Introduction of Innovative Adaptive Building Envelopes to Improve Energy Efficiency of Apartment Buildings

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Abstract. Currently, there are many varieties of facade systems. Some of them have become obsolete and do not meet modern energy efficiency requirements, while others require enormous investments. However, the right choice of facade affects not only the appearance of the building, but also its final cost. Rising prices for thermal energy, including public utilities, brings the community to the need to improve the thermal protection of buildings and, as a consequence, to increase its energy efficiency, which is possible through the introduction of innovative adaptive building envelopes. Thus, the article considers advanced building envelopes in terms of improving energy efficiency of apartment buildings (AB). The analysis of adaptive facade systems, their advantages and disadvantages, as well as the prospects for the development of these systems has been carried out.

Keywords: Building envelopes · Adaptive system · Energy efficiency · Apartment buildings

1 Introduction

Currently, more and more scientific papers are being published, devoted to the development of methods to reduce and control energy consumption [1–6]. Opinions of scientists differ. Some scientists insist on increasing the requirements to the level of thermal insulation of building envelopes, while others consider the existing regulatory requirements excessive. The third group of scientists offers the optimized models in which a number of economic and ecological requirements are balanced.

It is known that about 50% of heat losses fall on the walls of apartment buildings. Therefore, their impact on energy consumption cannot be underestimated. Improving the energy efficiency of building envelopes of residential buildings is achieved by application of effective heat insulation in constructions of external walls, coatings, flooring and partition walls. Energy-saving measures to insulate the facade of apartment buildings

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are promising and guarantee significant savings of heat energy and, as a consequence, leads to a decrease in the volume of consumption of public utilities.

When carrying out a major structural renovation through the use of innovative building envelopes and modernization of old residential buildings, one-time capital investments are required, which is approximately 5–10% of the cost of the house, but the economic effect of this energy-efficient measure will be 50% savings on heating, which will further result in savings of money. Payback of this event is within 5–10 years. Thus, investing in innovative building envelopes is a contribution to the future development of the construction market and improvement of living conditions [7].

When analyzing the energy efficiency of certain building constructions one of the important factors is climatic indicators. It can be noted that the thermal and technical characteristics can vary significantly within the same city. Thus, O.D. Samarin in his scientific paper [8] considers the impact of climate change on the payback of additional insulation. As a result of studies done by the author noted that such measures as increasing the thermal insulation properties of building envelopes does not always lead to a positive result. This pattern is associated primarily with climatic features of a particular area, which are not always taken into account when carrying out thermal modernization of buildings. After all, saving thermal energy is a promising field of energy efficiency. If we consider traditional facades, they cannot fully respond to changing thermal and light conditions in the environment to improve the internal environment, because they are static systems. Thus, the ability of dynamic control and management of energy efficiency is limited. With the advent of innovative technologies, buildings with kinetic facades, which can change their appearance depending on the environment, are becoming more and more promising.

2 Materials and Methods

2.1 Advanced Building Envelopes in Terms of Energy Efficiency

Let's consider more advanced building envelopes in terms of energy efficiency - adaptive energy efficient systems. These systems are designed to respond dynamically to changes in the surrounding climatic conditions, which implies better efficiency in contrast to static systems. When considering apartment buildings, one can conclude that energy consumption directly depends on the efficiency of HVAC systems.

If we consider a high-performance facade, it is the exterior building envelope, which has properties such as the minimum amount of energy consumption to maintain the comfortable characteristics of the indoor environment. Energy efficient building shells not only maintain comfortable conditions indoors, but also protect the building from the external environment. These building envelopes have certain properties, which are presented in (Fig. 1) [9].

Energy efficient shells include an adaptive building envelope, which has the ability to control various required characteristics, including changing its properties depending on changes in the environment or depending on changes in the indoor environment. Changes in properties are achieved in various ways (by introducing air flow, moving components, etc.).

The adaptivity system can be divided into 3 categories (Fig. 2).

