Vacuum glazed units – energy efficient glazing

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Abstract. The article summarizes the prerequisites for the improvement of translucent structures in terms of energy conservation. It is noted that there is a high potential of application of vacuum glazed units. On the basis of EN 673 and the application of numerical methods, a research was made to calculate the theoretical thermal resistance on the pillars and between them, and a thermal resistance of a central part of a vacuum glazed unit taking into account a heterogeneity. To compare with theoretical values, experimental laboratory examinations on a model vacuum glazed unit and a conventional single-chamber glazed unit were conducted using methods of GOST 26602.1-99. The data obtained from measuring sensors of temperature and thermal flux was processed using thermal imaging. The areas of pillars influence and the given resistance of the central part of the vacuum glazed unit were calculated. The results obtained from practical and theoretical studies showed high convergence. The accuracy of the experiment is confirmed by taking simultaneous measurements of the vacuum, and the conventional single-chamber glazed unit. It should be noted that confirmed high thermal qualities of vacuum glazed units can be compared with the required heat conductance values of Moscow for non-translucent wall constructions. A brief economic analysis is done to determine the practicability of application of vacuum glazed units.

1. Introduction.
For the past ten years, among the high-priority problems facing a construction industry there is an issue to increase the energy efficiency of buildings. The solution to this problem is a part of a global challenge for the implementation of the economic development strategy of the Russian Federation. The increase energy efficiency program involves use of complex of measures to reduce the use of energy resources spent on building maintenance.

The main part of energy loss in an operation of residential and public buildings happens through the external building envelope. The outer of enclosure of the building has non-uniform heat-resistant properties. On average, glazing occupies 18-22% of the facade area of a modern residential building. The share of heat loss through the glazing system can reach 35% making it the primary source of heat loss through the envelope of enclosure [2]. Thus, the vast majority of heat loss in glazing systems is due to the translucent part as glazed units.

Today, two-chambered glazed units with argon fillers with the use of i-stack are commonly used. Further development of a glued glazed unit structure by increasing the number of glazing layers is
irrational, as the most part of a heavy weight and low translucent properties will limit the application of these structures. One of the most promising technologies in this area is the use of vacuum glazed units. Vacuum glazed unit consists of two layers of tempered glass separated by a thin vacuum layer. Glasses are bonded to each other around their perimeter. In order to compensate the atmospheric pressure pillars as special spacers are installed between glass panes. The pillars are placed at a distance of 4-5 cm apart from each other, in rows or in a checkerboard pattern (see Figure 1).

![Figure 1](image)

**Figure 1.** General view of the vacuum glazed unit.

a – General view of the vacuum glazed unit; b – a scheme of the glazed unit with a broken-out sectional view; c – a cross-sectional view of the vacuum glazed unit.

1 – Glass, 2 – pillar, 3 – hole for air exhaustion, 4 – metallic solder, 5 – airless space.

Creating a deep vacuum between glass panes allows eliminating the influence of convection and heat conduction of gas from the heat exchange process between the internal surfaces of the glass panes (Figure 2). Usage of highly selective coatings helps to reduce heat loss from radiation.

![Figure 2](image)

**Figure 2.** A dependency graph of coefficient of heat transmission of the vacuum gap and the pressure of the internal chamber.

2. Theoretical studies

For the theoretical evaluation of thermotechnical properties of the glazed unit, calculations were done on the basis of EN 673 using numerical simulation methods (FEM). A three-dimensional numerical model was constructed in accordance with the scheme presented in figure 3. The simulated fragment of the
The studied fragment has the shape of a square with a side equal to 300 mm. Heat loss of the calculated model is examined without the influence of the border effect; therefore there is no bonding of glass panes around perimeter.

The emission coefficient of the glass pane was taken as equal to 0.04, which is the equivalent of common magnetron coating. The thermal resistance of the vacuum layer has been calculated analytically.

\[
\begin{align*}
{h}_s &= {h}_r = 4\sigma \cdot \left( \frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} \right)^{-1} \cdot T^3, \\
\sigma &= \text{Stefan-Boltzmann constant, } W/(m^2 \cdot K^4); \\
\varepsilon_{1,2} &= \text{emission coefficient of inner surfaces of glass panes (ordinary glass 0.837, low-emission } 0.04); \\
T &= \text{average absolute temperature of the inner surfaces of the glass panes in accordance with EN 673 K.}
\end{align*}
\]

\[
\begin{align*}
{h}_s &= 4\sigma \cdot \left( \frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} \right)^{-1} \cdot T^3 = 4 \cdot 5.67 \cdot 10^{-8} \cdot \left( \frac{1}{0.837} + \frac{1}{0.04} \right)^{-1} \cdot 283^3 = 0.204 \text{ W/m}^2 \cdot \text{K} \\
R_s &= \frac{1}{{h}_s} = \frac{1}{0.204} = 4.9 \text{ m}^2 \cdot \text{K/W} \\
\lambda &= \frac{\delta}{R_s} = \frac{0.0003}{4.9} = 6.12 \cdot 10^{-5} \text{ W/m} \cdot \text{K}
\end{align*}
\]

\(\delta\) – thickness of the vacuum gap, m;
\(\lambda\) – equivalent conductivity of the vacuum gap of a given thickness, W/(m·K).

