

This study investigates a corner element in a multi-story building with varying numbers of stories. The task addressed relates to the vulnerability of building corner elements to temperature fluctuations.

The energy efficiency of corner elements in external wall structures of buildings with vertical air ducts and a heat-reflecting screen was numerically evaluated under conditions of significant seasonal temperature gradients and varying numbers of stories.

The thermal and humidity conditions of corner zones in building envelopes, characterized by spatial heat transfer and increased thermal vulnerability, were analyzed. Numerical modeling was performed using the finite element method in the ANSYS programming environment, using coupled heat and moisture transfer calculations under various climatic scenarios. The influence of corner zone geometry and building height on temperature distribution and the risk of condensation in the outer envelope was analyzed.

The study results showed that in winter, pronounced non-uniformity of the temperature field occurs in corner zones due to the thermal bridge effect. Moreover, the relative temperature reduction in the corner zone, compared to straight wall sections, ranges from 7% to 12%. During transitional and summer periods, temperature gradients are significantly reduced, and the influence of building height is insignificant. Analysis of the humidity regime revealed the possibility of short-term condensation without conditions for long-term moisture accumulation.

The results could be used in the design of energy-efficient adaptive external wall structures for buildings in regions with pronounced seasonal temperature fluctuations

Keywords: energy efficiency, wall structures, heat transfer, numerical modeling, temperature gradients

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DETERMINING THE EFFECT OF TRANSFORMABLE AIR DUCTS AND A HEAT-REFLECTING SCREEN INSIDE THEM ON THE THERMAL-HUMIDITY CONDITION OF THE CORNER ELEMENT CONSIDERING SIGNIFICANT SEASONAL TEMPERATURE GRADIENTS

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1. Introduction

Improving the energy efficiency of buildings in the face of climate change and rising energy costs is a key challenge in

modern construction science and engineering practice. The need to adapt to the impacts of climate change is driving the growing attention to regulatory frameworks for energy efficiency and sustainability in buildings. Buildings worldwide

consume a significant share of energy, a significant portion of which is spent on heating, ventilation, and air conditioning. Their operational energy footprint is directly linked to the sustainability of urban planning systems and the climate targets of international agreements to reduce greenhouse gas emissions.

Changing climate loads significantly impact the energy needs of buildings, including heating and cooling. The performance of building envelopes, including external walls and facade systems, is becoming a critical factor in sustainable architecture, especially in the face of increasing extreme weather events and increasing seasonal temperature fluctuations predicted by modern climate models. These climate changes increase the load on building thermal systems in both cold and warm seasons.

Therefore, studies that consider energy-efficient external enclosures require a fundamental revision of conventional approaches to the design of enclosing structures and the implementation of adaptive solutions to minimize energy consumption and improve the indoor microclimate.

2. Literature review and problem statement

A review of research on the adaptive design of building envelopes in cold climates is given in [1–3]. In particular, in [1], analysis was performed on the scale of an entire building [2], using the example of a wooden structure without taking into account corner joints, or the adaptive component was investigated without analyzing individual elements in the form of a thermal bridge [3]. In the external building envelopes, energy losses are largely determined by the spatial heterogeneity of the thermal regime, especially in zones where the assumptions of one-dimensional heat transfer become inapplicable. Thus, areas with geometric heterogeneities, including wall corners, facade element joints, and other thermal bridges, are characterized by two- and three-dimensional heat flow distributions, which leads to an increase in local heat losses compared to flat sections of the envelope and requires the use of more complex numerical models for their analysis, as shown in [4, 5]. This multidimensional nature of heat transfer in corner zones is due to the presence of spatial temperature gradients, which lead to increased heat flow and the formation of local temperature minima on the interior surfaces of the enclosure. This, in turn, increases the risk of condensation and worsens the microclimate of interior spaces [6]. These characteristics make corner zones critical elements for the overall thermal balance of a building, especially under conditions of pronounced seasonal temperature gradients.

