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Energy-Efficient Windows for Passive Buildings

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Abstract—We presented scientific, methodological, and engineering approaches to the application of energy-active window units in the construction of passive houses, taking into account the climatic conditions of the Republic of Uzbekistan's regions, which significantly enhance the energy efficiency of buildings. We examined international regulations governing the use of passive strategies and based on these, proposed boundary conditions for the parameters and indicators of energy-active window units to ensure their compliance with current standards. A critical analysis of the designs of energy-active window units was conducted, with a proposed classification based on functional purpose, frame material, construction type, tranclucent-filler type, number and arrangement of sealing contours, as well as sash design solutions and operational characteristics. We also evaluated the maximum and minimum outdoor temperatures by month for the period from 2000 to 2023 and developed temperature distribution maps across the regions of the republic. These maps serve as a basis for analyzing seasonal fluctuations and for developing window systems that provide effective insulation and reduce heat loss during cold periods. In light of the increasing number of days with extremely high temperatures, an analysis of data on the average number of hours with temperatures above 35°C was conducted. This provides a comprehensive understanding of the temperature conditions affecting the thermal load on buildings in the republic and serves as a foundation for developing effective energy-saving solutions. A new design of energy-active window units with a triple-glazed transparent enclosure and a heat transfer coefficient reduced to 0.5 W/(m^2 K) is proposed, which improves thermal efficiency by 30–50%, utilizing an air layer and L-shaped brackets to simplify operation and enhance insulation properties and efficiency in various climatic conditions.

Keywords: energy-active and energy-saving window units, energy efficiency, thermal efficiency, thermal conductivity coefficient, partially tinted glass, phase-change heat-accumulating material, radiation-absorbing surface, thermal load, ambient temperature, thermal insulation

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INTRODUCTION

Uzbekistan has made significant efforts to improve energy efficiency and reduce greenhouse gas emissions in the national economy [1]. However, there are large untapped reserves of energy efficiency among end users, especially in buildings [2]. To achieve energy efficiency goals on the demand side, a targeted and clearly formulated policy at a national scale is necessary, otherwise the increase in supply will not be able to cope with the growth in consumption, which threatens sustainable economic growth, energy security, and the state of the surrounding environment (SE) [3].

The construction of residential and public buildings using energy-efficient technologies is aimed at improving their thermal excellence and energy efficiency through the use of new engineering approaches, highly efficient materials, and renewable energy sources (RESs) [4].

It is known that in Uzbekistan at least 75% of the energy consumed is in the communal sector, mainly for space heating, which is due to poor thermal insulation of enclosing structures, old windows and doors, as well as inefficient heating systems of buildings [5].

Currently, in the construction sector of Uzbekistan, special attention is paid to the construction of residential, social, and administrative buildings using passive heating systems. Such systems are divided by energy efficiency class into the following types [6–8]:

— Energy-saving house: a house with an average energy consumption for heating of no more than 60–70 kWh/m^2 per year.

— Passive house: a house with an average energy consumption for heating of no more than 15 kWh/^{2} per year.

— Building with zero centralized energy consumption: a building with the same architectural characteristics as a passive house, but designed to consume only the energy generated by its own systems (the average energy consumption from the electrical grid and heating network for heating is 0 kWh/m^2 per year.

When implementing passive design strategies in Uzbekistan, it is necessary to take into account local climatic features, available materials, and existing building codes. These strategies can not only improve the energy efficiency of buildings, but also improve the indoor microclimate and reduce the environmental impact of construction. However, these approaches need to be adapted to local conditions and needs.

In this context, the results of studies on the development of bioclimatic maps of the regions of Uzbekistan using the Giovanni diagram [9] revealed opportunities to reduce energy consumption through passive architectural solutions, such as the correct orientation of the building relative to the cardinal directions, the use of energy-active window units (EAWUs) and sun protection devices to control solar radiation (SR).

An analysis of the practical experience of building passive houses in different climatic conditions of the regions showed that traditional approaches to passive construction are not always justified due to differences in the heat balance of a vast territory. Features of heat gain and loss in certain regions require increased thickness of thermal insulation of buildings, which confirms the need to adapt strategies for the construction of low-energy buildings, including alternative solutions with elements of passive houses [5, 10].

A critical analysis of scientific research [11, 12] confirms that the integration of passive strategies into construction significantly improves the energy efficiency of buildings and ensures comfortable living conditions. This dictates the need to adopt or revise relevant standards. In this regard, the authors studied the international regulatory framework, codes and standards governing this area, in order to ensure that the developed solutions comply with current requirements and recommendations. These include:

— The International Energy Conservation Code (IECC) of the International Code Council (ICC) is the most common energy code for residential buildings in the United States, revised every three years with an emphasis on energy efficiency, building envelopes, RESs, and low-CO_2 emission buildings.

— Directive 2002/91/EC of the European Parliament and of the Council on the energy performance of buildings is the main legislative instrument of the EU aimed at improving the energy performance of buildings with mandatory targets for reducing CO_2 emissions.

— The International Passive House Standard, developed by the Passive House Institute of the USA (PHIUS), sets criteria for all climate conditions, including the creation of a continuous highly insulated building envelope, the elimination of thermal bridges, passive solar energy use, and heat recovery.

— The Passive House Planning Package (PHPP) defines requirements for the specific heat consumption for space heating (no more than 15 kWh/m^2 per year) and the total primary energy consumption (no more than 120 kWh/m^2 per year).

