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Case study

Analysis of the influence of thermal insulation material on the thermal resistance of new facade structures with horizontal air channels

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ABSTRACT

The research proposes new energy-saving façade constructions with closed horizontal vents, the analysis of which was carried out in ANSYS environment by the finite element method. The result of the analysis of the thermal resistance of the developed facade structures shows that a decrease in the volume of thermal insulation material by 31.25% leads to a significant decrease in the thermal resistance of the fence for all values of the external temperature, that is, at the absolute minimum by 26.31%, at the absolute maximum temperature by 26.41%, at the average temperature of the coldest five-day security 0.92 by 26.47% and at an average temperature of the first month after the end of the heating period (April) 26.54%. A similar decrease was also observed when comparing facade structures with a heat-reflecting screen: at an absolute minimum temperature of 24.9%, at an absolute maximum temperature of 24.76%, at an average temperature of the coldest five-day security of 0.92 by 24.28% and at an average temperature of the first month after the end of the heating period (April) of 24.07%. At the same time, during the analysis, it was additionally found that with the same volume indicator of the heat-insulating material in the developed new façade constructions, the heat-reflective screen presence results in an increase in the heat resistance value by 10–19%, depending on the climatic conditions of the outdoor environment. Thus, the research results can be used in buildings' design and construction in order to reduce heat consumption and energy saving.

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1. Introduction

Energy saving has recently become a very important goal in the world community. In different Western countries, various strategies and programs are being developed, laws are being issued, regulatory documentation is being developed, and scientific activity is being carried out to save energy [1–6], this problem has not bypassed the Republic of Kazakhstan [7,8].

According to the available data, in most countries, most of the energy-related costs are in the residential sector and account for the largest part of the expenditure item. So, for example, according to [9], buildings consume about 30% of all final energy in the world, and in the European Union this figure is more than 40% of the total energy intake [10]. This is connected with the fact that about 80% of the energy is spent on heating buildings [11]. Given these circumstances, there is a need to establish comfortable temperature regimes for people living inside buildings, taking into account the savings in thermal energy. According to the research [12], heat losses in residential premises mainly occur through façade walls up to 40%, through ventilation systems up to 30%, through windows and entrance doors up to 25%, through roofs up to 20% and through basements up to 6%. Given these circumstances, research in the development of new energy-efficient façade wall structures is a very urgent task, the solution of which can indirectly reduce the cost of maintaining structures designed to store raw materials [13–16].

In scientific bases there are several researches on energy-saving façade constructions. Thus, in [17], some mathematical calculations were found and an empirical model was developed that describes the air temperature in the cavity as a function of external climatic parameters. These results can be useful for evaluating the performance of similar façades during the design phase, as well as for comparing behavior under various climatic conditions. These tests show that in winter, in humid and rainy climates, the predominant effect is insulation, and ventilation does not increase heat losses. The developed system makes it possible to effectively control the moisture content in the enclosing structure materials. However, this paper does not cover the issue of the insulating layer thickness (volume) influence on the structure efficiency. The research [18] examines the energy benefits of opaque ventilated façades compared to lining façades in multistory residential buildings located in nine Brazilian climatic zones. Computer simulation was used with software capable of automatically synchronizing simulation data and energy analysis for a full year. The research evaluated a wide sample of 16 cities from all climatic zones, the analysis covered the whole building within one year, becoming the most comprehensive research to date, carried out at a high speed provided by accepted computer simulation methods. This research shows that the behavior of a ventilated façade is an improvement in terms of passive building cooling compared to lining façades, providing energy savings of up to 43% per year in the hottest cities. However, this research refers only to hot climates and the heat-insulating material effect was not studied.

The paper [19] investigated how different materials and thermal masses affect the performance of narrow cavity ventilated façades, measuring differences in terms of heat flows and ventilation efficiency. The ventilated space was mainly studied, and the heat-insulating material influence was practically not discussed. At the same time, special attention has recently been paid to the thermal characteristics of enclosing structures with an air space and the heat-insulating material presence in the structure [20,21], where field experiments are also carried out [22,23], as well as various methods [24] and methods of classical mathematical simulation and calculation [25–27]. So, in the research [28], it was experimentally determined that the most effective air space is 6 cm. However, these researches were limited by virtue of the fact that spaces of more than 6 cm were not investigated, the influence of the heat-insulating material volume indicator presence in the structure was not studied.

