INFLUENCE OF THERMAL PROPERTIES OF ARCHITECTURAL GLASS ON ENERGY EFFICIENCY OF SUSTAINABLE BUILDINGS

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Abstract. In times of climate change and globalisation, there is a demand for studies that address long-term environmental security, efficient use of energy and other recourses, as well as the preservation of the identity and uniqueness of particular places. Sustainable building involves complex solutions and practices that lead to more energy-efficient houses that consume less energy, water, and other natural resources. It encompasses constructing buildings in such a way as to minimise the material input per unit, and managing them to reduce the power-intensity as well as any negative impact on the health of people or the environment. The concept of sustainable building was developed in other countries, but it is becoming more popular also in Latvia [1; 2]. Sustainable city life is one of the seventeen Global Goals that make up the 2030 Agenda for Sustainable Development; accordingly, an integrated approach is crucial for achieving progress across the multiple goals [3]. In order to increase energy efficiency in buildings, reduce CO_2 emissions in the world and prevent global warming, it is very important to pay attention to the thermal properties of skylights. The impact of glazing on the thermal performance of a building is complicated. There are several aspects that need to be considered: the climatic conditions of the location, such as temperature, humidity, sunshine, and wind, as well as the orientation, form and layout of the building, the building materials, especially their mass and insulating properties, the size and location of windows and shading and the thermal properties of glazing systems. The impact of glazing is the result of the interaction of all of these aspects. The aim of this study is to provide some insight into how thermal properties, in particular vertical heat flow, are affected by the thickness of the air separation layer in horizontal and sloped skylights. Glass structures made from organic glass and aerogel layers, which are characterised by a low thermal conductivity coefficient, were studied. An experiment was carried out with different translucent materials (selective glass, organic glass, aerogel filling) and the distance between the glazing layers was varied. The aim was to measure the dependence of the thermal conductivity coefficient on the thickness of the air separation layer and the direction of the heat flow.

Keywords: architectural glass, energy efficiency, sustainability, skylight thermal properties.

Introduction

The 2030 Agenda for Sustainable Development was adopted on September 25, 2015 and includes a set of 17 Sustainable Development Goals (SDGs), which are meant to be universally applicable and to address sustainable development in its environmental, social, and economic dimensions. The SDGs replace the Millennium Development Goals (MDGs). Among these goals are "sustainable cities and communities", which refers to cities that are inclusive, safe, resilient, and sustainable.

Living in bright, naturally illuminated spaces with large glazed areas is becoming increasingly popular even as energy performance requirements are becoming more stringent. Therefore, improvements in the thermal properties of glazed building envelopes are in high demand [4]. In order to increase the energy efficiency of glass window parts, multi-chamber windows with low-E coatings and various gas fillings have been designed, and the thermal transmission coefficient U values of the glass package up to 0.5 $W \cdot m^{-2} \cdot K^{-1}$ have been achieved, with an overall U value for the window between 0.7 to 0.8 $W \cdot m^{-2} \cdot K^{-1}$ [5]. The shading coefficient (*g*) also has an impact on a building's thermal performance, especially on small spaces that have a large glass area. The g value is the total solar energy transmittance (or solar heat gain coefficient) of glazing for solar radiation in the wavelength range between 300 nm and 2500 nm. The value is significant for heating, ventilation, and air-conditioning (HVAC) calculations [6, 7]. This aspect is not discussed further in this paper, because the legislation of the Republic of Latvia does not address the shading coefficient [8].

Although initially it might seem that there are no significant differences between integrated wall and roof windows, in fact, thermal processes in these constructions differ markedly. As a result, the specific type of glass structure must be carefully chosen according to each application to achieve the desired values of the thermal transmission coefficient. Thermal performance depends on the window orientation and heat flow direction. The heat flow is horizontal for a vertically oriented window, and may be upwards or downwards for a horizontal window, depending on the location of the higher temperature.

This study addresses the relationship between the thermal properties and the thickness of the separating air layer for vertical heat flow in horizontally integrated skylights. Glass structures made of organic glass or aerogel layers were studied, since these materials have a low thermal conductivity coefficient. The goal of the study was to determine how the thermal transmition coefficient depends on the thickness of the separating air or aerogel layer at the vertical heat flow.