— The ASHRAE Standard 140-2020 provides testing methods for software tools for assessing the energy consumption of buildings.

— The Energy Saving Ordinance (EnEV 2002, Germany) – strengthens the requirements for the energy efficiency of buildings, combining previous standards for thermal insulation and heating equipment, aimed at reducing energy consumption and CO_2 emissions.

— BREEAM Green Certification System (UK) encourages the environmental performance of buildings and stimulates demand for sustainable buildings through certification schemes (BREEAM Communities, BREEAM New Construction, etc.).

— LEED (Leadership in Energy and Environmental Design) System covers assessment categories including location, transport, water efficiency, energy and air quality, materials and resources, indoor environmental quality, and innovation.

It should be noted that in Uzbekistan, within the framework of the UN sustainable development programs, the SNiP Passive Buildings: Residential developed by the authors has been introduced, which limits the use of primary energy to 120 kWh/m^2 per year, taking into account all household needs in the building [13].

The authors, by generalizing the existing terminologies in the area under consideration [14–19], use the term EAWU in this paper. Despite the fact that this term was first used by Vasiliev [17], he does not provide a clear definition of this term. In this regard, its definition is proposed as follows: "EAWU denotes a window structure equipped with control elements that allow increasing heat input from outside in winter, reducing light discomfort, and reducing heat input and reducing cooling costs in summer." This term and concept are also used in the draft state standard, Energy-Active Translucent Enclosures. General Specifications, which is currently undergoing review and approval. According to the draft standard, EAWUs are classified by their functional purpose, materials of profile elements, types of construction, types of translucent filling, number and location of sealing contours in the rebate, as well as design solutions for sash rebate and operational characteristics.

In this regard, the authors performed a system analysis of existing designs of window units [17–31]. As a result, six main types of EAWUs and their components were identified, classified by energy parameters as follows:

— EAWUs with heat-carrying modules and photovoltaic converters. Such units reduce the heat transfer coefficient to ~0.8 W/(m^2 K) and increase thermal efficiency by 50–70% compared to traditional double-glazed windows. This is achieved through the integration of special thermal modules and solar photocells, providing maximum heat recovery in winter and minimizing heating of rooms in summer [18, 19, 25, 26].

— EAWUs with inert gas in the glass unit. The use of insulating glass units filled with argon or krypton allows achieving a U-value of about 0.8 W/(m^2 K), which improves thermal performance by 20–30% compared to conventional double glazing. Such window units provide better thermal insulation and increased efficiency in different climatic conditions by preventing heat loss in winter and overheating in summer [20].

— EAWUs with heated glass unit. Built-in electric heating elements allow active control of the glass unit temperature, reducing heat loss by 10–20% compared to traditional units. This increases indoor comfort during cold periods and is especially useful in regions with harsh climates, providing additional window heating [22, 30].

— EAWUs with sun protection coating. Special metallized coatings on glass block up to 60–80% of solar radiation, significantly reducing the load on air conditioning systems in summer. The use of heat-insulating polymer films with a reflective layer allows for the effective reflection of incoming solar heat. Such structures are especially relevant for hot climates, as they significantly reduce solar heating of premises [20].

— EAWUs with low-emission heat-insulating coatings. The use of glass with low-emission and anti-reflective coatings reduces the heat transfer coefficient to ~0.6 W/(m^2 K) or lower, increasing thermal efficiency by 25–40% compared to conventional double-glazed windows. The effect is achieved due to additional air layers and highly efficient coatings, which makes such windows optimal for cold climates, ensuring maximum heat retention [23, 27–29].

— EAWUs with hollow film glass. By using special film layers and polyethylene film bags inside double glazed windows, U-values of up to ~0.5 W/(m^2 K) are achieved. This improves thermal efficiency by 30–50% due to significantly increased insulating properties of the window unit [24, 31].

Summarizing the operating experience of the listed types of EAWUs shows that the use of the listed technologies allows increasing the replacement factor (RF) of traditional fuel by 40–45% during the heating season and reducing heat input by up to 50% in the summer. In total, this reduces the cost of cooling premises, especially considering that due to climate change, Uzbekistan is increasingly acquiring the features of a hotter climate.

METHODS AND MATERIALS

In order to test the put forward assumptions and carry out studies to determine the thermal efficiency of a multilayer transparent enclosure (TE) in the conditions of Tashkent (for their use in passive houses and assessing the degree of practical use during the heating season), a climatic database was formed, which covers the period from 2000 to 2023 and is obtained from the average hourly data of the ERA5-Land database, a global reanalysis with a grid of 0.1° × 0.1° (approximately 9 km) for the period from 1950 to the present. The data are available with an hourly resolution, in GRIB format, and are updated monthly with a delay of about 3 months relative to the current date [32]. It should be noted that the ERA5-Land temperature data, according to literary sources [33, 34], are in good agreement with the results of ground-based meteorological observations in Uzbekistan. The following parameters and characteristics were analyzed within the framework of this study:

1.Maximum temperatures by month: The data on maximum SE temperatures by month for the 2000–2023 period were analyzed based on which maps of the spatial distribution of maximum temperatures by regions of the republic for each month of the year were compiled. These maps make it possible to assess the most extreme temperature conditions that must be taken into account when designing EAWUs to effectively reduce the heat load in buildings.