In [29], the benefits of multilayer heat insulation with two air spaces are studied and the space thickness effect on the enclosure's heat resistance is discussed. The research established that the maximal heat resistance is achieved when these spaces are 3 cm thick. It is shown that a further increase in the space thickness results in a reduction in heat resistance due to convection. The problem of heat-insulating materials' environmental characteristics was discussed in the researches [30–32], the improvement of the enclosing structures' heat-insulating characteristics through the use of wastes was studied in [33]. The recommendation [34] highlights the problem of using materials that have a wide range of thermal energy accumulation, including solar radiation. The research of reducing heat losses through an enclosure due to the air space's parameters and heat insulation optimal choice was carried out in a hot climate [35]. It is shown that heat losses are decreased by 24% and 26% when applying heat insulation with a thickness of 3 and 5 cm and a 2-cm air space compared to an enclosure without an air space. The research [36] developed a framework for determining the optimal material to be used to achieve the highest level of energy efficiency in building retrofits, taking into account environmental and economic elements and comparing different scenarios. The research was applied in an industrial plant in Italy. The results showed that among ten materials of different origin, namely of plant, animal, mineral and fossil origin, the optimal thickness ranged from 0.023 m of linear fiber to 0.082 m of stone wool. This research revealed a methodology for comparing traditional and ecologically clean materials and measuring the benefits of properly insulating a building. The issue of moisture resistance in the house walls was investigated in [37], where field experiments were carried out. The results showed that using water-repellent materials as insulation reduces the accumulation of moisture by up to 10%. A study was also conducted [38] on the development of an air-cooled temperature control module by connecting a unique radiator of different geometries, which can positively solve energy saving problems.

The review of literature sources showed that research in the field of multilayer enclosing structures with an air space, including the heat-insulating material volume effect, is insufficient. The solution of which will make it possible to fully assess the issue of energy saving in the design and construction of buildings, which is a very urgent task. Taking into account these tasks, at this stage of the study, it is proposed to analyze the temperature fields of the proposed facade structure taking into account the volume of the thermal insulation layer and determine the thermal resistance of the structure with and without the influence of a heat-reflecting screen.

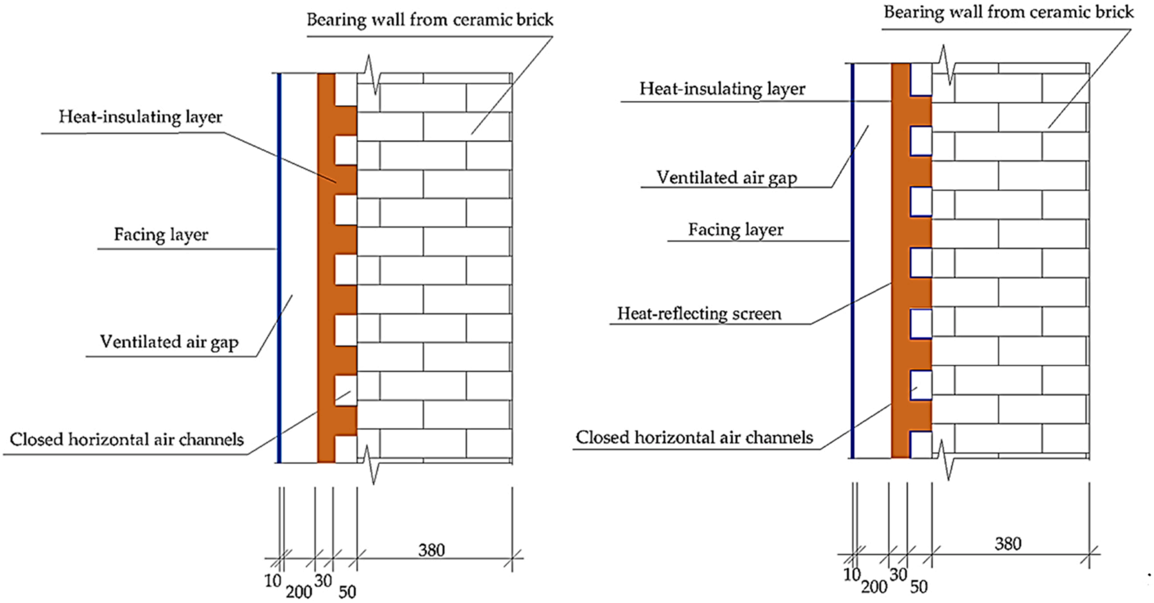

Fig. 1. Multilayer wall enclosing structure with a uniform bearing layer and a slab heat-insulating layer with horizontal closed air vents, in case of a reduction in the heat insulation volume,.