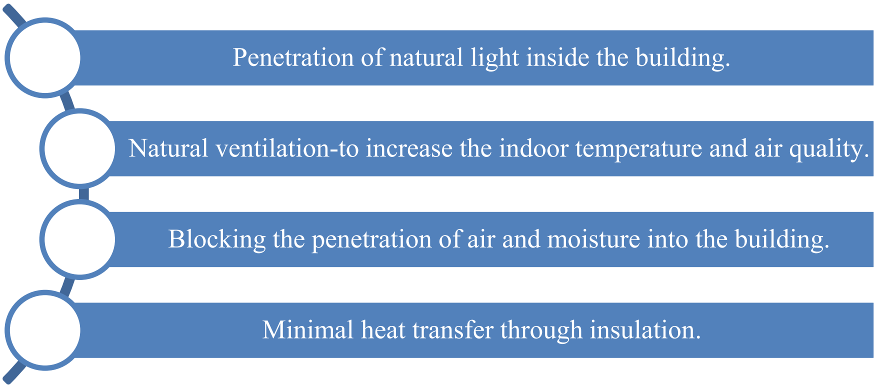

Fig. 1. Properties of energy efficient building envelopes

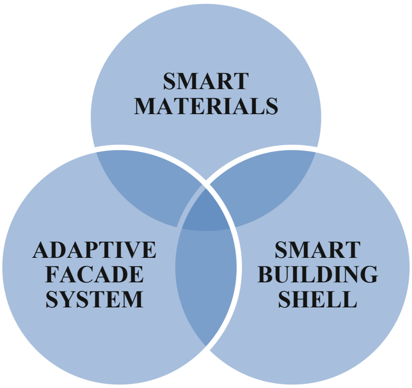

Fig. 2. Categories of division of the adaptivity system.

Let's have a closer look at each category:

1. **Smart materials**. As the name suggests, these are materials which characteristics can be changed under the influence of changes in external factors, such as changes in temperature, changes in electric or magnetic fields. In this case materials that change their characteristics under the influence of heat, light or moisture are used. Such materials used in high-performance facades include aerogel, salt hydrates, thermochromic polymer films, etc.
2. **Smart building shell**. This system is "intelligent" and "independent". It takes into account weather fluctuations and makes appropriate changes accordingly. This is achieved by building automation and physically adaptive components (intelligent prefabrications, sun shades, etc.).
3. **Adaptive facade system**. Adaptive facade system has the same characteristics as the smart building shell. This system also, like the smart building shell, includes real-time measurements, intelligent materials, human ability to make changes independently.

The distinguishing feature of this system from the smart building shell is the use of computing algorithms that allow the system to adapt to the changing environment and provide timely information to the residents about its changes and energy load. Thus, the residents are provided with information about the change of environmental conditions, thereby they can adjust the living conditions depending on the climatic and energy load [9].

2.2 Types of Adaptive Facade Systems

Multifunctional adaptive facades make it possible to design a new generation of buildings with nearly zero energy consumption. Adaptive building envelopes can be considered the next milestone in facade technology. In recent decades there has been a powerful impetus in the development of adaptive building envelopes due to the integration of smart materials into adaptive building envelopes. Advanced adaptive structures in terms of energy consumption can be distinguished such as integrated facades [10], smart windows [11], dynamic solar shading [12], phase change materials [13] and multifunctional facades [14].

Adaptive facade systems can be divided into [15, 16]:

1. ***Dynamic facade***. In this type of facade, the moving parts (moving shutters, blinds, roller blinds) are activated automatically, using built-in sensors that respond to changes in the weather, time of day, etc. It is also possible to activate them manually. This facade allows you to control the microclimate in the rooms, for example, cooling during the warm season or thermal insulation during the cold season. Such a facade was used in the construction of the Kiefer Technic Showroom (Austria).
2. ***Chromogenic facade***. This facade includes such types of glazing as: electrochromic glazing, liquid crystal glazing and thermochromic glazing. In this type of facade - the glazing changes its degree of transparency, thermal conductivity, as well as the coefficient of light transmission depending on various factors (voltage transmitted through the element, temperature, brightness and illumination).
3. ***Adaptive solar facades***. There are several types of facades: with photovoltaic panels (solar panels), bioclimatic facades (with external greenery), light-concentrating facades (collecting sunlight for lighting the rooms) and double-walled facades. For example, BIPV solar panels were applied in Madrid during the construction of the Jose Villarreal Social Services Center (Spain).
4. ***Active ventilated facades***. The essence of these facades is the ability to control air circulation in the building, through the distribution of air flow inside the cavities of the facade elements. It is also possible to control the incoming air in the building, with the help of automated control of the glass elements of the building. Such a variant of the facade was applied during the construction of the head office of Thussenkrupp Quartier (Germany) in Essen.

The cost of implementing adaptive facades is much higher than static facades. The main advantageous factors over static facades are:

– obtained comfort during the operation of the premises;

- modern and unique appearance of the building;
- saving natural resources;
- complete automation of the facade system management without human participation (introduction of artificial intelligence) [17].

