn will reduce energy consumption and provide a proper level of expectations regarding thermal comfort.

Providing an adequate level of thermal comfort is an important and relevant task, changing of the comfort conditions under the condition of dynamic changes in the parameters of the environment, and therefore

the objective parameters of thermal comfort shows a wide range and opportunities for reducing energy consumption by reducing the air temperature in the room during high values mean radiant temperature.

6. Conclusions

In this paper, a dynamic modelling of the building energy characteristics with energy-saving double-glazed windows was carried out. It is established that a double-glazed, argon-filled glass with a selective coating on the outer and inner glass can reduce the energy demand for the building by 8-10% compared to a double-glazed unit without a selective coating and the filling of the chambers with air. The load on the heating system is significantly different for N and S orientations. It is provided that the glows of glassing coefficient in S orientation during the off-season (autumn / spring), the heating is less (switched on / off later).

It should be noted that, in the standard DBN V.2.6-31 [27], the heat transfer coefficients are 5-15% higher than the values gained in EnergyPlus and the Window subprogram. The smallest difference (2-5%) for windows with a selective coating on the inner and outer glass. In addition, the transmission coefficients of solar radiation by translucent elements in standard [27] are not given for all types of windows.

The analysis of change in average radiating temperature and PMV (thermal comfort index) for the dynamic change of environmental parameters and various variants of the building glazing have been carried out. The range of t_r variations during the year for different fencing options is found to be within the range of 18-25 °C, and PMV, as the main indicator of thermal comfort, is -0,5-0,7. This analysis shows a wide range of changes in objective parameters and indicators of thermal comfort, and the possibility of reducing energy consumption by reducing the air temperature in the room during the period of high values of the mean radiant temperature.

In addition, the influence of fencing on the change of PMV was analysed, it was established that by changing the parameters of the fences it is possible to change the PMV practically twice, which indicates the necessity of an integrated approach to the estimation of thermal comfort. Namely, the importance of taking into account the dynamic changes in environmental parameters and possible thermo-modernization.

In the future, it is planned to use dynamic energy

state models to analyse the impact on energy demand and the conditions for the comfort of insulation and heating of buildings.

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Оцінка впливу заміни вікон на енергопотребу та умови комфорту в будівлі на основі динамічного моделювання

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У роботі було проведено динамічне моделювання енергетичних характеристик будівельних конструкцій за допомогою енергозберігаючих склопакетів. Проаналізовано вплив різних варіантів заміни

вікон на теплоенергетичний стан будівлі масової забудови для різних коефіцієнтів засклення в динамічних сіткових моделях, створених на базі програмного продукту EnergyPlus. Встановлено, що склопакет, наповнений аргоном, скло з селективним покриттям на зовнішньому та внутрішньому склі може знизити потребу на енергію для будівлі на 8-10% порівняно із склопакетом без селективного покриття та наповнення камер з повітрям. Навантаження на систему опалення суттєво відрізняється для орієнтації Пн і Пд. Передбачається, що коефіцієнт склоподібного скла в орієнтації Пд протягом міжсезоння (осінь / весна), нагрівання менше (включається / вимикається пізніше). Для Пн та Пд орієнтацій енергозберігаючі вікна з селективним напиленням та/або заповненням камер інертним газом мають різний ефект, що пояснюється коефіцієнтами пропускання сонячних теплових потоків, що було отримано на основі імітаційної моделі. Крім того, діючі стандарти в Україні не дають всіх варіантів коефіцієнтів оптичних характеристик пропускання сонячних теплових потоків. У роботі проведено динамічне погодинне моделювання енергопотребителів будівлі в опаленні для репрезентативних приміщень Пн та Пд орієнтації для різних коефіцієнтів засклення та типів вікон. Проведено аналіз зміни середньої температури випромінювання та ПТК (показника теплового комфорту) для динамічної зміни параметрів навколишнього середовища та різних варіантів скління будинку. Оцінено діапазон зміни ПТК, середньої радіаційної температури та температури повітря у приміщенні для опалювального періоду. Наведені рекомендації щодо регулювання зміни температури повітря у приміщенні для забезпечення відповідної категорії будівлі щодо забезпечення комфортних умов.

Ключові слова: Енергопотреба; Тепловий комфорт; Прогнозована середня оцінка тепловідчуттів людини; Середня радіаційна температура; Операційна температура

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