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REVEALING PATTERNS OF THERMOPHYSICAL PARAMETERS IN THE DESIGNED ENERGY-SAVING STRUCTURES FOR EXTERNAL FENCING WITH AIR CHANNELS

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This study reports the design of new models of energy-saving enclosing structures with air channels. To calculate the thermophysical parameters of external fences, the Maple computer algebra system was used; the value of thermal resistance of structures was determined on the basis of a finite-element method in ANSYS. The result of the structure analysis showed that the value of thermal inertia of the traditional design and the average value of the thermal inertia of the developed structures were equal. However, the vibration amplitude of the designed enclosing structures was up to 20.72 % more efficient than the traditional one. At the same time, it was revealed that the air gaps did not affect the thermal inertia of the strucure, and its parameters depended only on the total thickness of the material. The analysis showed that the vapor permeability of the inner wall of the designed structures was equal to the traditional one. However, the value of resistance to vapor permeation of the fence of the developed structures was 3.21 % more effective. At the same time, the use of a closed air layer with a heat-reflecting screen makes it possible to shift the possible condensation zone towards the outer surface of the fence. An analysis of the check for the non-condensation of condensate in the ventilated air gap showed that condensate did not fall out in the ventilated air gap in all the considered schemes, and the results of the analysis by the air permeability value showed that all fencing schemes met the requirements for air permeability. Solving the problems of energy saving in construction through the development of new energy-efficient designs of enclosing structures help reduce the cost of thermal energy of buildings, which is an urgent task all over the world today

Keywords: heat resistance of an external fence, humidity regime of an external fence, air regime of an external fence, closed air channels, heat-reflecting screen

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1. Introduction

All over the world, with increasing prosperity in developing countries and population growth, there will be an increase in energy consumption. This could lead to the fact that electricity consumption would increase up to 50 % [1]. So, from 1990 to 2008, the average per capita energy consumption increased by 10 %, while the world population increased by 27 %. Regional energy consumption also increased from 1990 to 2008: in the Middle East up to 170 %, in China up to 146 %, in India up to 91 %. The same figure in Africa and Latin America was up to 70 %. In the United States and the European Union, consumption increased to 20 % and 7 %, respectively, and globally to 39 % [2–4]. Given these circumstances, energy saving in construction is becoming one of the topical issues where the development of

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new strategies, energy-saving structures and technologies in this area has become the main task of scientific communities and engineers [5–7]. At the same time, the solution of the problem of energy conservation will indirectly lead to energy savings, the cost of reconstruction, the construction of facilities for the storage and transportation of raw materials. These include industrial pipelines [8], tanks [9–13], and other shell structures [14–16].

Therefore, research on the development of new external enclosing structures is the most important task to improve the energy efficiency of buildings and reduce energy costs for the population as a whole.

2. Literature review and problem statement

The literary sources include a number of works tthat consider enclosing structures with air gaps, which are mostly traditional [17], and do not tackle the issue of closed gaps in the presence of heat-reflecting screens [18]. Experimental studies were also carried out to determine the optimal thickness of the air gap between the walls and thermophysical parameters without taking into account the thickness of the interlayers [19, 20] and numerical studies using various methods [21], as well as the effect of the heat-insulating layer on the thermal resistance of the fence with air channels [22] and designed new structures with interlayers [23]. However, in the cited works [21–23], there are certain limitations in terms of the geometry of the ventilated duct, consideration of not all thermophysical parameters, or considered not in all climatic environmental conditions. Given these circumstances, the studies also reported a number of reviews to improve the properties of enclosing structures. The development of a structure taking into account temperature fluctuations [24], different configurations of the fence [25, 26] and taking into account renewable energy [27], but at the same time, the issue of the presence of closed layers was not considered in all structures.

Wide-spread use of opaque ventilated facades as an enclosing structure solution in various types of buildings, climatic conditions, and structural configurations, where the ventilated facades affect buildings, is an ongoing problem. Given these circumstances, the paper considers the thermal and energy characteristics of opaque ventilated facades. The influence of both external environmental conditions and design solutions (material of the outer layer, joints, width of the air cavity...) on the energy and thermal characteristics of the structure are also taken into account [28]. At the same time, the issue of closed interlayers with a heat-reflecting screen was not considered, and the use of materials [29] that depend on the number of carbon atoms for accumulating various thermal energy, including solar energy, was considered in [30, 31]; the issue of using solar panels was considered in [32, 33]. Study [34] offers a comprehensive comparison of the thermal performance of an opaque ventilated facade and a conventional non-ventilated facade, taking into account two control days for winter and summer periods [35]. The analysis is carried out considering different facade orientations, and two states of windiness were taken into account, which are a calm wind state and a state with a wind speed above zero (i.e., 5.0 m/s at a height of 10 m). The results of the cited study show that energy savings were in the range of 20 to 55 %. At the same time, the highest figure on a summer day is for the facade facing East/West, while the possibility of using the influence of heat-reflecting screens was not considered.

In study [36], the thermal performance of this facade was evaluated using long-term experimental tests. A real scale prototype of the facade was constructed and installed in a full-scale test chamber in Toronto, Canada. The results of various tests have shown that the facade can pre-supply fresh air, acting as a decentralized ventilation module, owing to its high heat recovery efficiency of 81 %. However, it has also been shown that solar radiation has a significant effect, which requires constant adjustment of the fan schedule on the facade. In [37], comparative experiments were carried out on two full-scale test facilities to evaluate thermal and energy performance in the cold zone of China. It was emphasized that surface solar radiation control functions had the greatest effect on performance in summer while cavity ventilation limiting functions dominated in winter. Owing to the integration of optimal solutions for each design feature, optimal facade configurations for summer and winter were proposed. The proposed configurations provide a reduction in energy consumption by 11.4 % and 6.5 % compared to a conventional monolithic facade, respectively, while closed channels were not taken into account in the cited work. Study [38] reports a new statistical approach to the selection of daily reference scenarios, aimed at comparing the thermal field and ventilation with two degrees of openness of the gratings in the air gap. The analysis showed that the open channel is always characterized by higher airflow velocities: 75 % of the controlled values are less than 0.4 m/s, and peak values are about 2.0 m/s compared to the semi-closed configuration. In seasonal analysis, the surface temperature of the insulation averages 4.5 °C lower than in the semi-enclosed configuration while the third quartile is 36.5 °C and 41.1 °C, respectively. Taking into account the temperature difference across the entire back wall, with an open configuration, about 25 % of the values indicate outgoing heat flow. During the sunniest hours, the average value is 3.3 °C in the case of an open channel and 7.4 °C in a semi-closed channel. However, the proposed method also did not take into account additional closed channels with a heat-reflecting screen.