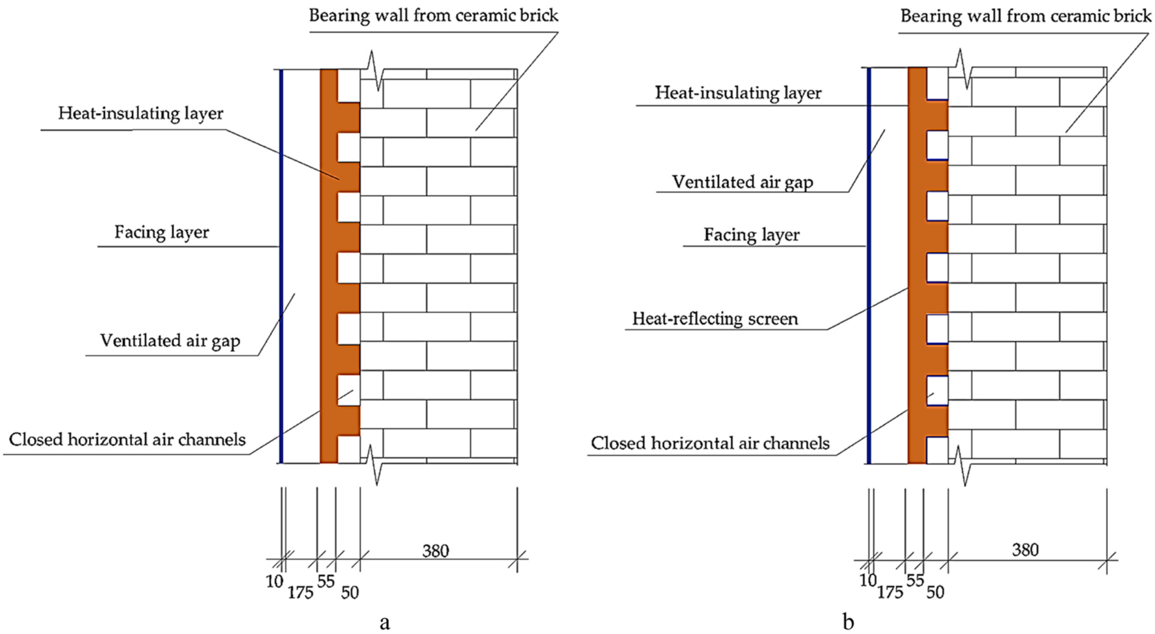

Fig. 2. Multilayer wall enclosing structure with a uniform bearing layer and a slab heat-insulating layer with horizontal closed air vents, without reducing the heat insulation volume,.

2. Materials and methods

At the first stage, the cladding's multilayer façade constructions were developed (Figs. 1, 2), the properties of the layer materials were determined (Table 1) and the climatic conditions were accepted in concordance with the area under consideration (Table 2).

where: a. without heat-reflective screen; b. with heat-reflective screen.

where: a. without heat-reflective screen; b. with heat-reflective screen.

For all patterns of the enclosure, a stationary temperature field was calculated in ANSYS environment under the following climatic conditions:

Table 1
Characteristics of the enclosing structure layers from Figs. 1, 2 [39–41].

Layer number	Description	Thickness, mm	Width, mm	Thermal conductivity coefficient, W/(m·K)	Heat absorption (with a period of 24 h), S.W/(m•C)	Vapor permeability, μ, mg/ (m•h•Pa)	Emissivity factor	
							without heat-reflective coating	with heat-reflective coating*
1	Cement-sand plaster	10	–	0.76	9.6	0.09	–	–
2	Ceramic brick laying	380	–	0.58	7.91	0.14	–	–
3	Cement-sand plaster	10	–	0.76	9.6	0.09	–	–
4	Insulant – compacted polystyrene foam with a density of *25 kg/m³*	80/ 105	–	0.03	0.3	0.005	–	–
5	Alternating horizontal stripes of compacted polystyrene foam / closed vents with heat-reflective screen and without it	50	100	–	–	–	0.9	0.039
6	Ventilated air space	200/ 175	–	–	–	–	–	–
7	Facing layer from ceramic granite	10	–	3.49	25.04	0.008	–	–

Table 2
Climatic conditions of the area under consideration, Shymkent, Republic of Kazakhstan [42].