3 Results

3.1 Energy-Efficient Transparent Structures

Consider the advantages and disadvantages of transparent structures, which are classified as adaptive facades. The advantages include a high coefficient of resistance to heat transfer, as well as high light transmission, but the disadvantage is expensive and labor-intensive production. Transparent structures are made depending on [18]:

- materials used;
- thermal performance;
- bearing capacity;
- method of fixing the insulating glass unit;
- variant of filling the structural opening;
- method of installation, etc.

The energy efficiency of transparent structures is affected by the filling of structural openings. There are two ways of heat loss: ventilation heat loss and transmission heat loss.

The thermal conductivity of the glass itself and the convection of air belong to the ventilation ones, and the transmission losses are the infrared radiation directly through the glass area, which accounts for up to 70% of the heat loss.

Consequently, the efficiency of transparent structures depends primarily on the window profile, glass unit and the quality of installation. By energy-efficient glazing is meant the glazing, which allows to regulate the energy flows through the window structures. In this case there is a delay of thermal infrared radiation inside the building and the ultraviolet spectrum of solar radiation is not transmitted to the outside. Energy efficient glazing is divided into several types (Fig. 3) [18].

Low-emissive glass is the most common type of energy-efficient glazing, as it has high light transmission and transparency and quite high thermal insulation coefficient values. A distinction is made between hard energy-saving coating (K-glass) and soft energy-saving coating (I-glass).

Hard energy-saving coating is distinguished by the fact that the reflective layer is applied directly during the glass production process. A reflective layer based on $InSnO_2$ metal oxides is applied to hot glass, resulting in a strong hard film. The emissivity of this glass is lower than standard glass and is 0.2. The hard energy-saving K-glass is almost indistinguishable from standard glass.

The soft energy-saving coating is more advanced and surpasses the I-glass in its heat-saving properties. The reflective layer is created on the basis of silver and dielectric and is applied by vacuum deposition on the surface of already finished glass. The reflective layer is deposited in 3 or more layers, in which metal and dielectric are alternated [17].

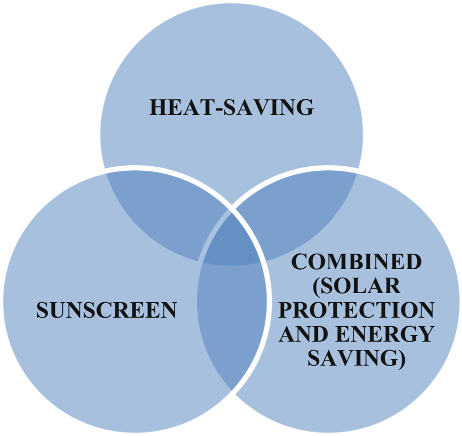

Fig. 3. Types of energy efficient glazing

Table 1 shows the advantages and disadvantages of hard energy saving coating and soft energy saving coating.

Table 1. Advantages and disadvantages of low-emissive energy-saving glass

	Hard energy-saving coating (K-glass)	Soft energy-saving coating (I-glass)
Advantages	Resistant to mechanical stress; stronger than the soft coating; suitable for single glazing; not mistier; does not crumble over time; looks like standard transparent glass; has an unlimited storage life	Almost does not retain visible sunlight; as good as standard float glass; retains ultraviolet rays; additionally, protects against overheating
Disadvantages	Retains less heat than glass with soft coating (about 70%); reduces the light transmission capacity of windows; almost doesn't protect from overheating by sunlight; the technical characteristics are superior to K-glass; allows you to keep the room 90% or more of the heat flux that falls on the window	Vulnerable to mechanical stimuli (the side on which the coating must be applied must face the inside of the glass unit); loses its properties when exposed to oxygen for a long time; has a finite life (from 20 to 25 years); on average, 2.5 times more expensive than standard glass

Table 2 shows the internal glass temperature measurements for different types of glass under the same conditions.

From the table you can see that standard windows retain heat worse than energy-saving glass. If we compare between the energy-saving glass, the I-glass has better performance than the K-glass.

Table 2. Measurements of the internal glass temperature of different types of glass under the same conditions.

Type of coating in a single-glazed window	The temperature of the internal glass in the windows when the frost outside −27 °C, when the interior is heated to +21 or +22 °C (°C)
Standard float glass without a thermal insulation layer	+6
Hard energy-saving coating (K-glass)	+12 or +13
Soft energy-saving coating (I-glass)	+15 or +16

Let's summarize the pros and cons of using energy-efficient windows regardless of the coatings (Table 3).