Despite the fact that there are many studies [17–38] on the development of an energy-saving structure of an external fence, discussed in this chapter, the question of studying this direction remains open. This is due to the fact that in some cases energy saving is achieved through the use of modern materials, thickening of the heat-insulating layer, or the thermophysical processes occurring in the air gap are not fully understood. This circumstance leads to the idea of studying thermophysical processes with the development of a new energy-saving structure of the outer enclosure with the presence of additional closed channels with heat-reflecting screens.

3. The aim and objectives of the study

The purpose of this study is to identify the features of the thermophysical parameters for the newly designed energy-saving structures of the external fence with air channels. This will make it possible to fully assess the issue of energy saving through enclosing structures when designing and constructing buildings.

To achieve the goal, the following tasks were set:

– to analyze the heat resistance of the newly designed structures of the external fence;

– to analyze the moisture regime of the newly designed structures of external fence with air channels;

– to analyze the air regime of the newly designed structures of external fence with air channels.

4. The study materials and methods

The calculation of the thermophysical parameters of the developed structures of the outer fence (Fig. 1) with air channels was carried out on the basis of [39–41]. The study is a continuation of works [20, 22–24] where the boundary and initial conditions, the geometric dimensions of the structure layers, as well as the thermophysical characteristics of the materials of the structure layer are similar [20, 22, 23].

The calculations were carried out in the Maple computer algebra system; the value of the thermal resistance of the structures was taken according to [20, 22, 23], which was previously found by a finite-element method in the ANSYS software [42].

The methodology for calculating the thermophysical parameters of traditional and designed energy-saving structures of enclosing structures was carried out in accordance with standards [39–41]; according to the tasks set, an analysis was carried out according to:

1. Heat resistance of the outer fence [39].
2. Moisture regime of the fence [39].
2. 1. Resistance to vapor permeability of the layers of the enclosing structure.
2. 2. Condensation zone in the enclosure.
2. 3. Prevention of condensation in the ventilated air gap.
2. 4. Determining the amount of condensate in the enclosure.
2. 5. Determining the drying time of the fence.
3. Air regime of enclosing structures [39].

5. Results of the analysis of thermophysical parameters of the designed energy-saving structures of the external fence with air channels

5. 1. Analysis of the thermal stability of enclosing structures

The results of calculating the heat resistance of fences according to schemes 1–5 are summarized in Table 1 [39].

Table 1

Results of calculation of heat resistance of enclosing structures

Layer indicator	Fencing scheme number				
	1	2	3	4	5
D_1	6.235	6.485	6.485	6.485	6.485
D_2	–	5.985	5.985	5.985	5.985
A_1^{des}	0.021	0.0163	0.0163	0.0163	0.0163
A_2^{des}	–	0.0170	0.0223	0.0281	0.0222

Here, D_1, D_2 denote thermal inertia in the cross-section of a solid insulation and an air gap or channel, respectively, $J{\cdot}m^{-2}K^{-1}s^{-1/2}$; A_1^{des}, A_2^{des} – the amplitude of temperature fluctuations in the cross-section of a solid insulation and an air gap or channel, respectively, °C.

Air gaps do not affect the thermal inertia of the fence and its parameters depend only on the total thickness of the material. In this case, the sequence of materials does not play a role, and the thermal inertia of the fence does not depend on the location and heat-reflecting properties of the air layers. The thermal inertia of the fences under consideration is extremely high (more than 5.7).

5. 2. Analysis of the humidity regime of enclosing structures

5. 2. 1. Determination of resistance to vapor permeability of the layers of enclosing structures

Table 2 gives the values of resistance to vapor permeability of the fence for different schemes, where R_1 – resistance to vapor permeability of the inner wall of the fence in the cross-section of a solid insulation, $m^2{\cdot}h{\cdot}Pa/mg$; R_2 – resistance to vapor permeability of the inner wall of the fence in the cross-section of the air channel, $m^2{\cdot}h{\cdot}Pa/mg$; $\overline{R}_1$ – resistance to vapor permeability of the fence in the cross-section of a solid insulation, $m^2{\cdot}h{\cdot}Pa/mg$; $\overline{R}_2$ – resistance to vapor permeability of the fence in the cross-section of the air channel, $m^2{\cdot}h{\cdot}Pa/mg$.