Significant attention in scientific research is given to ventilated facade systems [7], which have proven effective in hot climates due to the removal of excess heat through an air gap [8]. At the same time, under conditions of a sharply continental climate, such systems have a number of limitations. During the cold period of the year, constant air circulation in the gap can increase heat loss, and the fixed operating mode of the facade does not allow the thermal characteristics of the structure to be adapted to changing external conditions. One of the promising areas of development of enclosing structures is the use of transformable air ducts, the operating mode of which can change depending on the season of operation [9, 10]. In winter, such ducts can function under a closed mode, forming an additional heat-insulating air gap [11, 12], while in summer they switch to ventilation mode, providing natural heat dissipation [13]. Most of existing research in this area analyzes flat wall sections, while the operating features of transformable air ducts in cor-

ner areas remain insufficiently studied. This is characterized by the complexity of three-dimensional analysis, the presence of pronounced thermal bridges at corner junctions, difficulties with experimental validation, etc.

A number of earlier studies have examined heat transfer in multi-layer walls and the influence of air gaps on the thermal performance of enclosing structures [14–16]. It has been shown that, with sufficient air tightness, air gaps can significantly reduce the heat transfer coefficient. However, study [14] does not take into account the influence of air gaps or the design features of the external enclosure. Paper [15] considered the economic aspects of the design only, without exploring technical improvements. Study [16] considered straight sections of the structure only and did not examine the corner junctions of buildings.

Studies [17–19] investigated ventilated facades in detail and found their high efficiency in summer but noted a decrease in thermal resistance during the cold season. However, paper [17] did not consider the influence of the enclosure geometry. Also, the influence of corner joints and the number of stories of buildings on heat transfer was not taken into account in [18, 19]. The relevance of facade systems and the need for their development in the face of climate change are emphasized in [20–22]. However, work [20] is purely conceptual in nature and does not consider numerical studies at joints. A similar approach is demonstrated in [21], which also did not take into account the influence of air gaps and corner joints [22].

The influence of architectural elements and facade solutions on the heat transfer of external enclosing structures is the subject of active research as such elements significantly alter the aerodynamic conditions at the building surface and, as a consequence, the intensity of convective heat transfer. In [23], a detailed study of forced convective heat transfer on the windward facade surface of a building equipped with vertical sun protection lamellas was conducted. The results emphasize that even additional facade elements intended for sun protection can significantly affect the thermal regime of enclosing structures. However, the study was conducted relative to a steady-state regime without taking into account corner zones and seasonal fluctuations. A similar approach was used in [24], which investigated the influence of balconies on convective heat transfer processes on the facades of multi-story buildings. However, corner abutments and seasonal reconstructions were also not taken into account in the study. In [25, 26], the influence of vertical landscaping of facades on heat transfer through the external walls of buildings was considered. However, these studies only considered bioclimatic facades and flat areas, respectively. Paper [27] examines heat and mass transfer in the windward facade of a building with vertical sun protection slats. It is shown that the use of vertical external screening systems significantly affects the aerodynamics of airflow near the facade surface and the intensity of convective heat transfer. This should be considered when designing adaptive facade solutions to improve building energy efficiency. Although the study examined a wide range of factors, it did not consider design adaptation parameters.

Taken together, the research results show that local changes in facade geometry significantly affect the aerodynamics and heat transfer of external enclosing structures. This confirms the need to consider spatial effects and the multidimensional nature of heat transfer when analyzing the energy efficiency of complex facade systems, including corner areas of external walls where the influence of geometric factors is particularly pronounced. Despite a significant amount of research into energy-efficient facade systems, the issue

of numerically assessing the thermal performance of corner exterior walls with transformable air ducts and heat-reflecting screens under conditions of significant seasonal temperature gradients remains understudied. Specifically, a systematic analysis of the influence of spatial geometry of the corner on the distribution of temperature fields and integrated energy efficiency indicators is lacking.

3. The aim and objectives of the study

The aim of our study is to determine the impact of transformable air ducts in corner wall elements of buildings on the thermal and moisture state of the building's corner element under dynamically varying climatic conditions. Achieving this goal will address the issue of additional thermal protection during the winter and the thermal stability of the building envelope during hot periods, resulting in overall energy savings.

To achieve this goal, the following tasks were set:

- to conduct a thermal analysis of the building's corner zone under varying climatic conditions using additional air ducts and a heat-reflecting screen in the envelope, taking into account the building's height;
- to perform a moisture analysis of the building's corner zone using additional air ducts and a heat-reflecting screen.