No	Environment name	Temperature name	Temperature, °C	Mean internal temperature, °C
1	Atmospheric temperature	Absolute minimal	-30.3	20
2	Atmospheric temperature	Absolute maximal	44.2	28
3	Atmospheric temperature	The mean temperature of the coldest five days with 0.92 occurrence	-14.3	20°
4	Atmospheric temperature	The mean temperature in April	13.5	20

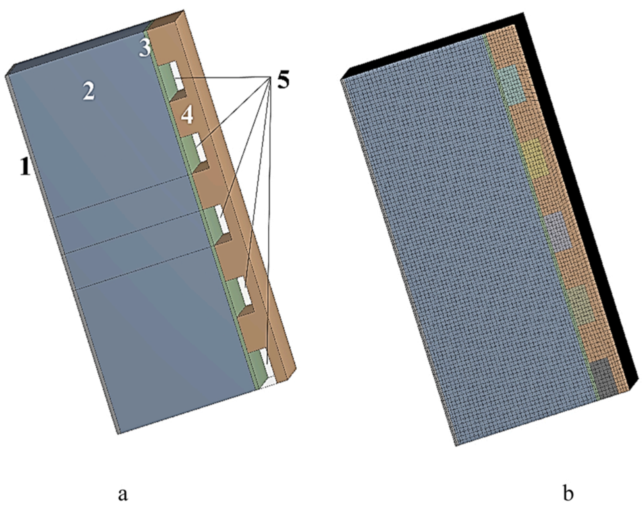

Fig. 3. Section of the enclosure from Figs. 1 and 2: a. sketch: 1, 3 – cement-sand plaster; 2 – bearing layer from ceramic brick; 4 – insulant – compacted polystyrene foam; 5 – horizontal closed air vents with heat-reflective screen and without it; b. finite element model.

At the second stage, a methodology for analysis of enclosing structures' temperature fields was developed in order to analyze the developed façade constructions' heat resistance, to calculate the enclosure's temperature field, a finite element model of the enclosure is used (Fig. 3), in which the ventilated air space effect is changed with a boundary condition of Convection type with the space temperature, and the Film coefficient parameter, which is responsible for the intensity of convective heat transfer, equal to 1000 [43], which corresponds to moving air. On the internal surface of the enclosure, a boundary condition of Convection type is set with the minimal allowable mean temperature when calculating for the cold period of the year and the maximal allowable temperature for the warm season. The Film coefficient parameter, which is responsible for the convective heat transfer intensity, on the internal surface of the enclosure is taken equal to 10 [43], which corresponds to the low-moving air in the room.

To calculate temperature fields in enclosing structures, the method of finite element modeling in the ANSYS environment is used. A

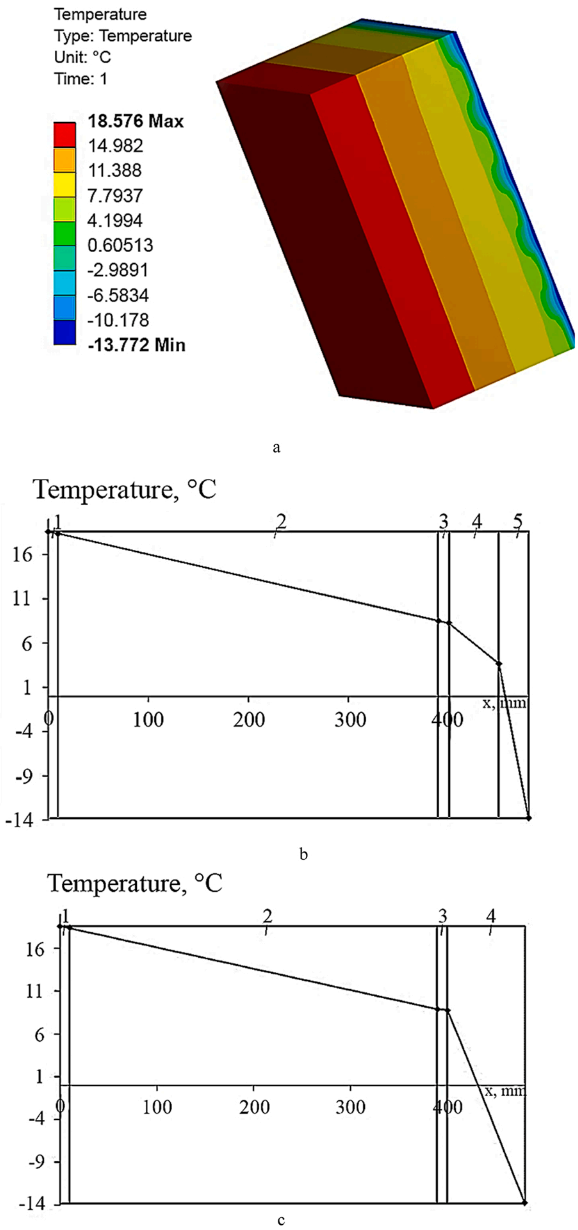

Fig. 4. Temperature field in the enclosure at the mean temperature of the coldest five days with 0.92 occurrence: – three-dimensional model; b. – diagram of temperature change along the enclosure thickness in the solid insulant section: 1, 3 – cement-sand plaster; 2 – bearing layer from ceramic brick; 4 – insulant – compacted polystyrene foam; c. – diagram of temperature change along the enclosure thickness in the air vent section: 1, 3 – cement-sand plaster; 2 – bearing layer from ceramic brick; 4 – closed air vent; 5 – insulant – compacted polystyrene foam.