2.Minimum temperatures by month: The minimum SE temperatures by month for the 2000–2023 period were studied based on which maps of the distribution of minimum temperatures by regions of the republic for each month were created. These data are necessary for understanding seasonal temperature fluctuations and developing window systems that provide effective insulation and minimize heat loss during cold periods of the year.

3.Average number of hours with temperatures above 35°C: Due to the increase in the number of days with extremely high temperatures, an analysis of data on the average number of hours when the SE temperature exceeds 35°C was conducted to better understand the heat load on buildings and potential ways to reduce it. This analysis provides a comprehensive understanding of the temperature conditions affecting the

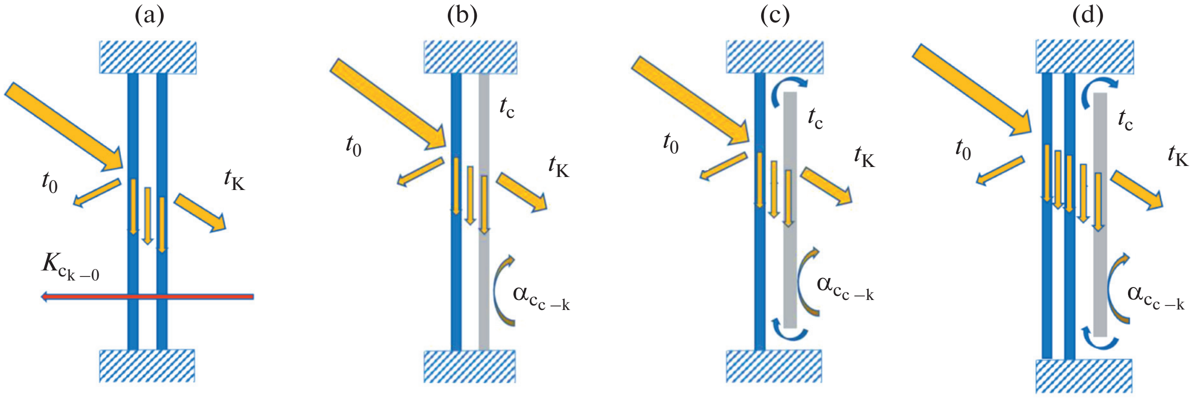

Fig. 1. Thermal diagram of multilayer TE: (a) conventional multilayer TE, (b) multilayer TE with a partially absorbing layer, (c) TE with a partially absorbing layer and a vent, (d) multilayer TE with a partially absorbing layer and a vent (yellow arrows—sun rays; dark yellow arrows—convective heat flow from TE to indoor air; red arrow – heat loss; blue arrows—directions of moving air in the vent; gray rectangle—partially absorbing layer; blue rectangle – conventional glass).

heat load of buildings in the republic and serves as a basis for developing effective energy-saving solutions.

4.Optical characteristics of multilayer TE: Under the supervision of Prof. R.R. Avezov, calculations of the optical characteristics of glazing consisting of more than two layers with different optical properties (including one partially radiation-absorbing layer) were performed [35–38]. He was the first to propose a simplified method for calculating the coefficients of reflection, absorption, and transmission of solar radiation (SR) for multilayer systems, taking into account multiple internal reflections in the layers. This made it possible to more accurately evaluate the optical properties of complex TEs.

As is known, the thermal efficiency index (η_c) of TE depends on their optical and thermal parameters [34] and can be calculated using formula:

$$\eta_c = \tau_c - \frac{K_{C_{r-o}}}{q_{inc}}(t_r - t_o), \quad (1)$$

where τ is the transmittance coefficient of the total SR for a given TE, $K_{C_{r-o}}$ is the heat transfer coefficient through the TE, q_{inc} is the surface flux density of the total SR incident on the front surface of the TE, t_r and t_o are the room and outdoor air temperatures, respectively. Since η_c depends on many parameters, determining the effective transmittance coefficient of the TE window units is of practical interest.

Calculation of the effective transmittance coefficient of direct SR for a three-layer TE ($\tau_{eff_{(3)}}$) can be calculated using formula [35]:

$$\tau_{eff_{(3)}} = \frac{\tau_{eff_1}\tau_{eff_2}\tau_{eff_3}}{(1-\rho_{eff_1}\rho_{eff_2})(1-\rho_{eff_1}\rho_{eff_3}) - \rho_{eff_2}\rho_{eff_3}\tau_{eff_1}^2}, \quad (2)$$

where ρ_{eff_1}, ρ_{eff_2}, and ρ_{eff_3} are the effective radiation reflectivity coefficients of the first, second, and third layers of the TE, τ_{eff_1}, τ_{eff_2}, and τ_{eff_3} are the effective radiation transmittance coefficients of the first, second, and third layers of the TE taking into account multiple internal reflections between the interfaces of the layers and air gaps.

Formula (2) allows us to take into account multiple reflections inside a three-layer structure and calculate the actual transmission capacity of the system for solar radiation.

Figure 1 shows the thermal diagram of multilayer TE used in buildings with passive solar heating and cooling systems.

We can see from Fig. 1, in a conventional multilayer glass unit (Fig. 1a) the sun's rays pass through the glass unhindered, and a significant portion of the thermal energy is lost through thermal conductivity and convection (shown by the red arrow). In more complex configurations (Figs. 1b–1d), partially absorbing layers reduce the intensity of solar energy penetration, reducing the thermal load on the interior. In the case of a multilayer glazing unit with a partially absorbing layer and a vent, blowing air between the layers (blue arrows) improves heat exchange, reducing convective losses, which significantly reduces the total amount of lost thermal energy.