Materials and methods

The study was carried out with organic glass and aerogel, which are relatively new, energy-efficient materials that have been investigated more extensively since the 1980s [9]. Aerogel is usually obtained from quartz sand, but it can also be synthesized from transition metal oxides, lanthanide oxides, actinide oxides, main group oxides, and mixed oxides, as well as from polymers, metals, and carbides.

When used as a building material, aerogel improves the thermal performance of the structures in both land and hydro-technical industrial constructions. Aerogel granules are porous, very finely made, lightweight, hydrophobic, synthetic amorphous silica (quartz) dioxide. Aerogel is a light-permeable and light-dispersive material. It is the lightest solid material that has been developed in recent times with a density from 120 to 150 $kg \cdot m^{-3}$. For density between 30 to 100 $kg \cdot m^{-3}$, the porosity of unit reaches values greater than 90 % [10].

Aerogel filler can be used to diffuse light. The thermal conductivity depends on the aerogel particle composition, shape, density and temperature. The thermal conductivity coefficient of typical monolithic aerogel with a density of 100 $kg \cdot m^{-3}$ is between 0.010 and 0.020 $W \cdot m^{-1} \cdot K^{-1}$, which is two to three times better than that of polyurethane foam (PUF) or polystyrene. Aerogel mats (Aspen aerogel "Spaceloft") have a thermal conductivity coefficient of 0.014 to 0.021 $W \cdot m^{-1} \cdot K^{-1}$. On the other hand, aerogel granules (Cabot's aerogel "Lumira") have a thermal conductivity coefficient of 0.009 to 0.012 $W \cdot m^{-1} \cdot K^{-1}$. The thermal conductivity coefficient is lower in aerogel granules with a smaller diameter [10]. Light transmittance ranges from 70 % (filled 10 mm thick polycarbonate sheet) to 50 % (25 mm polycarbonate sheet). Aerogel filler can be used to diffuse light (Fig. 1).

Fig. 1. **Sample with aerogel – 4S-4A-4P** (the authors' photograph)

For the experimental purposes, samples with dimensions 290 x 290 mm were made, which had materials of diverse thickness, changeable thickness of air parting layers and aerogel fillings. They were marked as: inorganic glass 4 mm-4P; glass with selective coating 4 mm-4S; organic glass 4 mm-4O; air parting layer 25 mm-25; and aerogel filling 4 mm-4A (Fig. 2).

A Netzsch HFM 436/3/1 E Lambda heat flow meter was used to obtain the experimental results. The sample was placed in a horizontal position between two heated plates with temperature difference ΔT. The specific heat flow q was measured with a calibrated heat flow transducer. The measurement was completed when thermal equilibrium was reached, and the standard deviation for 10 measurements is lower than the required value of 1 % or 0.5 %. In order to decrease the impact of the edges, measurements were made over a square 101.6 mm x 101.6 mm patch near the sample centre. The heat flow rate depended on various factors: the sample's thermal conductivity λ, the sample's thickness Δx, the temperature difference ΔT between the two surfaces of the sample, and the medium through which the heat flows.

Fig. 2. **Experimental sample 4S-25-12S-25-4 (the authors' photograph)**

After reaching of thermal equilibrium λ is determined using the Fourier equation (1), taking into account all the above factors [11]:

$$Q = \lambda A \Delta T / \Delta x , \quad (1)$$

where Q – the heat flow;
A – the area of the surface through which the heat flows.

The heat flow carrier signal V is directly proportional to the heat flow through the carrier,

$$Q = N \cdot A, \quad (2)$$

where N – a calibration factor related to the medium, in which the heat flow takes place, and the voltage is measured between the surfaces perpendicular to the heat flow through the sample [13].

The thermal conductivity coefficient is calculated using the expression:

$$\lambda = k = N V \Delta x / \Delta T, \quad (3)$$

The method of using a heat flow meter is a standardized testing method [14].

The thermal transmission coefficient U is calculated using the expression:

$$U = \lambda a / \Delta x, \quad (4)$$

Where λ – the thermal conductivity coefficient;
Δx – thickness of the material.

Experimental procedure

The goal of the experiments was to determine the dependence of the thermal conductivity coefficient of the samples on the width of the air separation layer, samples with aerogel filling and three layers of the sample under vertical heat flow conditions. The study was conducted in three stages:

1. Measurements of the thermal conductivity coefficient of the sample for different widths of the air separation layer;
2. Measurements of the thermal properties of the sample with aerogel filling;
3. Measurements of the thermal properties of the sample with organic and selective glass as the third layer.