Characteristics of materials are: \(\lambda_{\text{glass}} = 0.75 \text{ W/(m·K)},\ \lambda_{\text{steel}} = 14.6 \text{ W/(m·K)}\). The emission coefficient from the surface of the stack was taken as equal to 0.04 (low-emission coating).

The peaks of temperature and thermal flux correspond to the location of the pillars. Integral values of temperature and thermal flux are presented in table 1.
Calculate the thermal resistance $R_{0\,\text{min}}$ on the pillars (minimum value) and between them $R_{0\,\text{max}}$ (maximum value) using formula 1.

$$R_0 = \frac{1}{h_e} + \frac{t_1 - t_2}{q} + \frac{1}{h_i}$$  \hspace{1cm} (1)$$

$h_e$ and $h_i$ are the coefficients of heat transmission of external and internal surfaces of the glazed unit respectively, W/m$^2$K (in accordance with EN 673: 7.7 W/m$^2$K and 25 W/m$^2$K).

$t_1$ and $t_2$ – temperature on the inner and outer surfaces of glass panes, °C

$q$ – Thermal flux, W/m$^2$

$$R_{0\,\text{min}} = \frac{1}{7.7} + \frac{17.04 + 18.87}{18.34} + \frac{1}{25} = 2.13 \text{ m}^2\cdot\text{K/W}$$

$$R_{0\,\text{max}} = \frac{1}{7.7} + \frac{18.13 + 19.76}{10.29} + \frac{1}{25} = 3.85 \text{ m}^2\cdot\text{K/W}$$

Reduced thermal resistance $R_{0\,\text{mid}}$ on the analyzed site:

$$R_{0\,\text{mid}} = \frac{1}{7.7} + \frac{17.95 + 19.66}{11.31} + \frac{1}{25} = 3.49 \text{ m}^2\cdot\text{K/W}$$

**Figure 4.** a - Graph of temperature distribution on a heated surface; b - Graph of temperature distribution on a cold surface; c - Graph of thermal flux distribution.

**Table 1.** Results of numerical simulation.

|                  | $t_1$, °C | $t_2$, °C | q, W/m$^2$ |
|------------------|-----------|-----------|------------|
| **Between pillars** | 18.13     | -19.76    | 10.29      |
| **On pillars**    | 17.04     | -18.87    | 18.34      |
| **Average**       | 17.95     | -19.66    | 11.31      |

**3. Experimental studies.**

To compare theoretical data, laboratory experiments were conducted.

The experiment was conducted in the test laboratory "Translucent and facade structures" in NRU MGSU on test facility 3025/650 KS. The stand was mounted with a frame with two samples for parallel measurement: 1. vacuum glazed unit 4i-0.3VAC-4; 2. single-chamber glazed unit 4M-12 Ar 90% - 4i. Sample sizes are 800x800 mm single-chamber glazed unit and 800x600 mm vacuum glazed unit (see Figure 5).
The method of determining the thermal resistance of glazed units is analogous to GOST 26602 and it was to create a time-constant temperature difference on both sides of the test samples (inside the test chamber -20 °C, outside - indoor conditions 22 °C), to measure the surface temperature of the samples and the thermal flux through the samples under stationary test conditions. Sensors and measurement devices are ITP-MG4.03/X(II) "Flux" (SKB Stroypribor).

Due the varied designs of vacuum glazed units (having pillars) 7 pairs of sensors were installed (for temperature and thermal flux) in the Central zone (to eliminate the border effect) of the glazed units according to the scheme in table. 2. Two pairs of sensors were installed in the central area of the single-chamber glazed unit.

Figure 5. General view of the experimental setup.

Figure 6. a - measurements of the inner surface temperature in relation to time; b - measurements of the external surface temperature in relation to time; c - sensor reading of the thermal flux in relation to time.
The measurements were carried out for 3 days; Measurements were made with an interval of 1 minute. Figure 6 shows measurement results of the central sensor on the vacuum glazed unit over the entire period of testing after statistical processing. Temperature fluctuations on the internal side of the sample cause forced-convection which is generated by the cooling unit. These fluctuations do not exceed 0.3 °C in 30 minutes, so we accept the terms of testing to be stationary.