In this case, the daytime thermal efficiency of a multilayer translucent system with a partially absorbing layer and a vent is determined as follows [39]:

$$\eta_c = \tau_c - \frac{\alpha_{Cc-r}}{q_{inc}}(t_c - t_r), \quad (3)$$

where α_{Cc-r} is the heat transfer coefficient from the TE to the internal air; t_c is the temperature of the internal surface of the TE.

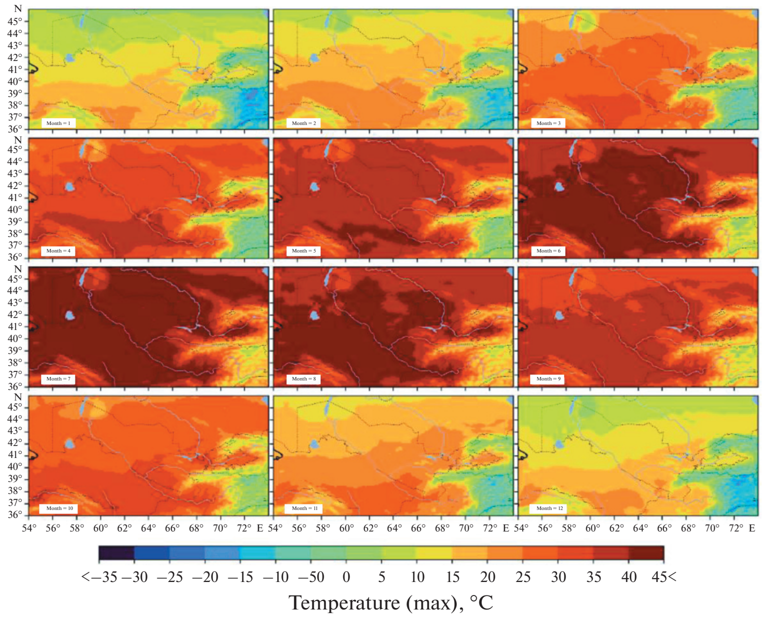

Fig. 2. Map of distribution of average monthly maximum temperatures by regions of Uzbekistan for the period from 2000 to 2023.

In this case, the daytime thermal efficiency of a multilayer translucent system with a partially absorbing layer and a vent is determined as follows [39]:

$$\eta_c = \tau_c + \frac{\alpha_{C\,c-r}}{q_{inc}}(t_c - t_r) + \frac{\dot{m}c\left(t_{out} - t_{in}\right)}{F_{TE}q_{inc}}, \quad (4)$$

where $\dot{m}$ is the mass flow rate of air through the vent; c is the specific heat capacity of air, F_{TE} is the surface area of the TE, as well as t_{out} and t_{in} are the air temperatures at the outlet and inlet of the vent.

It is worth noting that the methodology we propose develops the approach presented in [35], since it can be extended to a more complex configuration that includes a partially radiation-absorbing layer (sun protection glass) and a ventilation vent between the glasses.

RESULTS AND DISCUSSRON

Considering that one of the dominant factors in the thermal efficiency of the TE EAWU is the SE temperature, the authors studied the dynamics of changes in the average monthly values of maximum and minimum temperatures for the period of 2000–2023 in the regions of Uzbekistan (Figs. 2 and 3).

We can see from Fig. 2, that in the summer months (May–September), maximum temperatures in most regions of Uzbekistan and adjacent territories exceed 35°C. In the spring and autumn months (March, April, October, and November), a gradual decrease in maximum temperatures is observed, and in the winter months (December, January, and February), they reach minimum values. This trend indicates that in the southern and central regions, extremely high temperatures are recorded in summer, which increases the need for cooling systems and emphasizes the need to improve the energy efficiency of buildings.

We can see from Figure 3, that minimum air temperatures by month vary significantly across the regions of Uzbekistan and adjacent territories. In winter, temperatures drop to the lowest values, especially in the northern and eastern regions, where extreme cold (below –25°C) is recorded. In spring and autumn, minimum temperatures gradually increase, and in the summer months they reach their maximum, on average being in the range of 15–25°C. These data highlight the need to take seasonal temperature variations into account when designing buildings, especially to ensure adequate thermal insulation in winter.

Figure 4 shows a map of the distribution of the average number of hours with temperatures above 35°C by regions of Uzbekistan for the period of 2000–2023.

We can see from Fig. 4 that there are significant differences in the number of hours with temperatures above 35°C in the main cities of the country. In Tashkent and Urgench, this figure varies from 209 to 418 hours, while in the southern regions, such as Karshi and Termez, the number of such hours reaches 626–731. The data obtained indicate an increase in the number of extremely hot hours in the southern and central parts of the country, which increases the requirements for cooling systems and requires measures to improve the energy efficiency of buildings. These results highlight the increasing importance of using EAWUs that can effectively reduce heat gain and