finite element model of a fence section measuring 1 × 1 m is constructed, in which the temperature field is calculated under specified external conditions. At the same time, finite element modeling of the ventilated facade is not performed, and the influence of the ventilated air layer is replaced by boundary conditions on the outside of the fence without taking into account the ventilated facade. The task is divided into four stages, which are performed iteratively:

1. Calculation of the thermal properties of the fence without taking into account the ventilated facade and with the properties of closed interlayers and channels according to [39–42].
2. Calculation of the air parameters in the ventilated facade.
3. Analysis of the temperature field in the fence, replacing the ventilated facade with boundary conditions.
4. Calculation of the properties of a closed layer or channels.
5. Transition to item 1 with refined properties of the interlayer or channels.

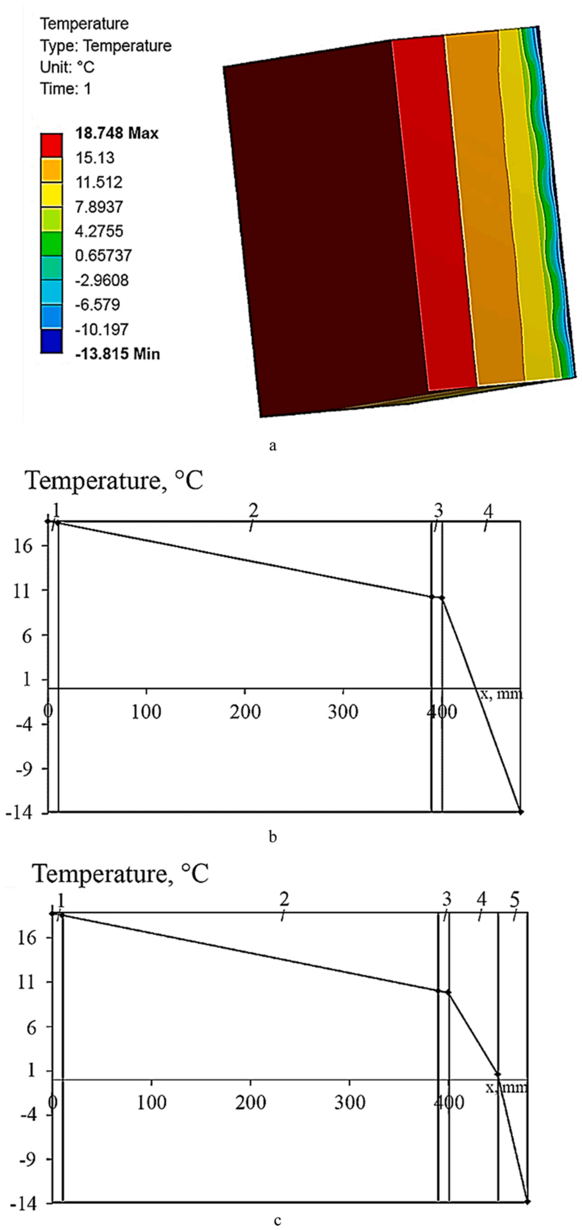

Fig. 5. Temperature field in the enclosure at the mean temperature of the coldest five days with 0.92 occurrence: – three-dimensional model; b. – diagram of temperature change along the enclosure thickness in the solid insulant section: 1, 3 – cement-sand plaster; 2 – bearing layer from ceramic brick; 4 – insulant – compacted polystyrene foam; c. – diagram of temperature change along the enclosure thickness in the air vent section: 1, 3 – cement-sand plaster; 2 – bearing layer from ceramic brick; 4 – closed air vent; 5 – insulant – compacted polystyrene foam.

The calculation is made for various options for the external temperature value: the absolute maximal, the absolute minimal, the mean temperature of the coldest five days with 0.92 occurrence, and the mean temperature in April (the first month after the heating period end).

The enclosing structure's total heat resistance is calculated by the formula:

$$R = R_{в} + R_{н} \tag{1}$$

where $R_{н}$ – heat resistance of the wall from the air space to the outdoor air, $м^2°C/Вт$.;.

$R_{в}$ – heat resistance of the wall to the ventilated air space, $м^2°C/Вт$.

Fig. 3 shows a sketch of the enclosure's square section with an area of 1 m^2 excluding the ventilated façade and its finite element model.