Initially, the values of the thermal conductivity coefficient were determined for each material individually. Each measurement was carried out twice, first using the rough settings of the heat flow meter (1 % error, 10 or more measurements) and then using the precise setting (0.5 % error, 10 or more measurements) at an average temperature 23 ºC, with a temperature difference ΔT of 20 K. Five samples were prepared for insertion into the heat flow meter. Each sample was labelled before being placed in the meter.

The graph in Figure 3 summarizes the results.

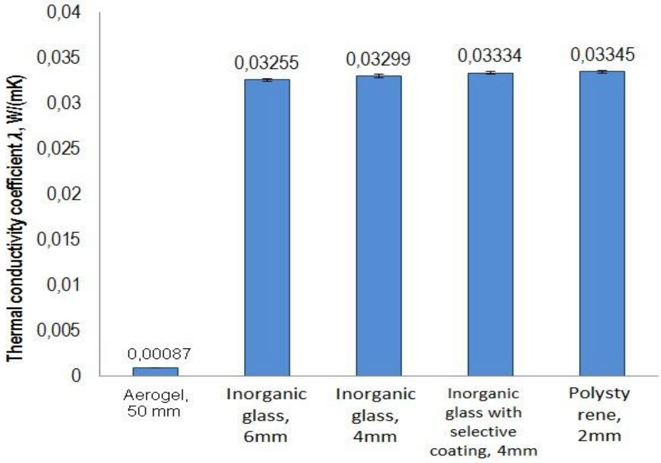

Fig. 3. **Values of the thermal conductivity coefficient λ ($W \cdot m^{-1} \cdot K^{-1}$) for each of the materials used in the experiment (average temperature $T_{average}$ = 23 ºC, temperature difference ΔT = 20 K, sample thickness Δx = 2 mm)**

The experimental results show that aerogel possesses the best heat insulation properties; aerogel is followed by inorganic glass of 6 mm and 4 mm thickness. Inorganic glass with selective coating and polystyrene show the worst results in this experiment.

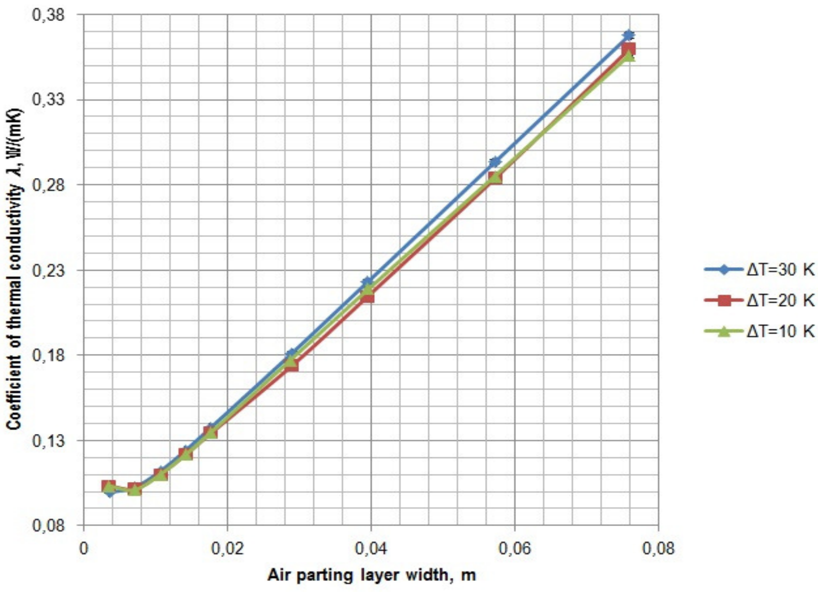

Fig. 4. **Dependence of the coefficient of thermal conductivity on the air parting layer width for a horizontally positioned sample**

Determination of the thermal conductivity coefficient by changing the width of the air separation layer

The experimental conditions – horizontally placed samples with the hot plate at the top and the cold plate at the bottom – approximate horizontal roof glass structures, for which the room temperature is lower than the outside air temperature. The experimental results are shown in Figure 4.

The graph in Figure 5 shows that the thermal properties of horizontally positioned constructions improve with increasing the width of the air separation layer. On the basis of the results, it can be assumed that air convection does not occur in the interlayer for downward vertical heat flow conditions.