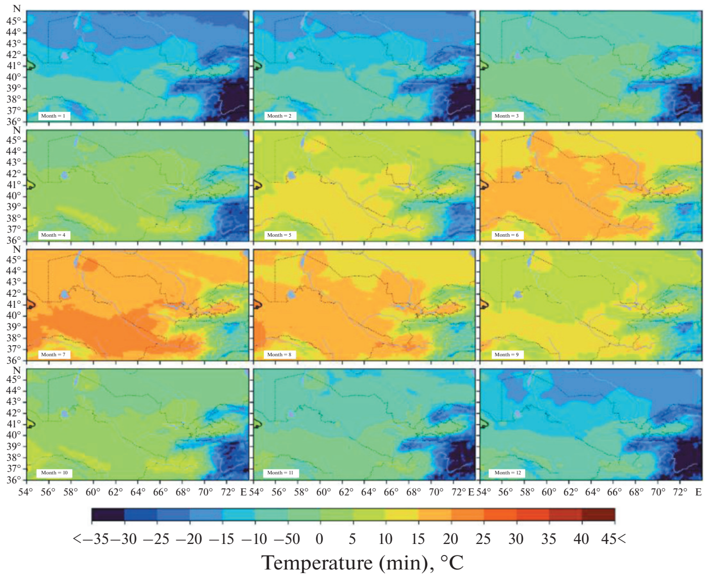

Fig. 3. Map of distribution of average monthly minimum temperatures by regions of Uzbekistan for the period from 2000 to 2023.

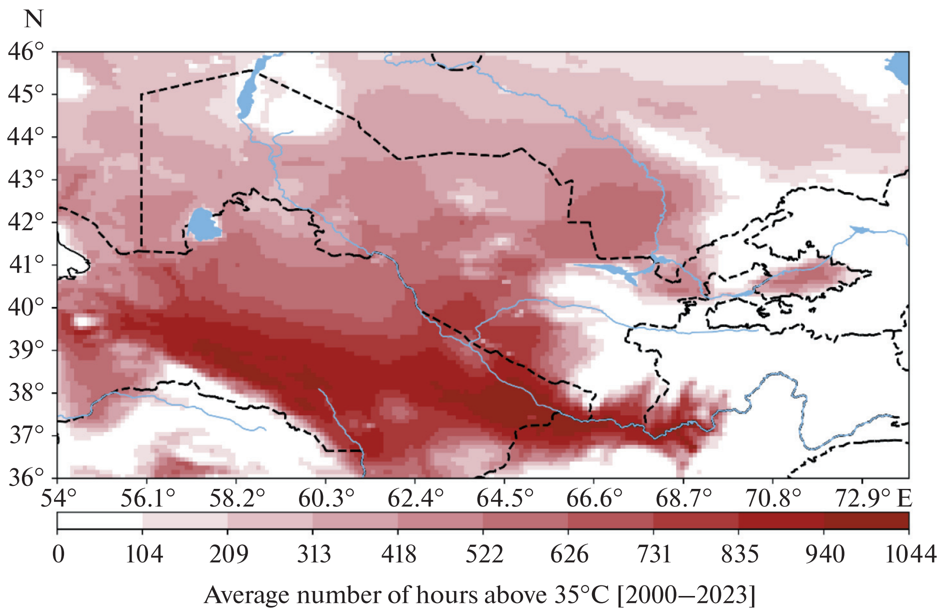

Fig. 4. Map of the distribution of the average number of hours with temperatures above 35°C by regions of Uzbekistan for the period from 2000 to 2023.

improve the energy efficiency of buildings in extremely hot weather conditions.

Analysis of the results of preliminary calculations performed in early studies [35] shows that the efficiency of three-layer glazing, taking into account multiple reflection of radiation between the layers according to formula (1), is: about 0.65 at a comfortable indoor temperature of 18°C, an air gap thickness between the glasses of 0.008 m, an ambient temperature of −5°C and a radiation flux density of 700 W/m^2 (noon); about 0.59 for a two-layer glazing under the same conditions; about 0.49 for a single-layer glazing under the same conditions. The glass transmittance coefficients in the calculations were taken to be 0.8; 0.65; and 0.51, and the heat loss coefficients through the glass in the ambient air were 6.35; 3.25; and 2.0 W/(m^2 °C) for single-, double-, and three-layer glazing, respectively.

Taking into account the obtained results on the average daily and average monthly total values of solar

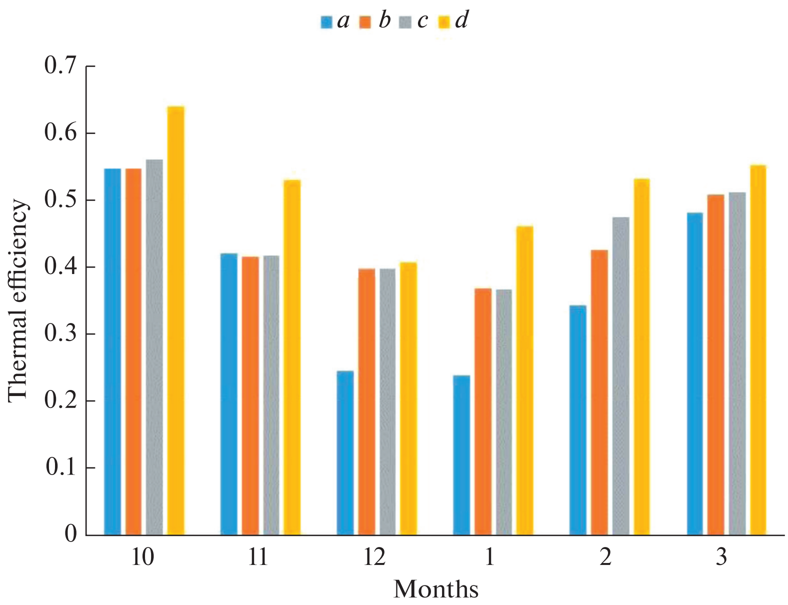

Fig. 5. Average monthly thermal efficiency indicators of multilayer TE in Tashkent for the heating season, for cases (a), (b), (c), and (d) according to Fig. 1.