4. The study materials and methods

4.1. The object and hypothesis of the study

Our paper examines the corner element of a multi-story building with varying numbers of stories. The principal hypothesis assumes that the use of transformable vertical air ducts (closed and ventilated) in corner junctions of buildings with heat-reflecting screens optimizes the thermal efficiency of the corner junction and reduces energy consumption in both winter and summer. This is because the additional closed ducts and heat-reflecting screen provide additional thermal protection, and in summer, these ducts, through ventilation, facilitate the removal of excess heat from the outer envelope.

It was assumed that the environmental and internal microclimate parameters were consistent with regulatory sources, that thermal bridges in the form of various types of fasteners were not considered, and that interlayer contacts were considered correct when calculating heat transfer resistance.

Simplifications adopted in the study included not taking into account air infiltration and/or exfiltration; the analysis was conducted under steady-state conditions only.

4.2. Model construction and configuration

Numerical heat transfer modeling was performed using the heat conduction equation discretized by the finite element method for a spatial three-dimensional thermal analysis problem, as discussed in detail in papers that resolve thermal conductivity by FEM [28, 29]. Standard thermal analysis functionality was used within ANSYS (United States of America), including the specification of convective boundary conditions and a mesh calculation procedure. Three-dimensional moisture and heat transfer modeling approaches implemented in ANSYS were used to evaluate the moisture regime and the interaction of thermal and moisture processes.

Geometric Model. To model the thermal state of the corner of the enclosing structure, a geometric model was constructed, as shown in Fig. 1.

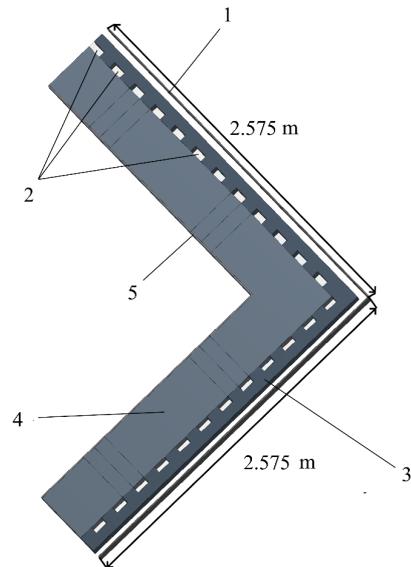


Fig. 1. Geometric model for calculating the fencing angle:
1 – porcelain stoneware; 2 – air ducts; 3 – insulation;
4 – brickwork; 5 – plaster

Thermal insulation scheme. This study examines a multilayer external wall enclosing structure consisting of a homogeneous load-bearing layer and a slab thermal insulation layer with vertical air ducts equipped with a heat-reflecting screen. The structure includes a 50 mm-thick ventilated air gap, a 75 mm-thick thermal insulation layer, and 50 mm-thick closed air ducts.

The study was conducted using the finite element method in ANSYS Workbench 19.2 (United States of America), which enables a comprehensive numerical analysis of the thermal state of multilayer enclosing structures, taking into account the associated thermal and moisture processes.

Finite element model. The mesh shown in Fig. 2 was constructed for the finite element calculation. Note that for summer calculations, ventilation ducts are replaced with appropriate convection boundary conditions.

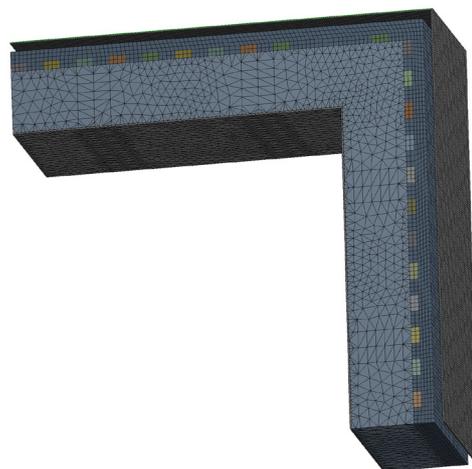


Fig. 2. Finite element model for thermal calculations

The model shown in Fig. 2 consists of 127,217 finite elements with 389,601 nodes. The average element quality is 0.71741. The model is primarily represented by 20-node hexahedral elements (Hex20) and 10-node tetrahedral ele-

ments (Tet10). The convergence of the numerical solution was verified using the standard method of successively halving the characteristic finite element size followed by a comparison of the key calculation parameters.

It was found that with further mesh refinement, the change in temperature fields does not exceed the permissible errors, indicating mesh convergence. The adopted computational mesh provides a rational compromise between the accuracy of the numerical solution and computational costs. Within the framework of our study, the described finite element model is considered optimal.