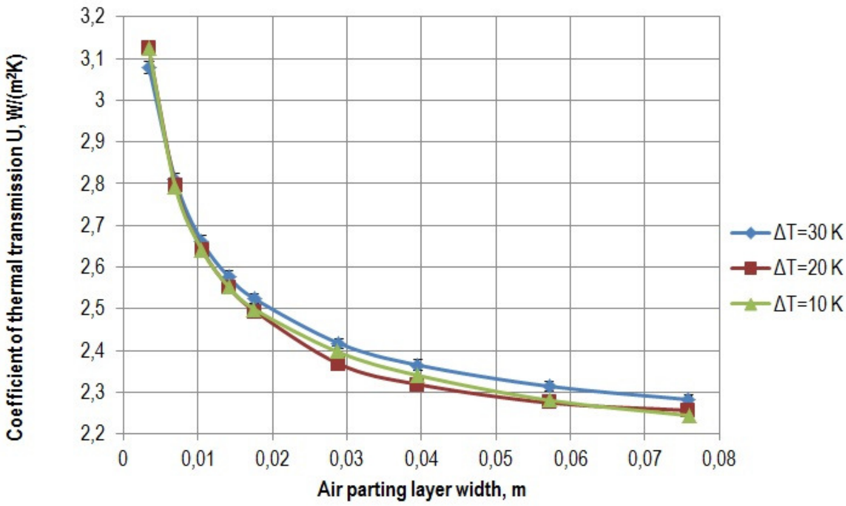

Fig. 5. **Dependence of the thermal transmition coefficient on the width of the air separation layer, the values of the coefficients of thermal transmission are calculated**

Thermal properties of samples with aerogel filling

For the samples with an air separation layer, the thermal conductivity coefficient increases with increasing the thickness of the separation layer as could be seen in the previous experiments, but the coefficient of thermal conductivity decreases in the samples with aerogel filling. This decrease can be attributed to the outstanding heat insulation properties of aerogel.

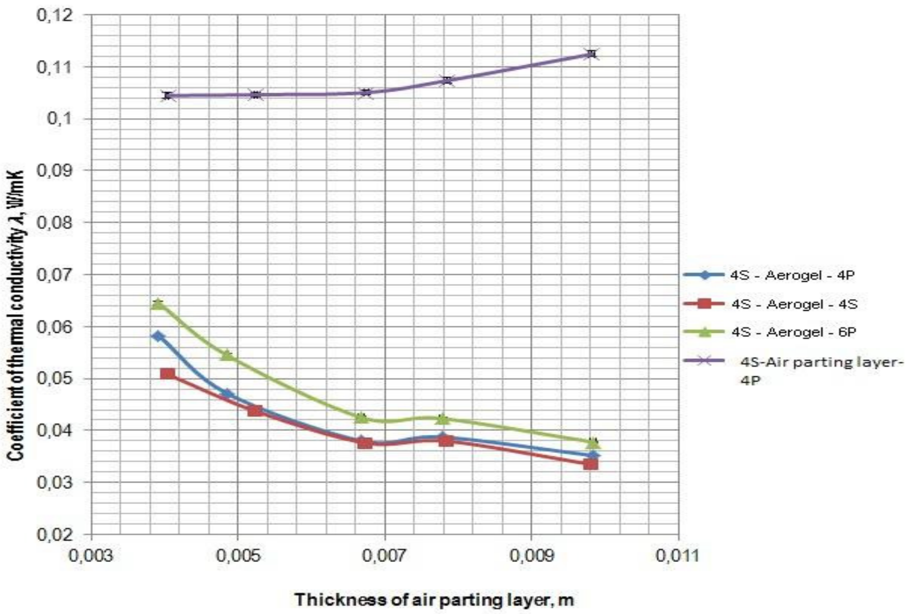

Fig. 6. **Thermal conductivity coefficient λ ($W \cdot m^{-1} \cdot K^{-1}$) values of the samples with aerogel filling and air parting layer**

The graph in Figure 7 shows the calculated values of the thermal transmission coefficient. The results show that thermal performance of glass constructions can be significantly improved by using aerogel when the structures are not very thick.