To calculate the values of thermal resistance averaged readings of each sensor were used. Averaging was done by calculating arithmetic mean values over the entire test period. The results are presented in table. 2,3.

The average value of the thermal resistance of single-chamber glazed unit lines up with the value declared by the manufacturer, which confirms the accuracy of the received data. By calculating the arithmetic mean, the values of the highest and lowest thermal resistance were obtained. $R_{\text{max}} = 3.5075 \text{ m}^2 \cdot \text{K}/\text{W}$, $R_{\text{min}} = 2.0566 \text{ m}^2 \cdot \text{K}/\text{W}$.

Due to the significant difference in thermal resistance on pillars and between them, to determine a given resistance of the central area of vacuum glazed unit boundaries of temperature zones were defined. The boundaries of the temperature zones were obtained by data processing of thermal imaging. Pictures taken with the thermal imager FLUKE Ti 50FT-10/20, are shown in figure 7.

### Table 2. Processing of results of vacuum glazed units.

| Layout of sensors in vacuum glazed units | No of the measuring point | $q$, W/m² | $t_1$, °C | $t_2$, °C | $\Delta t$, °C | $R$, m²·K/W |
|----------------------------------------|--------------------------|-----------|-----------|-----------|----------------|------------|
| Sensors located between pillars        | 1                        | 11.96     | 21.58     | -17.67    | 39.26          | 3.28       |
|                                        | 2                        | 11.06     | 21.57     | -17.99    | 39.56          | 3.58       |
|                                        | 3                        | 11.00     | 21.77     | -19.04    | 40.81          | 3.71       |
|                                        | 4                        | 11.65     | 21.72     | -18.57    | 40.29          | 3.46       |
| Sensors located on pillars             | 5                        | 18.63     | 21.26     | -17.76    | 39.02          | 2.09       |
|                                        | 6                        | 19.08     | 21.39     | -18.34    | 39.73          | 2.08       |
|                                        | 7                        | 19.51     | 21.11     | -17.88    | 38.99          | 2          |

### Table 3. Processing of results of the single-chamber glazed unit.

| No of the measuring point | $q$, W/m² | $t_1$, °C | $t_2$, °C | $\Delta t$, °C | $R$, m²·K/W |
|--------------------------|-----------|-----------|-----------|----------------|------------|
| 1                        | 47.72     | 17.15     | -11.98    | 29.13          | 0.61       |
| 2                        | 46.98     | 17.21     | -11.78    | 28.99          | 0.62       |
The average value of temperature on the selected part of the graph was obtained graphically. The graph areas in which the temperature fell below average are located in the influence zone of the pillar. Geometric boundaries of the temperature zones of a specified cross section were obtained by graphic constructions (Figure 8).

![Figure 7. Thermal imaging of the test samples](image)

![Figure 8. Boundaries of temperature zones.](image)

According to GOST 26602.1-99, the given thermal resistance of translucent structures is calculated using formula 2.

\[ R_k = \frac{\sum_{i=1}^{m} A_i}{\sum_{i=1}^{m} \left( \frac{A_i}{R_{ki}} \right)} \]

\( i \) – number of the temperature zone;
\( A_i \) – area of \( i^{th} \) temperature zone, \( m^2 \);
\( R_{ki} \) – thermal resistance of temperature zones, \( m^2 \cdot K/W \).

The total area of influence of spacers was determined by multiplying the area of influence of one spacer by the number of spacers located in the measuring area. The average value of the radius of influence is obtained in figure 8 and it is equal to 9.75 mm.

\[ A_2 = n\pi R^2, \]
\[ A_2 = 49 \cdot \pi \cdot (9.75 \cdot 10^{-3})^2 = 0.0146 \, m^2 \]

The area of the first temperature zone is determined by the formula:

\[ A_1 = A_{total} - A_2; \]
\[ A_1 = 0.4^2 - 0.0146 = 0.1454 \, m^2, \]

Substituting the value of thermal resistance, the following value for the given thermal resistance of the vacuum glazed unit was obtained:
\[ R_k = \frac{0.4^2}{0.1454/3.5075 + 0.0146/2.0566} = 3.29 \text{ m}^2 \cdot \text{K}/\text{W} \]

Calculating the given thermal resistance using formula 1.

\[ R_{\text{mid}} = \frac{1}{7.7} + 3.29 + \frac{1}{25} = 0.78 \text{ m}^2 \cdot \text{K}/\text{W} \]