4. 3. Seasonal boundary conditions

Four boundary conditions were used for the cold season calculation:

- convection on the inner wall surface;
- convection on the inner surface of the ventilated facade gap;
- convection on the outer surface of the ventilated facade gap;
- convection on the outer surface of the enclosure.

Table 1 gives parameters for the corresponding boundary conditions for various calculation options. The calculation was performed under the following conditions: minimum absolute air temperature, average air temperature of the coldest five-day period with a probability of 0.92, and average air temperature in the first month after the heating season (April).

Fig. 3 shows boundary conditions for calculating the temperature regime using the example of conditions of absolute minimum air temperature.

Five boundary conditions were used for the warm-season calculation:

- convection on the inner wall surface;
- convection on the inner surface of the ventilated facade gap;
- convection on the outer surface of the ventilated facade gap;
- convection on the outer surface of the enclosure;
- convection on the inner surface of the ventilated ducts.

Table 2 gives parameters for the corresponding boundary conditions for various calculation options.

Fig. 4 shows boundary conditions for calculating the temperature regime using the example of the conditions of the average air temperature for a building with a height of 48 m.

The calculation was carried out under the conditions of maximum absolute air temperature and average air temperature in July for buildings with a height of 18 and 48 m, taking into account solar radiation.

Table 1

Boundary conditions parameters for calculations during the cold season

Boundary condition position	Film coefficient	Absolute minimum temperature, °C	Average temperature of the coldest five-day period, °C	Average temperature in April, °C
Inner wall surface	10 ⁻⁵	20	20	20
Inner surface of the ventilated facade gap	10 ⁻³	-29.685	-13.829	13.625
Outer surface of the ventilated facade gap	10 ⁻³	-29.685	-13.829	13.625
Outer surface of the enclosure	10 ⁻³	-30.3	-14.3	13.5

- A** Convection: 20. °C, 1.e-005 W/mm².°C
- B** Convection 2: -29.685 °C, 1.e-003 W/mm².°C
- C** Convection 3: -29.685 °C, 1.e-003 W/mm².°C
- D** Convection 4: -30.3 °C, 1.e-003 W/mm².°C

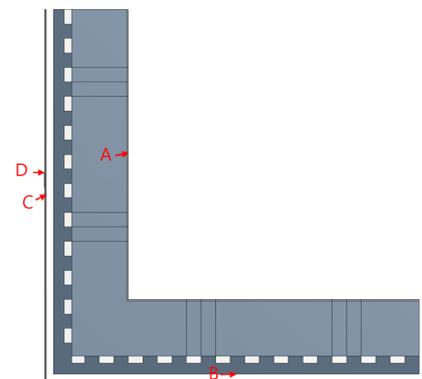


Fig. 3. Boundary conditions for calculating the cold season

Table 2

Boundary conditions parameters for calculations during the warm season

Boundary condition position	Film coefficient	Absolute maximum temperature, 18 m, °C	Average July temperature, 18 m, °C	Absolute maximum temperature, 48 m, °C	Average July temperature, 48 m, °C
Inner wall surface	10 ⁻⁵	28	28	24	24
Inner surface of the ventilated facade gap	10 ⁻³	63.335	63.334	45.712	45.711
Outer surface of the ventilated facade gap	10 ⁻³	63.335	63.334	45.712	45.711
Outer surface of the enclosure	10 ⁻³	63.891	63.891	46.091	46.091
Ventilated ducts	10 ⁻³	43.432	43.153	26.638	26.727

- A** Convection: 24. °C, 1.e-005 W/mm².°C
- B** Convection 2: 45.711 °C, 1.e-003 W/mm².°C
- C** Convection 3: 45.711 °C, 1.e-003 W/mm².°C
- D** Convection 4: 46.091 °C, 1.e-003 W/mm².°C
- E** Convection 5: 26.727 °C, 1.e-003 W/mm².°C