The experimental results show that glass with selective coating gives better results when compared to uncoated glass. However, when these materials are measured separately (Fig. 4), uncoated glass has a better thermal conductivity coefficient. This discrepancy may be due to the improvement of the selective overlay function in the presence of air. It should be noted that radiative heat transfer takes place in the heat flow meter.

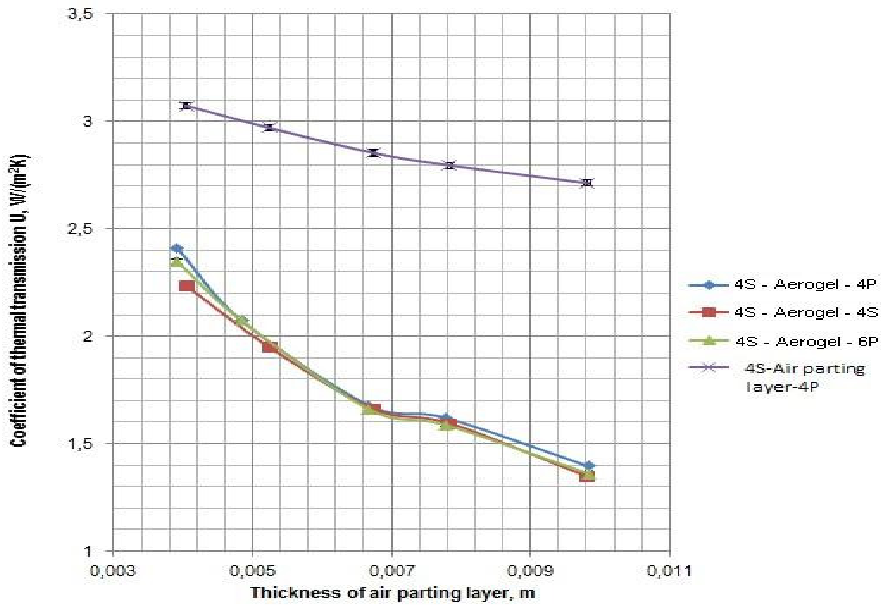

Fig. 7. **Thermal transmission coefficient *U* ($W \cdot m^{-2} \cdot K^{-1}$) values of the samples with aerogel filling and air gap (calculated)**

Thermal properties of samples of three layer packages

As it can be seen in Figure 8 and Figure 9, the samples with selective glass show better results than the samples with polystyrol, contrary to the results in the scientific literature [15] and to the values of the thermal conductivity coefficient in the norms [16].

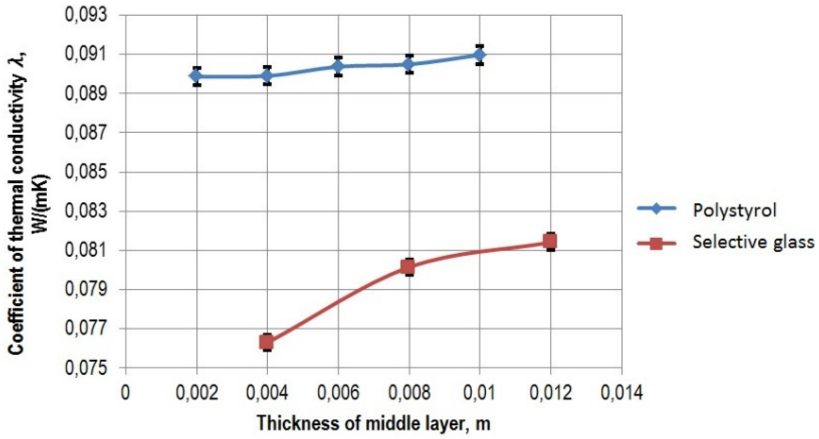

Fig. 8. **Thermal conductivity coefficient λ ($W \cdot m^{-1} \cdot K^{-1}$) values for the samples with organic glass (polystyrol) and inorganic glass with selective coating in the middle layer**