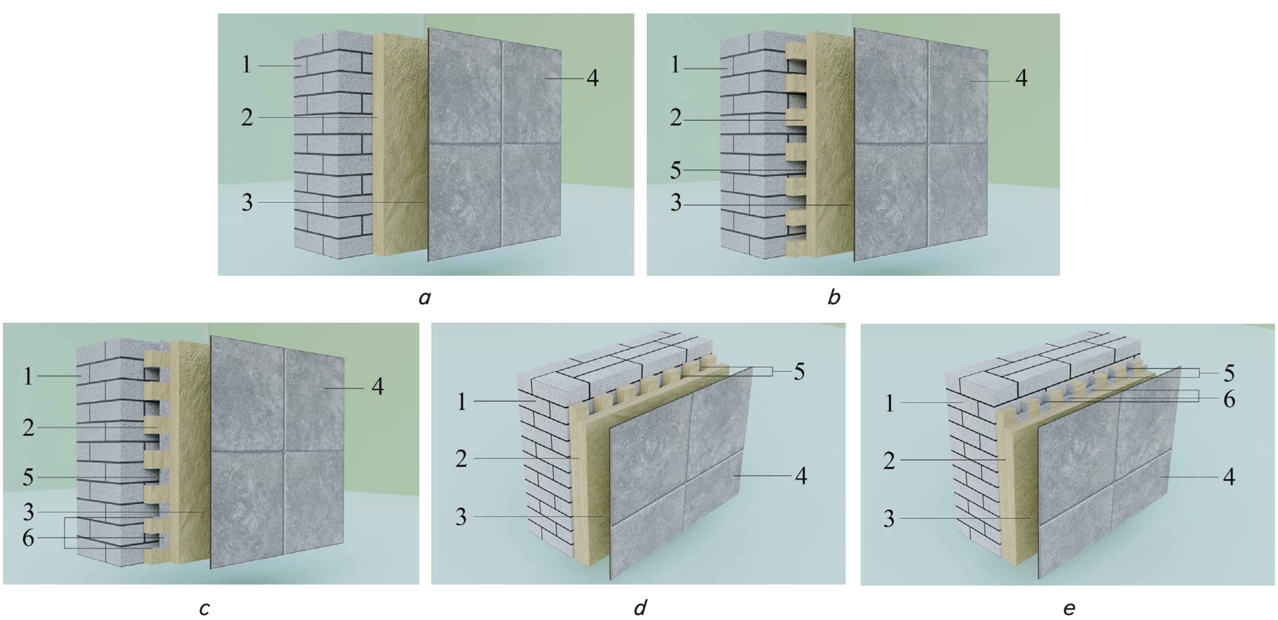


Fig. 1. Energy-saving structures of external fence:
a – traditional model (Scheme-1); *b* – designed model with horizontal channels (Scheme-2); *c* – designed model with horizontal channels and a heat-reflecting screen (Scheme-3); *d* – designed model with vertical channels (Scheme-4); *e* – designed model with vertical channels and a heat-reflecting screen (Scheme-5)

Table 2

Resistance to vapor permeation of fences according to different schemes

Layer indicator	Fencing scheme number				
	1	2	3	4	5
R_1	18.937	23.937	23.937	23.937	23.937
R_2	–	13.937	13.937	13.937	13.937
$\overline{R}_1$	18.941	23.949	23.944	23.944	23.945
$\overline{R}_2$	–	15.192	15.195	15.194	15.195

The characteristic of the resistance to vapor permeability of the fence poorly characterizes the possibility of condensation inside it since it does not depend on the order of the layers. For a qualitative study of this possibility, a dependence $\widetilde{R_T}\left(\widetilde{R_s}\right)$, is built where $\widetilde{R_T}(x)=R_T(x)/R_v$; $R_T(x)$ is the function of thermal resistance in the thickness of the fence; $\widetilde{R_s}(x)=R_s(x)/R_n$. Such dependences for fencing schemes 1–5 are shown in Fig. 2–6. The lower the dependence $\widetilde{R_T}\left(\widetilde{R_s}\right)$ is relative to the curve $\widetilde{R_T}\left(\widetilde{R_s}\right)$, the more difficult it is for ccapor to condense in the enclosure. Also, the area between the two curves qualitatively characterizes the amount of condensate in the enclosure: the larger the area above the curve $\widetilde{R_T}=\widetilde{R_s}$, the more condensate falls in the enclosure [42], Fig. 2–6.

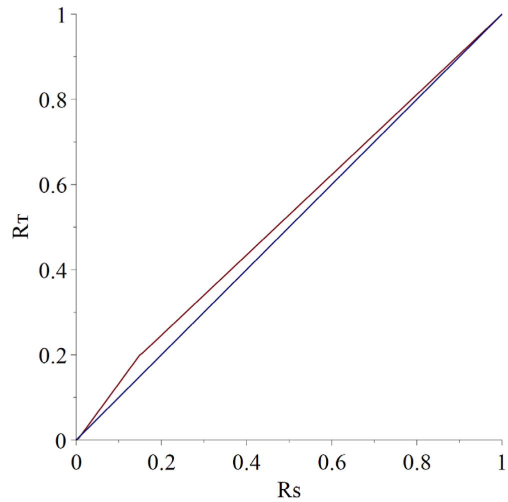


Fig. 2. Dependence $\widetilde{R_T}\left(\widetilde{R_s}\right)$ for scheme 1 in the cross-section of a solid filler

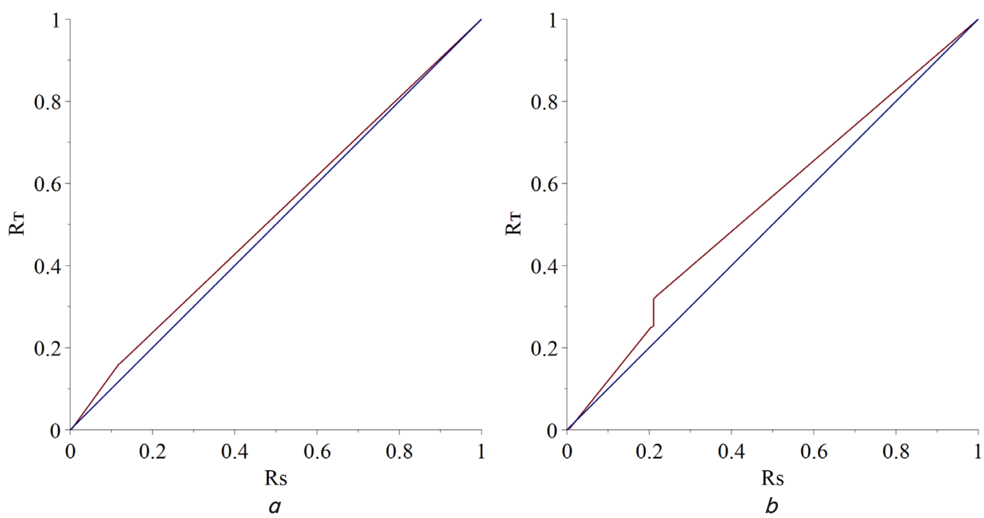


Fig. 3. Dependence $\widetilde{R_T}\left(\widetilde{R_s}\right)$ for scheme 2:
a — in the cross-section of a solid filler; *b* — in the cross-section of a closed horizontal channel