### Table 4. Comparison of theoretical and experimental data.

| Thermal resistance of vacuum glazed unit 4i-0.3VAC-4, m²·K/W | Theoretical data | Experimental data | Δ, % |
|---------------------------------------------------------------|------------------|-------------------|------|
| \( R_{\text{min}} \) | 2.13             | 2.06              | 3.3  |
| \( R_{\text{max}} \) | 3.85             | 3.51              | 8.8  |
| \( R_{\text{mid}} \) | 3.49             | 3.46              | 0.9  |

Thermal resistance of single-chambered 4M-12 Ar 90% - 4i, m²·K/W

\( R_0 = 0.63 \quad 0.62 \quad 1.6 \)

### 4. The economic feasibility.

For the economic evaluation of vacuum glazed units feasibility compared to widespread use of single-chamber glazed units, the heat loss through 1 m² of glazing of both units was calculated.

The total thermal resistance of the single-chamber glazed unit 4M-12 Ar 90% - 4i is defined by formula 1.

\[ R_{\text{mid}} = \frac{1}{7.7} + 0.62 + \frac{1}{25} = 0.78 \text{ m}^2 \cdot \text{K}/\text{W} \]

### Table 5. A comparison of the costs and thermal resistance of various glazed units.

| Characteristics                       | Vacuum glazed units | Single-chambered glazed unit |
|---------------------------------------|---------------------|-----------------------------|
| Thermal resistance, m²·K/W            | 3.46                | 0.78                        |
| Cost, Rub.                            | 15960               | 1680                        |

\[ Q = 0.024 \cdot \text{HSDD} \cdot \frac{A}{R_0} \]

\( Q \) – heat loss per year kW · h/year
\( A \) – area of sample (1 m²)
\( \text{HSDD} \) – heating season degree-days of the period (for Moscow 4676.2 °C · day/year)
\( R_0 \) – thermal resistance, m²·K/W

\[ Q_1 = 0.024 \cdot 4676.2 \cdot \frac{1}{3.46} = 32.44 \text{ (kW·h/year)} \]

\[ Q_2 = 0.024 \cdot 4676.2 \cdot \frac{1}{0.78} = 143.88 \text{ (kW·h/year)} \]
Table 6. Heat energy consumption through 1 m² of glazing.

|                           | kW·h/year | MJ/year | Gcal/year |
|---------------------------|-----------|---------|-----------|
| vacuum glazed units       | 32.44     | 116.78  | 0.1       |
| single-chamber glazed unit| 143.88    | 514.8   | 0.44      |

The cost of the heat loss passing through a square meter for a specified period of time given the norm growth rate of the tariff is calculated according to the formula:

$$S_n = \frac{\alpha_1 - \alpha_1 \cdot q^m}{1-q},$$

\(\alpha_1\) – the cost for year of operation
\(q\) – the average annual norm growth rate
\(m\) – accounting period.

Calculate the cost of the first year of operation. The tariff of thermal energy for the population of Moscow in 2017 including VAT 1747.47 (Rub/Gcal).

Vacuum glazed units:

$$\alpha_{1\text{vac}} = 0.1 \cdot 1741.47 = 174.15 \text{ rub}$$

Single-chamber glazed unit:

$$\alpha_{1\text{tot}} = 0.44 \cdot 1741.47 = 766.25 \text{ rub}$$

The difference in values of compared samples is 14280 Rub. Calculate the time for self-repayment of vacuum glazed units compared with single-chamber glazed units with annual norm rates of the tariff growing by 5%.

$$S_{\text{tot} - S_{\text{vac}}} = 14280 \text{ rub}$$

$$S_{\text{tot}} = \frac{766.25 - 766.25 \cdot 1.05^m}{1 - 1.05}$$

$$S_{\text{vac}} = \frac{174.15 - 174.15 \cdot 1.05^m}{1 - 1.05}$$

$$S_n = S_{\text{tot}} - S_{\text{vac}} = \frac{(766.25 - 766.25 \cdot 1.05^m) - (174.15 - 174.15 \cdot 1.05^m)}{1 - 1.05} = 14280$$

$$m = \log_{1.05} 2.21 = 16.25$$
5. Conclusion
The experimental results show very high thermotechnical characteristics of vacuum glazed units when compared with the required resistance for non-translucent structures for Moscow conditions.

The accuracy of the experiment is confirmed by the presence of comparative sample and by carrying out all measurements simultaneously.

The current method GOST 26602 is not fully applicable for determining thermal resistance of non-uniform translucent structures (vacuum glazed unit).

Comparatively, using vacuum glazed units is economically justified taking into account the growing annual rate of heating prices by 5% and the declared operational lifetime of 25 years by the manufacturer. Unlike the multi-chamber glazed units, the use of vacuum glazed units will not reduce light transmission and will not increase the weight of the structure.

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