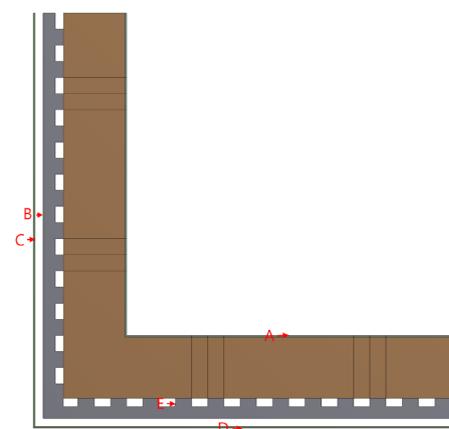


Fig. 4. Boundary conditions for calculating the warm season

4. 4. Analytical approaches

To analyze the thermal state of the corner exterior wall structures, numerical modeling was performed in ANSYS Workbench 19.2 (United States) using the finite element method. The calculation is based on the classical heat transfer model implemented in ANSYS, which takes into account the multilayer structure of the enclosing structure, local thermal bridges, as well as the spatial nature of heat flow in corner zones.

The mathematical statement of the problem is described by a non-stationary heat conduction equation

$$\rho c \frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T) + Q_{gen}, \tag{1}$$

where ρ is the material density, c is the specific heat capacity, T is the temperature, t is the time, λ is the thermal conductivity coefficient, and Q_{gen} is the volumetric density of the internal heat sources.

Convective and radiant boundary conditions were specified on the external and internal surfaces of the enclosing structures, implemented using standard ANSYS (United States of America) tools.

Convective heat transfer between the wall surface and the surrounding air was described by the following relationship

$$q_{conv} = h_c (T_{surface} - T_{\infty}), \tag{2}$$

where q_{conv} is the convective heat flux density, h_c is the convective heat transfer coefficient, $T_{surface}$ is the wall surface temperature, and T_{∞} is the ambient air temperature, specified as a boundary condition.

Radiant heat transfer was taken into account using the Stefan-Boltzmann law.

$$q_{rad} = \varepsilon \sigma (T_{surface}^4 - T_{sky}^4), \tag{3}$$

where q_{rad} is the radiant heat flux density, ε is the surface emissivity, σ is the Stefan-Boltzmann constant, $T_{surface}$ is the surface temperature of the enclosing structure, and T_{sky} is the effective ambient temperature. This model takes into account the nonlinear nature of radiative heat exchange and accurately describes heat loss processes from external surfaces, including the effect of nighttime radiative cooling.

The contact between different layers of the enclosing structure was modeled to ensure continuity of the tempera-

ture field and heat fluxes. Numerical calculations were performed for seasonal boundary conditions.

Based on the modeling results, temperature distributions, interior wall surface temperatures, local heat fluxes, and potential moisture condensation zones were determined.

5. Results of investigating the corner element of buildings using additional air ducts and a heat-reflecting screen

5. 1. Thermal analysis of a building corner zone under different climatic conditions

To assess the impact of the corner zone of an external wall on the thermal and humidity conditions of the enclosing structure, characteristic temperature control areas of the enclosing interior surface were identified in the calculation model (Fig. 5). These areas were chosen to compare heat and moisture transfer conditions in zones with different structural arrangements of the thermal insulation layer. Specifically, the model includes areas located opposite the air duct and opposite sections of continuous insulation. The area designated by letter K corresponds to the enclosing interior surface in the air duct area, where heat transfer occurs through convective and radiative processes within the duct. The area designated by letter Y is located opposite the continuous insulation layer and characterizes heat transfer conditions determined primarily by the thermal conductivity of the enclosing materials.

Identifying these zones allows for a precise comparative study of temperature conditions and associated humidity processes in structures with different insulation schemes under identical external climatic conditions. Furthermore, analyzing interior surface temperatures at these points is crucial for assessing the risk of condensation and ensuring sanitary and hygienic requirements for enclosing structures.

Fig. 6 shows the temperature field of the enclosing structure at the absolute minimum outside air temperature. Calculations show that a pronounced non-uniformity of the temperature field develops in the corner zone, due to the spatial nature of heat transfer and the presence of a thermal bridge. Minimum temperatures are observed near the inner corner of the load-bearing wall, confirming the increased thermal vulnerability of this area. The relative temperature drop in the corner averages 12%.