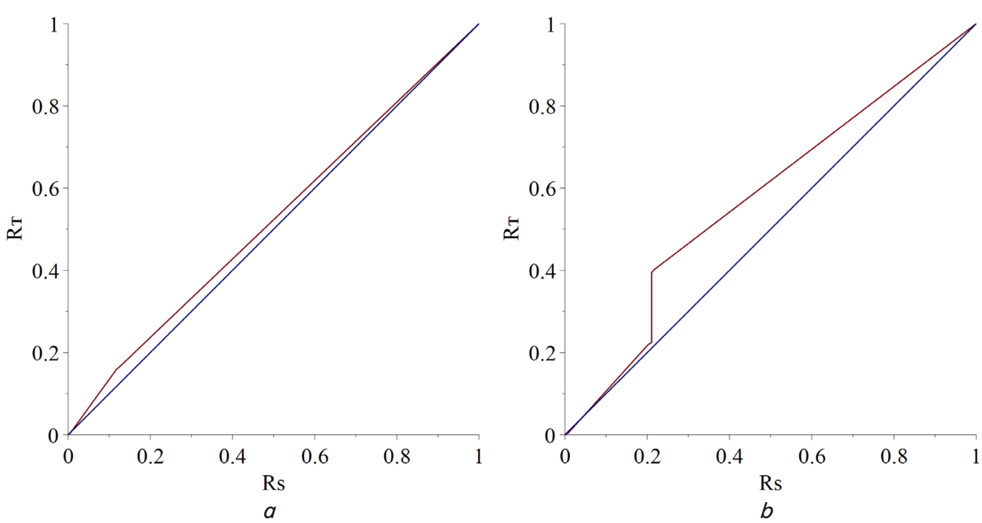
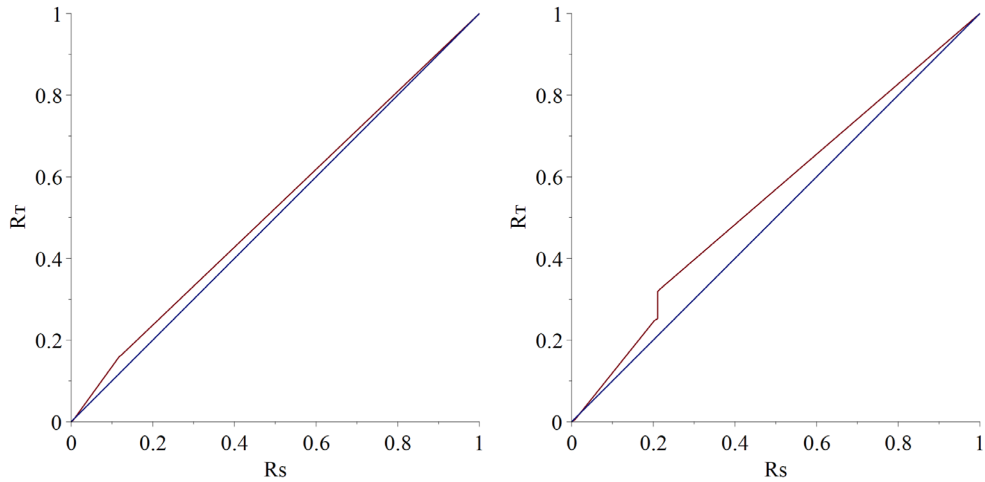
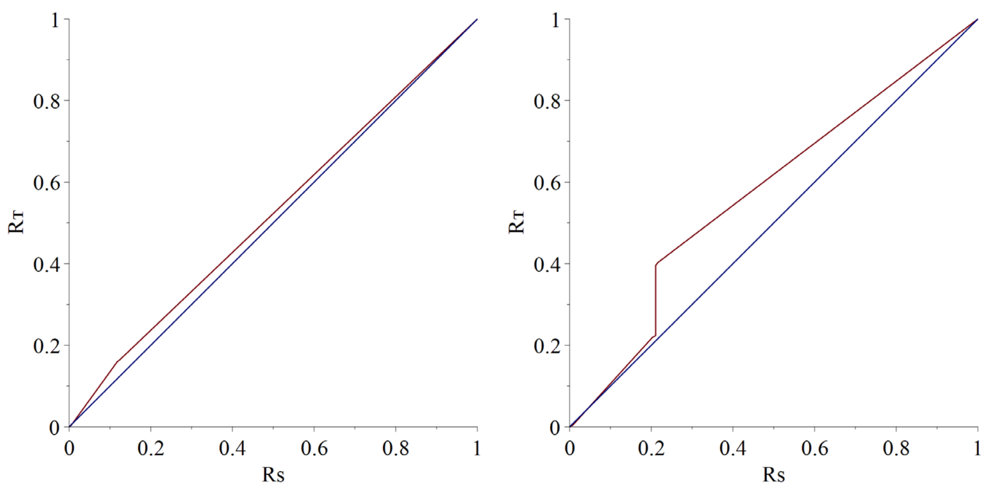


Fig. 4. Dependence $\widetilde{R_T}\left(\widetilde{R_s}\right)$ for scheme 3:
a — in the cross-section of a solid filler; *b* — in the cross-section of a closed horizontal channel with a heat-reflecting screen



a *b*

Fig. 5. Dependence $\widetilde{R}_T\left(\widetilde{R}_s\right)$ for scheme 4:
a – in the cross-section of a solid filler; *b* – in the cross-section of a closed vertical channel



a *b*

Fig. 6. Dependence $\widetilde{R}_T\left(\widetilde{R}_s\right)$ for scheme 5:
a – in the cross-section of a solid filler; *b* – in the cross-section of a closed vertical channel with a heat-reflecting screen

Fig. 2–6 demonstrate that the use of a closed air gap with a heat-reflecting screen makes it possible to shift the possible condensation zone towards the outer surface of the enclosure. At the same time, condensation of water vapor can occur in the fences according to all the proposed schemes.