Table 3. Pros and cons of using energy-efficient windows

Pros of energy-efficient windows	Cons of energy-efficient windows
Energy-saving glass units reduce the total heat loss of the premises by about 10%, preventing complete freezing	"Reflective" coatings are not recommended for using in areas of prolonged exposure to direct sunlight
38–40% less energy is lost through the window opening area	Not all types of energy-efficient glass are used in single glazing
Protect against overheating in the summer, as a consequence there is energy saving in air conditioning rooms	
Replacement of the standard double-glazed windows with single-glazed models	
UV protection	
Improved sound insulation (if inert gas (argon or krypton) is pumped in)	

3.2 The Innovative Adaptive «SELFIE» System

The SELFIE adaptive facade is implemented as a single system of curtain walls [19]. This facade is presented in three variants (prototypes).

The modular components of the first prototype "SELFIE" are an opaque panel that consists of several layers:

1. The first layer consists of 2 glass sheets with a PVB film between them. This film is combined with nanomaterials (oxides, nanometals) and is also capable of transmitting visible light and reflecting in the infrared zone.

2. The second layer is made with a honeycomb panel in the form of porous ceramic filled with TiO2. The room air purification effect is activated by visible light. This layer of the system, provides forced or natural air circulation. The wide surface of this material ensures homogeneous distribution of the photocatalytic material, which comes into direct contact with the air.
3. The next layer is made of mesoporous foam glass filled with polymer PCM, which, in turn, reduces energy consumption in air-conditioning rooms, as well as reducing peak loads.
4. The last layer is made with a sealant, which connects the foam glass to the materials.
5. The panel is equipped with slatted deflectors on both the interior and exterior surfaces.

This ventilation system reduces energy costs for heating in winter and reduces overheating in summer months.

Modular components of the second prototype "SELFIE" is an opaque panel, which consists of the following layers:

1. The outer layer of DSSC photovoltaic panels for renewable energy production, provides good architectural integration. This layer can also be implemented with polycrystalline photocells.
2. The next insulating layer is represented by a phase transition material.
3. A heat exchanger system, reducing the energy consumption of the building in winter and increasing micro ventilation inside in summer.
4. A heat exchanger system panel consisting of lightweight materials with good mechanical properties, which can provide mechanical safety.

The modular components of the third prototype "SELFIE" is a transparent panel consisting of the following layers:

1. A window with a thermal break frame with a transmittance factor of 1.2 W/m^2 K and a layer of glass.
2. A laminated sheet with a self-cleaning exterior treatment combined with PVB and nanomaterials to keep the glass transparent with visible light and be reflected in the infrared.
3. An air cavity containing an electrical shielding system designed to optimize daylight inside the building, including reducing thermal overheating during the summer months.
4. A window with a thermal break frame with a transmittance factor of 1.2 W/m^2 K and a layer of low emissivity glass on the outside.

It is also possible to integrate DSSC photovoltaic elements into the SELFIE 3 outer layer.

SELFIE 3 provides the following energy characteristics:

1. $U = 1.2$ W/m^2 K value with subsequent reduction of heat transfer coefficient of transparent parts of building envelopes.

2. Control of solar radiation due to the possibility of adjusting the shading device located inside the air gap between the two panes of glass.
3. Improvement of acoustic characteristics of internal spaces of the building.

4 Discussion

The SELFIE adaptive facade is implemented as a single curtain wall system. The modular components are available in different geometric configurations, colors and materials. The facade consists of movable and immovable parts, with which it is possible to ventilate the room and regulate the temperature inside the building throughout the year. Also, this facade has characteristics such as [20]:

1. Structural safety is characterized by: mechanical resistance to static and dynamic loads, impact resistance, fire resistance, resistance to deformation, safety.
2. Indoor comfort is provided by: air permeability, water resistance, heat transfer coefficient, hygrothermal insulation, thermal inertia, daylight and sun protection, sound insulation.
3. Maintainability is ensured by the choice of applied modular elements, which allow repairing the facade system without changing the general facade.
4. Guarantee for users to manage the facade even in the absence of an automated system.

The application of this adapted modular system allows a balance between aesthetics and efficiency [19].

5 Conclusion

With the development of technology, the variety of adaptive modular facades is only increasing. The development of these structures is influenced by both social and economic factors. The social factor influences the choice of the building with kinetic facades. As adaptive architecture allows to satisfy the preferences of people. The economic factor will limit the use of kinetic facades, since there are no ready-made design solutions for such facades, and the development and implementation of such facades is complex and labor-consuming, which makes the project more expensive. However, the introduction of adaptive building envelopes can be a profitable investment which will pay off. The effectiveness of adaptive building envelopes is unambiguous. The introduction of such technologies allows to save natural resources, reduce the power consumption of the building, minimize harmful emissions into the environment from the processing of traditional electricity.

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