radiation [40] falling on the vertical surface of the TE, as well as the indicators of maximum and minimum temperatures of the SE (items 1–3), the authors performed a numerical implementation of the proposed method for determining the daily thermal efficiency of the specified multilayer TE (Tashkent city). The calculations were carried out using the PTC Mathcad Prime 9.0 software package (the results are shown in Fig. 5). The methodology and algorithms of the numerical calculation are based on the results of the authors' previous studies [41, 42], where they are described in detail and verified, which ensures the reproducibility of the calculations performed and guarantees the correctness of the results, confirming the versatility of the proposed method in the analysis of various configurations of multilayer TE.

The calculations were performed under the following boundary conditions:

— Room temperature: 22°C.

— Glass thickness: 0.004 m.

— Glass thermal conductivity coefficient: 0.75 W/(m °C).

coefficients of reflection, absorption, and transmission of each layer are at given wavelengths.

We can see from Fig. 5, that the thermal efficiency of the four considered options of the TE significantly depends on the season. The highest and most variable efficiency is demonstrated by the multilayer TE with a partially radiation-absorbing layer and a vent: η varies from ~0.40 to 0.64 during the year, which exceeds the indicators of the other three designs. This type of design shows better characteristics compared to alternative options, which confirms its advantage for use in energy-saving technologies.

Further, Fig. 6 shows the results of calculating the average hourly values of the thermal efficiency of a multilayer TE with a partially absorbing layer and a vent in Tashkent for January, February, and March. The methodology and algorithms of the numerical calculation are similar to those described in [41, 42].

Figure 6 also demonstrates that the thermal efficiency of a multilayer TE with a partially absorbing layer and a vent varies depending on the time of day and month of the year. In January (curve *1*), η begins to increase from ~7 am, reaching a peak of ~0.5 between 11 and 12 pm, after which it decreases to ~0.1 by 4 pm. In February (curve *2*), the thermal efficiency increases from ~7 am, reaching a maximum of ~0.6 between 11 and 1 pm, then gradually decreases to ~0.2 by 4 pm and falls to ~0 by the evening. In March (curve *3*), the highest thermal efficiency is observed among these three months: the maximum of ~0.7 is reached between 10 and 14 h, after which the indicator decreases to ~0 by 17 h.

Note that the obtained results are based on the numerical implementation of the proposed methodology, experimental verification of the presented solutions is planned for the next stage of research.

The Proposed New Design of Energy-Active Window Units and the Operating Principle

Taking into account the above calculations of thermal efficiency and critical analysis of various designs of multilayer TEs [40–45], the authors proposed an

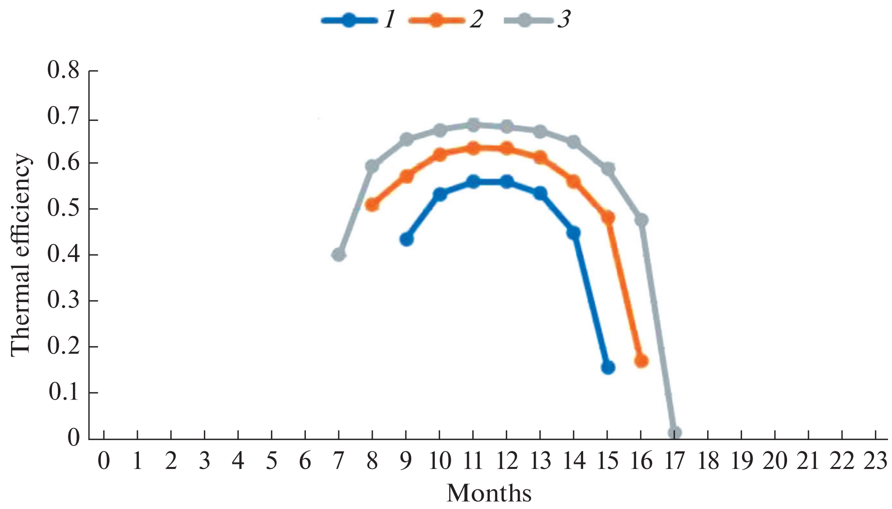

Fig. 6. Average hourly thermal efficiency indicators of a multilayer TE with a partially absorbing layer and air vent in Tashkent for January, February, and March.