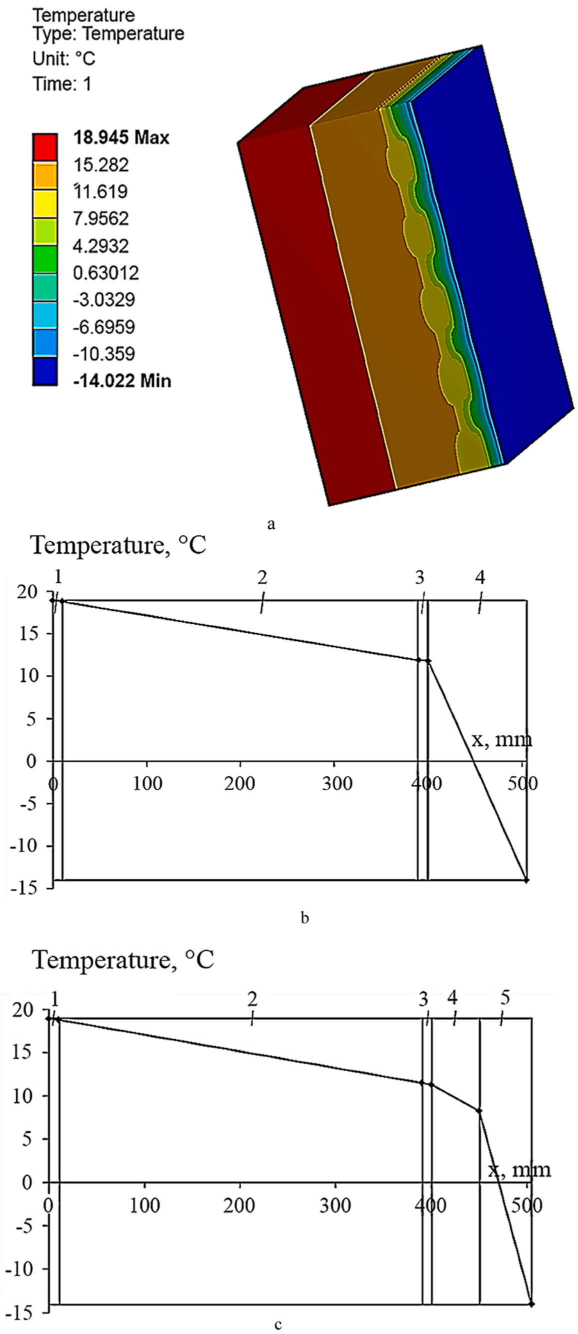

Fig. 6. Temperature field in the enclosure at the mean temperature of the coldest five days with 0.92 occurrence:– three-dimensional model; along the enclosure thickness in the solid insulant section: 1, 3 – cement-sand plaster; 2 – bearing layer from ceramic brick; 4 – insulant – compacted polystyrene foam;c. – diagram of temperature change along the enclosure thickness in the air vent section: 1, 3 – cement-sand plaster; 2 – bearing layer from ceramic brick; 4 – closed air vent; 5 – insulant – compacted polystyrene foam.

The content of the nodes for the façade construction model shown in Fig. 1, amounted to 1,785,679, and for the façade construction model shown in Fig. 2 amounted to 1,838,268.

The mean temperature value in the ventilated air space was determined for each pattern. This value was applied when defining the temperature boundary condition on the enclosure's external side excluding the ventilated space. Subsequently, an iterative algorithm was applied to search for the heat resistance of a closed space [44].