5. 2. 2. Determination of the condensation zone by the temperature field in the fence

For all fencing schemes, the water vapor condensation zone was determined by numerically solving the inequality from [43]. To assess the condensation zone, we used the results of modeling the temperature field at an internal temperature of 20 °C and an external air temperature equal to the average temperature of the coldest five-day period with a probability of 0.92 (–14.3 °C) [39, 44]. The relative humidity of the indoor air was assumed to be 55 %. The relative humidity of the outside air – the average humidity of the coldest month (January) – 73 %.

Fig. 7–11 show the dependences $E(t(x))-e(x)$. The beginning and end of the condensation zone correspond to the solutions to the equation $E(t(x))-e(x)=0$. All calculations were carried out in the Maple computer algebra software.

The coordinates of the beginning and end of the condensation zone for different fencing schemes are given in Table 3.

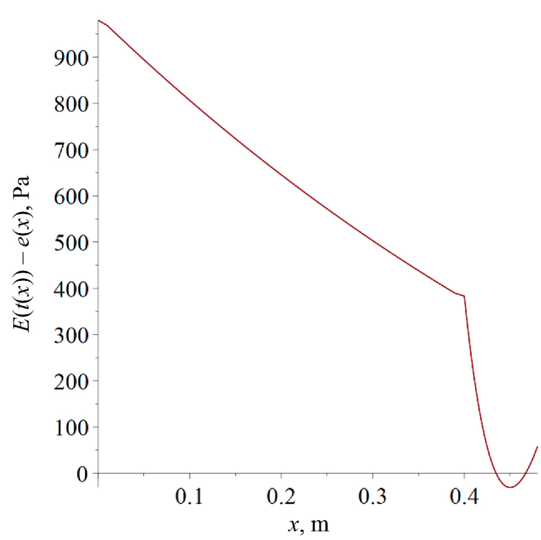
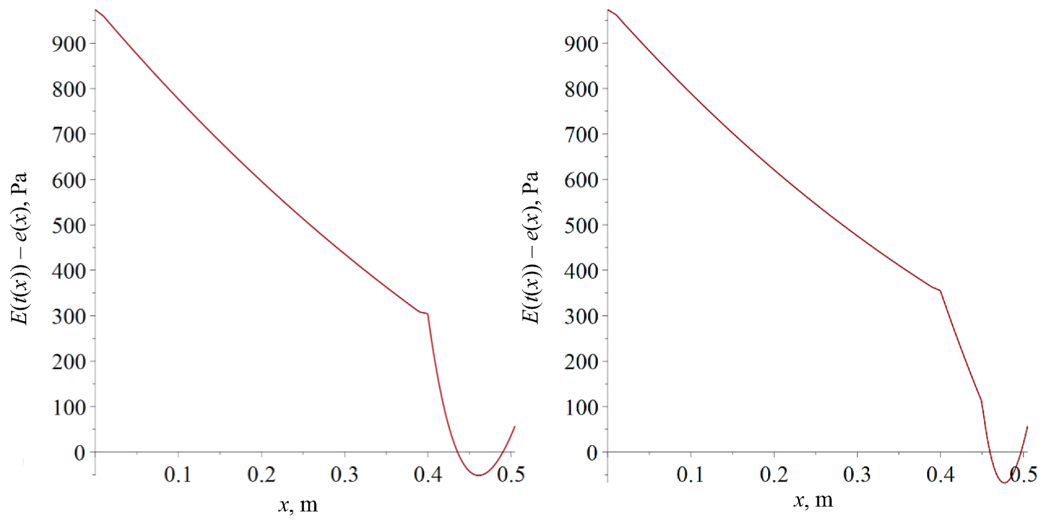
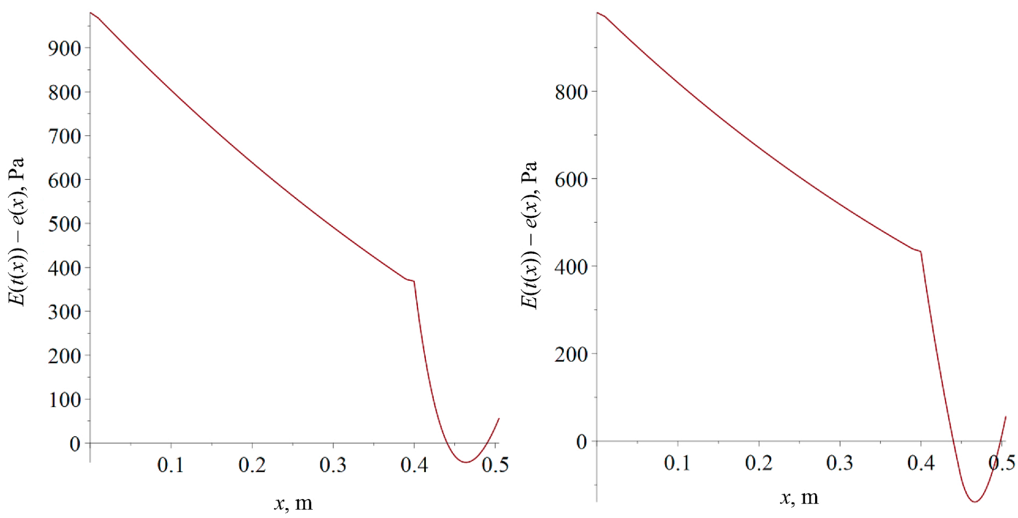