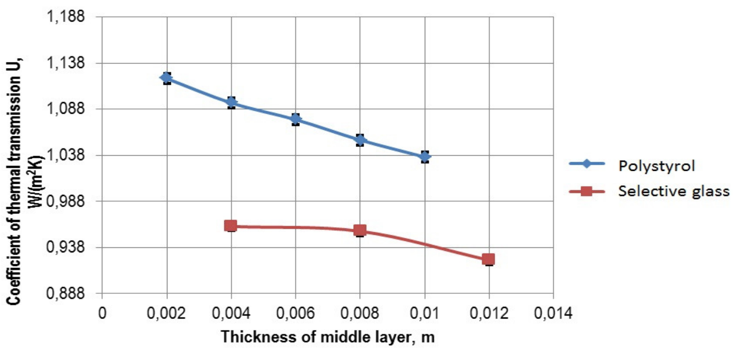

Fig. 9. **Thermal transmission coefficient for the samples of organic glass (polystyrene) and inorganic glass with selective coating in the middle layer**

Discussion

Figure 10 includes graphs that compare the values of the samples' thermal transmission coefficient U. The best thermal transmission coefficient values were observed in samples with selective glass (4S-25-Selective glass-25-4P). The thickness of the samples varied from 0.063 to 0.071 m. If the three-layer glass package has aerogel filling, then the selective glass does not give any considerable effect.

If a glass package is filled with aerogel, the selective glass does not give any considerable effect.

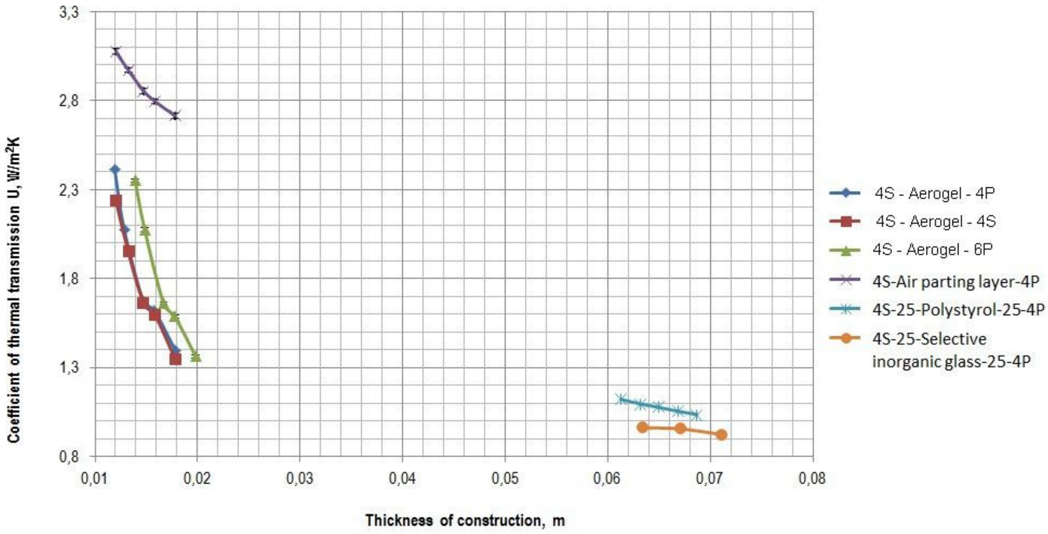

Fig. 10. **Dependence of the thermal transmission coefficient *U* ($W \cdot m^{-2} \cdot K^{-1}$) on sample thickness**

Taking into account the dynamics of the thermal transmission coefficient in the aerogel samples, it is possible to claim that the best thermal transmission coefficient values were observed in the samples with aerogel filling and low thickness.

Conclusions

1. Thermal processes in glass constructions depend on the position of the structure in relation to the direction of the heat flow. The smallest effect of convection was observed for vertically integrated glass structures with an air separation thickness of 0.01-0.02 m. However, with respect to the glass structures of roofs, convection is not taken into account in the downward heat flow conditions, but convection is more active in vertical glass structures, for which the thermal conductivity coefficient values increase by 30 to 50 %.
2. The good thermal properties of aerogel and organic glass make them suitable for glass fillings. Organic glass is characterized by good impact resistance, light transmittance, and heat insulation compared to inorganic glass. Aerogel, in turn, is distinguished by its very light weight and excellent heat insulation properties.
3. The best thermal transmission coefficient values in glass packages could be achieved by three-layer glass, thus increasing the thickness of the window. Glass with aerogel filling gives better thermal-technical indicators when the thickness is low; however, for the time being, it is expensive. Heat insulation properties improve by increasing the width of the air separation layer under downward vertical heat flow conditions; practically no heat convection is observed.
4. Although the thermal conductivity coefficient values are available in manufacturers' specifications and tables, deviations from these values are possible.

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