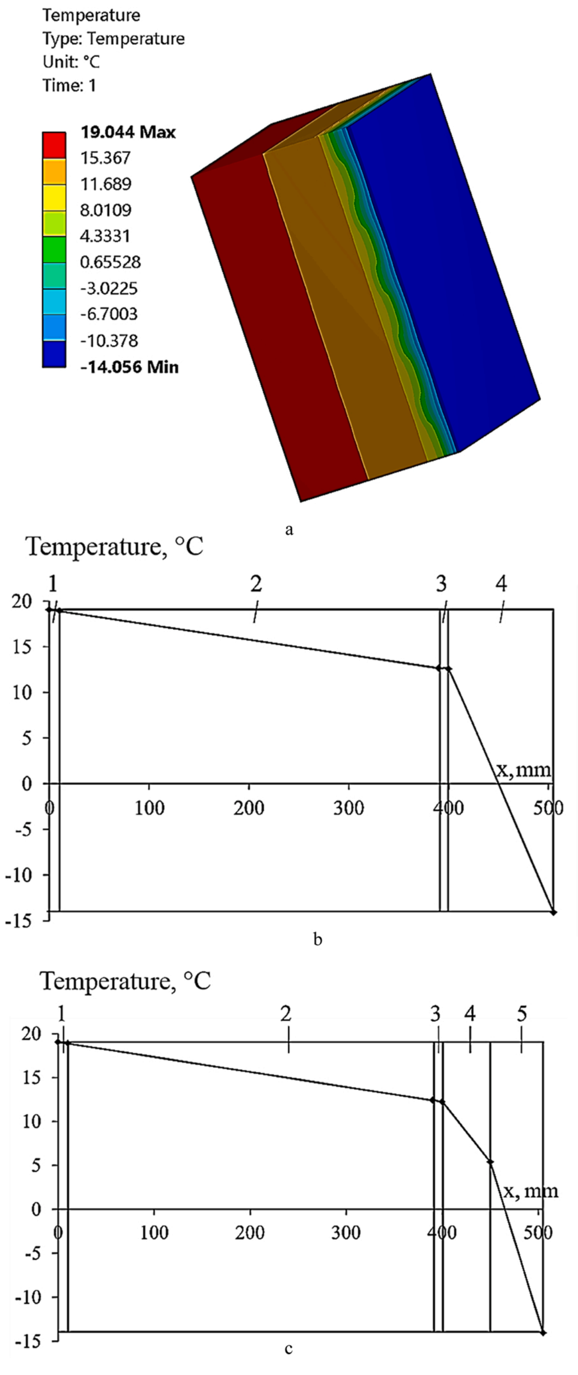

Fig. 7. Temperature field in the enclosure at the mean temperature of the coldest five days with 0.92 occurrence: – three-dimensional model; b. – diagram of temperature change along the enclosure thickness in the solid insulant section: 1, 3 – cement-sand plaster; 2 – bearing layer from ceramic brick; 4 – insulant – compacted polystyrene foam; c. – diagram of temperature change along the enclosure thickness in the air vent section: 1, 3 – cement-sand plaster; 2 – bearing layer from ceramic brick; 4 – closed air vent; 5 – insulant – compacted polystyrene foam.

3. Results and discussion

Figs. 4–7 below show an analysis of the developed façade constructions' heat resistance according to the mean temperature of the coldest five days with 0.92 occurrence, and the remaining values of the external temperature, such as the absolute maximal, the absolute minimal and the first month after the heating period end (April), were also calculated and presented in Tables 3–6.

Table 3 shows the results of calculating the enclosure's heat resistance (Fig. 1a).

Table 3
The enclosure's heat resistance according to Fig. 1a.

No	Parameter	Temperature value	Value, $m^2·(°C/ W)$
1	The internal wall's heat resistance	Minimal temperature	2.207
2	The internal wall's heat resistance	Maximal temperature	2.191
3	The internal wall's heat resistance	Five days	2.204
4	The internal wall's heat resistance	April	2.209
5	The enclosure's heat resistance	Minimal temperature	2.360
6	The enclosure's heat resistance	Maximal temperature	2.304
7	The enclosure's heat resistance	Five days	2.347
8	The enclosure's heat resistance	April	2.338
9	The air vent's heat resistance	Minimal temperature	0.181
10	The air vent's heat resistance	Maximal temperature	0.170
11	The air vent's heat resistance	Five days	0.179
12	The air vent's heat resistance	April	0.183

Table 4
The enclosure's heat resistance according to Fig. 1b.

No	Parameter	Temperature value	Value, $m^2·(°C/ W)$
1	The internal wall's heat resistance	Minimal temperature	2.498
2	The internal wall's heat resistance	Maximal temperature	2.603
3	The internal wall's heat resistance	Five days	2.542
4	The internal wall's heat resistance	April	2.895
5	The enclosure's heat resistance	Minimal temperature	2.651
6	The enclosure's heat resistance	Maximal temperature	2.716
7	The enclosure's heat resistance	Five days	2.685
8	The enclosure's heat resistance	April	2.880
9	The air vent's heat resistance	Minimal temperature	0.442
10	The air vent's heat resistance	Maximal temperature	0.555
11	The air vent's heat resistance	Five days	0.488
12	The air vent's heat resistance	April	0.731

Table 5
The enclosure's heat resistance according to Fig. 2a.

No	Parameter	Temperature value	Value, $m^2·(°C/ W)$
1	The internal wall's heat resistance	Minimal temperature	3.048
2	The internal wall's heat resistance	Maximal temperature	3.018
3	The internal wall's heat resistance	Five days	3.047
4	The internal wall's heat resistance	April	3.054
5	The enclosure's heat resistance	Minimal temperature	3.203
6	The enclosure's heat resistance	Maximal temperature	3.131
7	The enclosure's heat resistance	Five days	3.192
8	The enclosure's heat resistance	April	3.183
9	The air vent's heat resistance	Minimal temperature	0.180
10	The air vent's heat resistance	Maximal temperature	0.157
11	The air vent's heat resistance	Five days	0.179
12	The air vent's heat resistance	April	0.185

Table 6
The enclosure's heat resistance according to Fig. 2b.