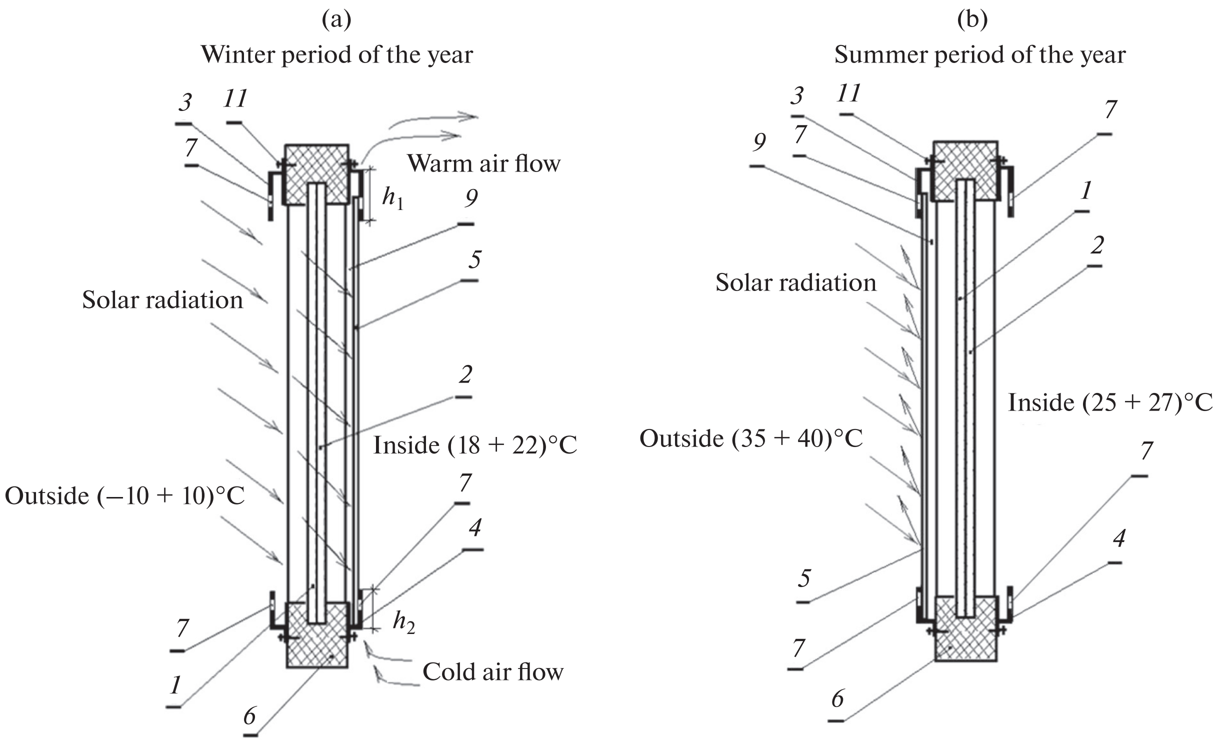

Fig. 7. Operating principle of the proposed EAWU in winter (a) and summer (b) periods of the year.

improved design of the EAWU [46]. It includes two-chamber glass units (outer and inner chambers) and is equipped with L-shaped brackets with magnetic tips for adjusting the position of the partially darkened glass (PTG). This design allows the window to be adapted to winter and summer conditions: to facilitate heating of the room in winter and to protect it from overheating in summer, optimizing the temperature regime and increasing comfort.

Figure 7 shows the operating principle of the proposed EAWU in winter (a) and summer (b) periods of the year.

In winter, radiant solar radiation passes through a two-chamber glass unit consisting of outward-facing

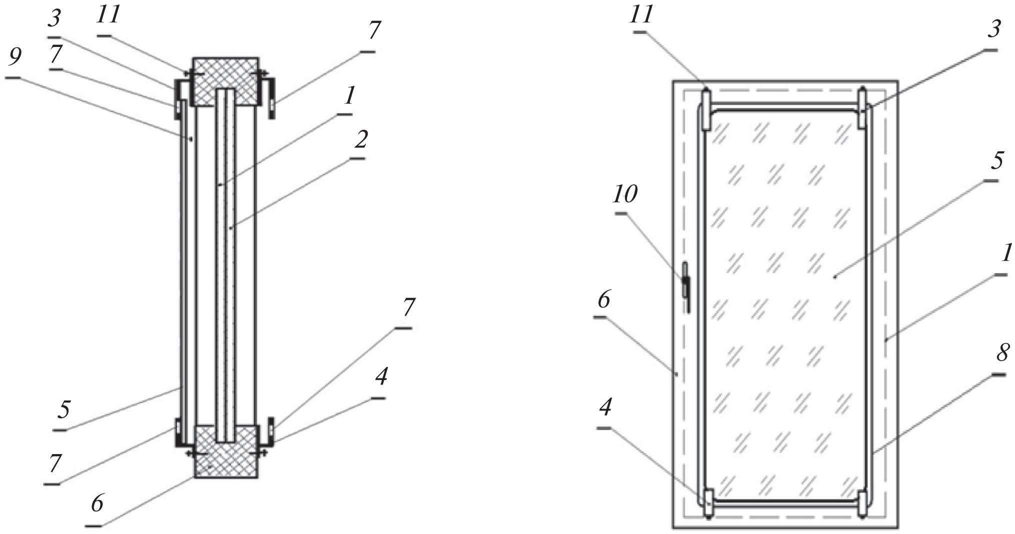

Fig. 8. The design of the EAWU proposed by Avezova et al. [46].

outer chamber (*1*) and inward-facing inner chamber (*2*) and reaches the surface of energy-active partially darkened glass (*5*), installed in a small removable frame. This frame is held in place by means of L-shaped brackets with magnetic tips: upper (large) bracket (*3*), fixed in the upper part of the main plastic frame of the window unit, and lower (small) bracket (*4*), fixed in the lower part of frame (*6*) using self-tapping screws (*11*). The ratio of the heights of the large and small L-shaped brackets is selected so as to reliably hold the energy-active PTG in the required position. Under the influence of solar radiation, the air in the vent between inner glass unit (*2*) and energy-active PTG (*5*) heats up (the thickness of the vent, depending on the height of the window, is 0.015–0.020 m). The heated light air rises upward, entraining colder air from below, creating convective heat exchange inside the room (Fig. 7a).