Fig. 7. Dependence $E(t(x))-e(x)$ for scheme 1 of the fence



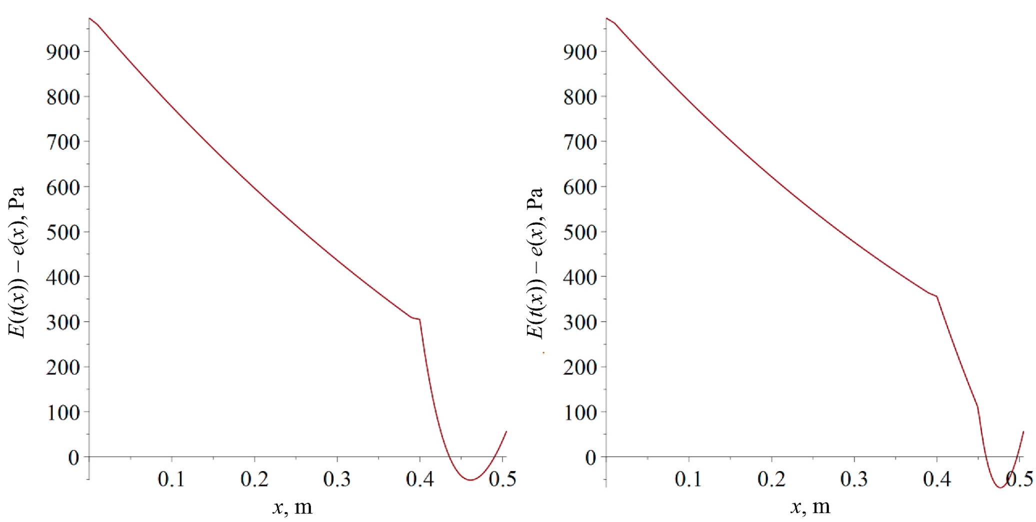
a *b*

Fig. 8. Dependence $E(t(x)) - e(x)$ for fencing scheme 2:
a – in the cross-section of solid insulation; *b* – in the cross-section of a closed air channel



a *b*

Fig. 9. Dependence $E(t(x)) - e(x)$ for scheme 3 of the fence:
a – in the cross-section of a solid insulation; *b* – in the cross-section of a closed air channel



a *b*

Fig. 10. Dependence $E(t(x)) - e(x)$ for fencing scheme 4:
a – in the cross-section of solid insulation; *b* – in the cross-section of a closed air channel

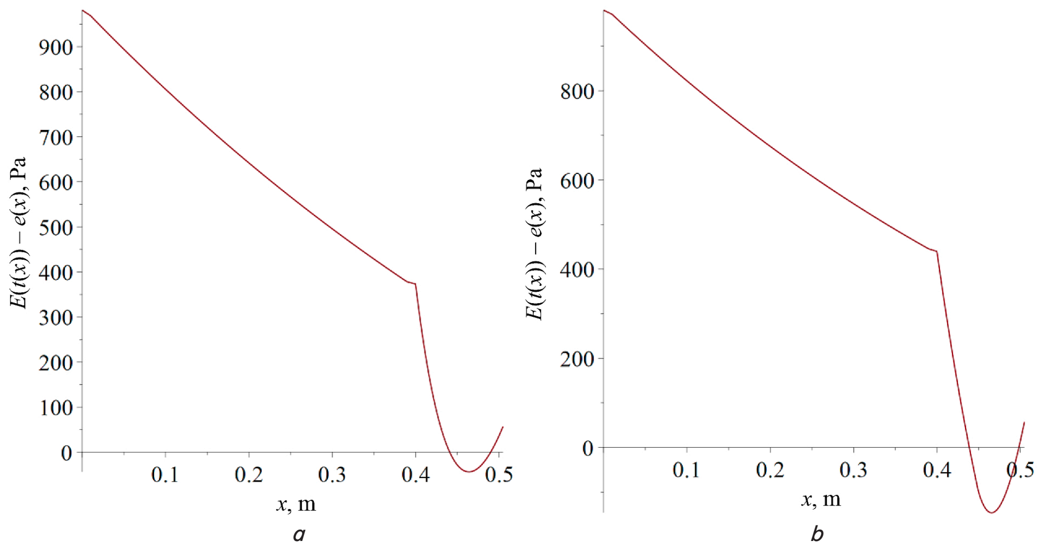


Fig. 11. Dependence $E(t(x))-e(x)$ for scheme 5 of the fence: *a* – in the cross-section of a solid insulation; *b* – in the cross-section of a closed air channel

Table 3

Location of the condensation zone in the fence

Fencing scheme number	The temperature of the dew point in the cross-section of the solid insulation, °C	The beginning of the condensation zone x_{k1}, m, in the cross-section of solid insulation	End of condensation zone x_{k2}, m, in the cross-section of solid insulation	Dew point temperature in the cross-section of the interlayer/air channel, °C	The beginning of the condensation zone x_{k1}, m, in the cross-section of the interlayer/air channel	End of condensation zone x_{k2}, m, in the cross-section of the interlayer/air channel
1	1.00	0.4355	0.4670	–	–	–
2	2.97	0.4358	0.4904	4.33	0.4597	0.4970
3	2.24	0.4407	0.4901	6.75	0.4401	0.4983
4	2.97	0.4358	0.4905	4.37	0.4595	0.4970
5	2.18	0.4410	0.4901	6.76	0.4389	0.4984

Thus, in all fencing schemes, condensation of water vapor occurs. In this case, the condensation zone in schemes 3, 5 in the cross-section of the interlayer or air channel begins in a closed air channel and ends in the insulation layer adjacent to the ventilated air gap. In schemes 1, 2, 4, and in the cross-sections of the solid insulation of schemes 2–5, condensation occurs in the insulation layer.

5. 2. 3. Checking for non-condensation in the ventilated air gap

Checking for the non-falling of condensate in the ventilated air gap was carried out according to the procedure described in [39]. The calculation results are given in Table 4.