№	Parameter	Temperature value	Value, $m^2·(°C/ W)$
1	The internal wall's heat resistance	Minimal temperature	3.375
2	The internal wall's heat resistance	Maximal temperature	3.496
3	The internal wall's heat resistance	Five days	3.401
4	The internal wall's heat resistance	April	3.663
5	The enclosure's heat resistance	Minimal temperature	3.530
6	The enclosure's heat resistance	Maximal temperature	3.610
7	The enclosure's heat resistance	Five days	3.546
8	The enclosure's heat resistance	April	3.793
9	The air vent's heat resistance	Minimal temperature	0.475
10	The air vent's heat resistance	Maximal temperature	0.616
11	The air vent's heat resistance	Five days	0.525
12	The air vent's heat resistance	April	0.769

Table 4 shows the results of calculating the enclosure's heat resistance (Fig. 1b).
Table 5 shows the results of calculating the enclosure's heat resistance (Fig. 2a).
Table 6 shows the results of calculating the enclosure's heat resistance (Fig. 2b).

The result of the analysis of the developed façade constructions' heat resistance shows that a reduction in the heat-insulating material volume by 31.25% when comparing Figs. 1a and 2a results in a significant reduction in the enclosure's heat resistance for all external temperature values, that is, at the absolute minimal temperature by 26.31%, at the absolute maximal temperature by 26.41%, at the mean temperature of the coldest five days with 0.92 occurrence by 26.47% and at the mean temperature in April (the first month after the heating period end) by 26.54%. At the same time, with a reduction in the heat-insulating material volume, also by 31.25%, the façade constructions with the heat-reflective screen were compared (Figs. 2a and 2b), where a significant reduction in the enclosure's heat resistance was also observed, namely: at the absolute minimal temperature by 24.9%, at the absolute maximal temperature by 24.76%, at the mean temperature of the coldest five days with 0.92 occurrence by 24.28% and at the mean temperature in April (the first month after the heating period end) by 24.07%.

This research, conducted by the authors, is a continuation of a previously initiated research [51], where, as a continuation, an analysis was made of the heat-insulating material volume effect on the structure's heat resistance indicator. As an example, two façade constructions with a different indicator of the heat-insulating material volume were discussed, taking into account the heat-reflective screen and without it. The results obtained indicate that reducing the heat-insulating material volume is not an effective solution in terms of the heat resistance indicator. However, a further increase in the façade construction layer thickness is also not advisable [45–53]. Considering these circumstances, the authors, not exceeding the heat-insulating material volume indicator of the traditional structure studied in the paper [54], as a novelty to increase the heat resistance indicator in the developed façade construction, introduced the heat-reflective screen into horizontal closed vents, as a whole, due to which the efficiency increased by 10–19% depending on external climatic conditions.

At the same time, the limitation of this research lies in the fact that the analysis was carried out with one type of the heat-insulating material, which also did not take into account the values of the humidity, air regime of claddings, as well as air infiltration through claddings. In the future, with a comprehensive analysis, the research results will be taken into account when choosing the most effective façade construction with air vents, which will enable engineers to fully assess the issue of energy saving through façade constructions during the design and construction of buildings.

4. Conclusions

The results of the research on the analysis of the heat-insulating material volume effect on the developed structures' heat resistance showed that a reduction in the heat-insulating material volume by 31.25% results in a reduction in the heat resistance value at the absolute minimal temperature by 26.31%, at the absolute maximal temperature by 26.41%, at the mean temperature of the coldest five days with 0.92 occurrence by 26.47% and at the mean temperature in April (the first month after the heating period end) by 26.54%. Similarly, a reduction in this indicator was also observed in case of the heat-reflective screen presence: at the absolute minimal temperature by 24.9%, at the absolute maximal temperature by 24.76%, at the mean temperature of the coldest five days with 0.92 occurrence by 24.28% and at the mean temperature in April (the first month after the heating period end) by 24.07%.

At the same time, the analysis of the results showed that in the heat-reflective screen presence in the developed façade constructions with closed horizontal vents, it results in an increase in the heat resistance indicator, depending on external climatic conditions, by 10–19%.

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Declaration of Competing Interest

The authors declare no conflict of interest.

Data Availability

Data will be made available on request.

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