In summer, energy-active PTG (*5*) installed on the small plastic frame is removed from the inner side of the window unit and repositioned from the outer side. There it is also fixed with L-shaped brackets with magnetic tips (large (*3*) in the upper part of the frame, small (*4*) in the lower part of frame (*6*)). Solar radiation falling on the surface of the energy-active glazing is retained outside the window block, and the resulting heat is dissipated in the external environment (Fig. 7b). Such a simplified rearrangement design implements the thermal diagram of in Fig. 1g.

The following brands of partially darkened glass for use in EAWUs are currently available on the market: Guardian SunGuard SNX 62/27 (visible light transmittance – 0.62; solar heat transmittance – 0.27; *U*-factor – 0.30–0.50 W/m^2 K; price ≈ 50–100 USD/m^2), Pilkington Suncool™ 66/33 (visible light transmittance – 0.66; solar heat transmittance – 0.33; U-factor – 0.50–0.60 W/m^2 K; price ≈ 70–120 USD/m^2), Saint-Gobain SGG Cool-Lite SKN 176 (visible light transmittance – 0.70; solar heat transmittance – 0.37; *U*-factor – 0.60–0.70 W/m^2 K; price ≈ 60–110 USD/m^2), 3M Sun Control Window Film (visible light transmittance – 0.2–0.6; solar heat – 0.18–0.40; *U*-factor – 0.50–0.75 W/m^2 K when used in double-glazed windows; price ≈ 15–35 USD/m^2), Llumar Solar Window Films (visible light transmittance – 0.15–0.50; solar heat – 0.17–0.38; *U*-factor – 0.50–0.70 W/m^2 K when used in double-glazed windows; price ≈ 12–30 USD/m^2).

The proposed EAWU allows to increase the temperature inside the building in winter due to the convective heat inflow, and in hot summer, to prevent the penetration of solar radiation inside and to reflect the generated infrared heat, preventing overheating of the premises. The design of the EAWU is shown in Fig. 8 and consists of: an outer chamber (made of transparent glass, facing outward) (*1*); an inner chamber (made of transparent glass, facing inward) (*2*); L-shaped brackets with magnetic tips (large) (*3*); L-shaped brackets with magnetic tips (small) (*4*); an energy-active PTG installed in small removable frame (*5*); main plastic frame (window body) (*6*); a magnet built into L-shaped bracket (*7*); the smallest removable plastic frame (*8*); vent (air gap) (*9*); a handle for opening/closing window unit (*10*); and self-tapping screws for fastening (*11*).

Thus, the introduction of energy-active and energy-saving window units provides significant economic benefits. Firstly, such window systems significantly reduce the costs of heating and cooling buildings due to improved thermal insulation and a reduced heat transfer coefficient. Research shows that EAWUs with improved thermal insulation properties can reduce energy consumption by 30–50% compared to conventional double-glazed windows [47]. Secondly, due to the use of solar energy and high light transmission, such windows can reduce the cost of artificial lighting, which further reduces the operating costs of buildings [48]. In addition, the introduction of EAWUs increases the value of real estate due to improved environmental characteristics and compliance with modern energy efficiency standards [49]. It should be noted that all of the above results are based on calculations and modeling; experimental verification of the effectiveness of the proposed solutions in real conditions has not yet been carried out and is planned for further stages of research.

CONCLUSIONS

The study of international regulations and standards has shown that existing window unit designs require improvement to achieve modern energy efficiency standards. In particular, boundary conditions have been proposed according to which the specific heat consumption for heating in buildings should not exceed 15 kWh/m^2 per year, and the total primary energy consumption should not exceed 120 kWh/m^2 per year. These figures correspond to international norms and standards for passive construction.

A critical review of EAWU designs shows that various models demonstrate significant improvements in energy performance, allowing the heat transfer coefficient to be reduced to 0.5–0.8 W/(m^2 K), which in turn leads to an increase in thermal efficiency by 25–70% depending on the technology used. Existing EAWU designs can be classified by functional purpose, materials of profile elements, types of structures, types of translucent filling, and the number and location of sealing contours. The results of calculating the daytime thermal efficiency of multilayer TE EAWUs (taking into account the climatic indicators of the regions) showed that EAWU structures equipped with multilayer TE with a U value of up to 0.5 W/(m^2 K) are capable of increasing the thermal efficiency of the window unit by 30–50%. This leads to a significant reduction in the costs of centralized heating and cooling of buildings and a decrease in the impact on the SE.

Developed maps of maximum and minimum air temperatures and the average number of hours with $t >$ 35°C for the period 2000–2023 show that in a number of southern regions of Uzbekistan, summer temperatures exceed 35°C for 209–731 hours per year. These data demonstrate the need to adapt window systems capable of reducing the heat load and providing effective thermal insulation at extremely high temperatures.

This paper is dedicated to the cherished memory of Professor Avezov Rabbankul Rakhmonovich, whose knowledge, scientific leadership, and dedication to the cause left an indelible mark in our hearts. We honor his legacy and strive to continue the work he began.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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