Table 4

Results of the test for non-condensation in the ventilated layer

Fencing scheme number	Vapor elasticity in the interlayer *e*, Pa	Saturated vapor pressure *E*(*t*), Pa	The presence of condensate in the ventilated layer
1	153.926	214.615	No
2	153.937	215.210	No
3	153.955	211.523	No
4	153.953	211.857	No
5	153.938	211.498	No

The high value of the thermal resistance of the fence, as well as the high resistance to vapor permeability of the insulation, leads to the fact that in the ventilated layer the temperature and air velocity change slightly from scheme to scheme. Therefore, the results of calculating the parameters of vapor in a ventilated layer differ little from each other.

5. 2. 4. Determination of the amount of condensate in the fence

The results of calculating the amount of condensate formed in the fence for the year are given in Table 5. They demonstrate that in schemes with closed air spaces and channels, condensation occurs more actively than in scheme 1. At the same time, schemes with heat-reflecting screens are characterized by more active condensation than schemes without them. Qualitatively, this phenomenon can be predicted from the charts shown in Fig. 2–6.

An important characteristic of the humidity regime is the relative moisture content of the insulation in the annual cycle. To study this parameter, the third column of Table 5 gives the value of the mass of condensed steam in relation to the mass of insulation β, %. This value was calculated as follows:

– for scheme 1:

$$\beta = \frac{m}{m_{in}} \cdot 100\,\%,$$

where m is the amount of steam condensed in 1 m^2 of insulation; m_{in}=2000 g – the mass of 1 m^2 of the insulation layer in which condensation occurs:

– for schemes 2–5:

$$\beta = \frac{0.5(m_1 + m_2)}{m_{in}} \cdot 100\,\%,$$

where m_1 is the mass of condensed steam in 1 m^2 of insulation in the cross-section of a solid insulation; m_2 – the mass of condensed steam in 1 m^2 of insulation in the cross-section of a closed air channel; m_{in}=2000 g is the mass of the insulation layer in which condensation occurs.

According to [45], the maximum moisture content of the insulation should not exceed the critical value $w_{crit}=w_B+\Delta w$, where w_B is the calculated moisture content of the material for operating conditions B; Δw is the maximum allowable moisture increment. For extruded polystyrene foam with a density of 25–40 kg/m^3, these values are w_B=2 %; Δw_{cp}=1.5 %. Thus, w_{crit}=3.5 % [43].

Analysis of the results given in Table 5 reveals that the fence according to scheme 1 withstands the requirements for wetting the insulation. At the same time, in schemes with closed layers, the insulation is significantly waterlogged. This is a known weakness of extruded polystyrene foam [45]. The use of air channels in the fencing scheme has made it possible to avoid waterlogging of the insulation, significantly reducing the accumulation of moisture. At the same time, we note that in schemes with air channels and a heat-reflecting layer, moisture condensation also occurs inside the channel. This phenomenon is not considered negative.

5. 2. 5. Determination of the drying time of the fence

Estimation of the drying time of the fence was carried out according to the procedure given in [39, 43, 46]. Table 6 shows the values of the drying rate of the fence in April and the drying time.

Thus, in the fences according to all the schemes considered, there is no accumulation of moisture on the annual balance.

5. 3. Analysis of the air regime of external fences

The analysis of the air regime of the fence is inextricably linked with the layout of the building, the type and number of translucent structures, the organization of heating and ventilation, and other aspects that go beyond the analysis of a homogeneous enclosing structure [47]. However, in [25], there is a requirement for a minimum value of air permeability of the fence; in addition, the use of a ventilated facade as part of the fence imposes additional requirements.

The air permeability resistances of the materials used in schemes 1–5 were taken according to [39]. The air permeability of extruded polystyrene foam is not given in scientific articles or building standards. Therefore, to assess the resistance to air penetration of this material, the similarity relation between vapor permeability and air permeability to expanded polystyrene, the data on which is contained in [39], was used.

The values of the required air permeability resistance R_{inf}^{req} and the calculated value of the air permeability resistance of the fence R_u are given in Table 7.

Table 5

Condensation of water vapor in the thickness of the fence

Scheme number	Mass of condensed steam during the heating period m, g, in 1 m^2 of cross-section of solid insulation	Mass of condensed steam during the heating period m, g, in 1 m^2 of interlayer/channel section	Relative mass of condensed steam during the heating period in the insulation layer, %	Mass of condensed steam during the heating period in 1 m^2 of fencing, g
1	31.44	–	1.57	31.44
2	31.11	59.70	2.3	45.41
3	31.11	105.85	3.1	68.48
4	31.14	59.99	2.3	45.57
5	29.27	114.02	3.22	71.65

Table 6

Condensation of water vapor in the thickness of the fence

Scheme number	Drying rate in the cross-section of solid insulation, g/day	Drying rate in the cross-section of the interlayer/channel, g/day	Drying time in the cross-section of solid insulation, days	Drying time in the cross-section of the interlayer/channel, days	Fence drying time, days
1	7.86	–	4.0	–	4.0
5	5.154	9.518	6.0	6.3	6.3
6	5.154	11.491	6.0	9.2	9.2
7	5.161	9.557	6.0	6.3	6.3
8	4.970	11.610	5.9	9.8	9.8

Table 7

Required air permeation resistance for different fencing schemes

Scheme number	R_{inf}^{req} without taking into account the ventilated air gap, $m^2 \cdot h \cdot Pa/kg$	R_u in the cross-section of solid insulation, $m^2 \cdot h \cdot Pa/kg$	R_u in the cross-section of the air channel, $m^2 \cdot h \cdot Pa/kg$
1	60	911	–
2	60	1034	788
3	60	1034	788
4	60	1034	788
5	60	1034	788

Thus, the fences meet the requirements for air permeability without taking into account the influence of the hinged facade. At the same time, the use of a hinged facade structure significantly increases the required air permeability, which is often ignored when designing fences [48–52].

6. Discussion of results of the analysis of thermophysical parameters of the designed outdoor energy-saving structures

In the study, an analysis of the thermophysical parameters of the traditional and designed energy-saving structures of the external fence was carried out. To determine the heat resistance, humidity, and air conditions of the newly designed structures of the external fence, the corresponding procedure for calculating the norm was applied [39]. The processing of the results of the parameters was carried out in the Maple computer algebra software; the value of the thermal resistance of the structures was taken according to the earlier works [20, 22, 23], studied on the basis of finite element modeling in the ANSYS software [42]. An analysis of the traditional (Scheme 1) and designed (Schemes 2–5) (Fig. 1) fences revealed that the designed structures of the external fence are more efficient in terms of certain indicators of thermophysical parameters. Thus, when calculating the thermal stability of structures, it was found that the value of thermal inertia (D) of a traditional structure and the average value of thermal inertia of the designed structures are equal. However, the analysis showed that the average value of the oscillation amplitude $\left(A_{\tau}^{des}\right)$ of the designed ones (Schemes 2–5) is up to 20.72 % more efficient than the traditional one (Scheme 1). At the same time, air gaps do not affect the thermal inertia of the fence, and its parameters depend only on the total thickness of the material. In this case, the sequence of materials does not play a role, and the thermal inertia of the fence does not depend on the location and heat-reflecting properties of the air layers. The thermal inertia of the fences under consideration is extremely high (more than 5.7).

An analysis of the vapor permeability value showed that the average vapor permeability resistance value of the inner wall of the designed structures (Schemes 2–5) is equal to the traditional one (Scheme 1). However, the average value of resistance to vapor permeability of the fence of the designed structures is 3.21 % more effective (Table 2). At the same time, Fig. 2–6 demonstrate that the use of a closed air gap with a heat-reflecting screen makes it possible to shift the possible condensation zone towards the outer surface of the enclosure. The analysis of the condensation zone by the temperature field in the enclosure showed that in all schemes of the enclosure water vapor condenses. In this case, the condensation zone in schemes 3, 5 in the cross-section of the interlayer or air channel begins in a closed air channel and ends in the insulation layer adjacent to the ventilated air gap. In schemes 1, 2, 4, and in the cross-sections of the solid insulation of schemes 2–5, condensation occurs in the insulation layer; Fig. 7–11, and Table 3. Analysis of the check for the non-fallout of condensate in the ventilated air gap showed that condensate does not fall out in the ventilated air gap in all the schemes under consideration; Table 4. The analysis of water vapor condensation revealed that the traditional fencing (Scheme 1) withstands the requirements for wetting the insulation. At the same time, we note that in schemes with air channels and a heat-reflecting layer, moisture condensation also occurs inside the channel (Table 5). However, this phenomenon is not considered negative since for all the considered structures (Schemes 1–5) there is no accumulation of moisture according to the annual balance; Table 6.

An analysis of the air permeability value without taking into account the influence of the hinged facade showed that all fencing schemes meet the air permeability requirements; Table 7. At the same time, the use of a hinged facade structure can significantly increase the required air permeability, which is often ignored when designing fences [41].

Our study to identify the features of the thermophysical parameters of energy-efficient designed structures of an external fence with air channels is part of the research reported in [20, 22–24]. As a limitation of this study, one can note the issue of the influence of ventilated channels, as well as their geometry, which were not taken into account. Solving these problems may be the subject of further research.

It should also be noted that when using a hinged facade system, the issue of air permeability remains open, which is a disadvantage of this study. However, this gap can be filled in further research through the use of hinged facades made of a more vapor-permeable facing material or by increasing the gaps between the facade slabs. In the future, based on a comprehensive analysis of the results of the study and addition of shortcomings, the most effective enclosing structure with air channels will be selected.

Solving the problems of energy saving in construction through the development of new energy-efficient designs of enclosing structures helps reduce the cost of thermal energy for buildings, which is an urgent task all over the world today. At the same time, the results of this study can be used by engineers and designers in the construction of buildings, as well as scientific communities conducting scientific research in this direction in order to develop energy-efficient structures for external fencing.

7. Conclusions

1. Our analysis of the thermal stability of structures revealed that the value of the thermal inertia of the traditional design and the average value of the thermal inertia of the designed structures are equal; however, the analysis showed that the average value of the vibration amplitude of the new ones developed is up to 20.72 % more efficient than the traditional one. At the same time, it was revealed that the air gaps do not affect the thermal inertia of the fence, and its parameters depend only on the total thickness of the material. Also, the sequence of materials does not play a role, and the thermal inertia of the fence does not depend on the location and heat-reflecting properties of the air layers.

2. Analysis of the value of vapor permeability revealed that the average value of the resistance to vapor permeability of the inner wall of the designed structures is equal to the traditional one. However, the average value of the resistance to vapor permeability of the fence of the newly designed structures is 3.21 % more effective (Table 2). When using a closed air layer with a heat-reflecting screen, it allows one to move the possible condensation zone towards the outer surface of the fence. The analysis of the condensation zone by the temperature field in the enclosure showed that in all schemes of the enclosure water vapor condenses. In this case, the condensation zone in schemes 3, 5 in the

cross-section of the interlayer or air channel begins in a closed air channel and ends in the insulation layer adjacent to the ventilated air gap. In schemes 1, 2, 4, and in the cross-sections of the solid insulation of schemes 2–5, condensation occurs in the insulation layer. An analysis of the check for the non-fallout of condensate in the ventilated air gap showed that condensate does not fall out in the ventilated air gap in all the schemes under consideration. The analysis of water vapor condensation revealed that the traditional fencing (Scheme 1) withstands the requirements for wetting the insulation. At the same time, in schemes with air channels and a heat-reflecting layer, moisture condensation also occurs inside the channel, but this phenomenon is not considered negative since for all the structures considered there is no accumulation of moisture according to the annual balance.

3. Our analysis of the air permeability value without taking into account the influence of the hinged facade demonstrated that all fencing schemes meet the requirements for air permeability. At the same time, the use of a hinged facade structure could significantly increase the required air permeation resistance, which is often overlooked in fence design.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

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