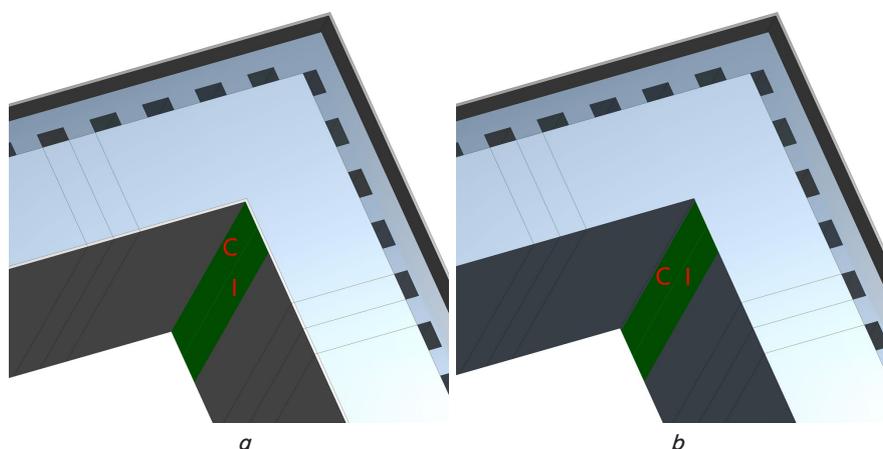


Fig. 5. Areas for moisture analysis: *a* – on the inner surface of the enclosure; *b* – on the inner surface of the load-bearing wall

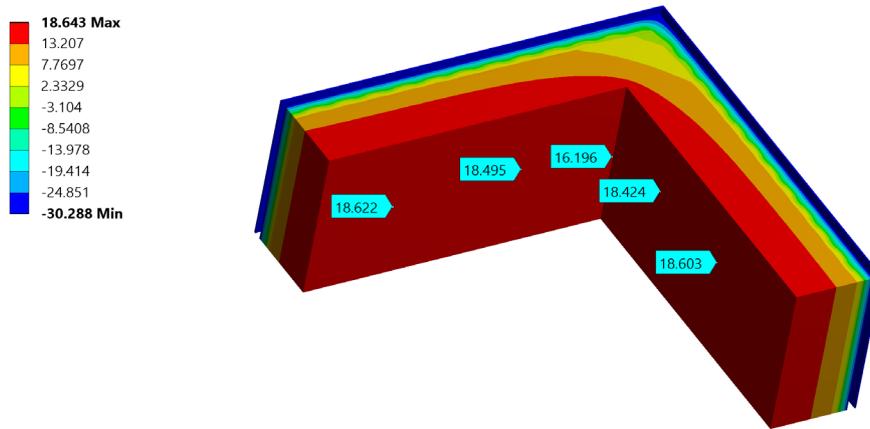


Fig. 6. Temperature field in the enclosure at the absolute minimum temperature of the outside air

At an outside air temperature corresponding to the average temperature of the coldest five-day period with a probability of 0.92 (Fig. 7), the temperature field becomes more uniform, but the corner zone still exhibits lower temperatures compared to the flat wall sections. The relative temperature reduction in the corner averages 7%. This indicates that the thermal bridge effect persists even under standard winter operating conditions.

The temperature field for an outside air temperature corresponding to the average April temperature is shown in Fig. 8. During the transition period, a leveling of the temperature field is observed. Local temperature deviations in the corner zone are insignificant, and the relative temperature decrease in the corner region averages 1.5%.

The results of temperature field calculations at the absolute maximum outdoor air temperature are shown in Fig. 9, 10 for buildings 18 and 48 meters tall, respectively.

A comparative analysis reveals that increasing building height leads to a slight decrease in temperature in the corner zone of the building envelope, from 32.07°C to 31.86°C. The relative temperature decrease is only 0.65%. Meanwhile, the temperature in the rest of the building envelope decreases, on average, from 30.3°C to 30.2°C (0.3%). This difference may be due to changes in the geometric conditions of heat transfer and the redistribution of heat flows in the spatial formulation of the problem, caused by the increase in the height of the computational domain and the corresponding change in the length of the external surfaces involved in heat exchange with the environment. In the absence of wind load and with identical boundary conditions for heat exchange, the influence of building height manifests itself primarily through the geometric factor and the spatial nature of heat transfer in the corner zone.

A temperature increase of slightly more than 5% is observed in the corner area.

Similar temperature field calculations were performed at an outside air temperature corresponding to the average July temperature (Fig. 11, 12). The modeling results show that increasing the building height from 18 to 48 meters has virtually no effect on the calculated temperature values, either in the corner zone of the building envelope or in the wall sections farthest from the corner. Only a slight increase in temperature is observed in the corner zone, not exceeding 1.5%.

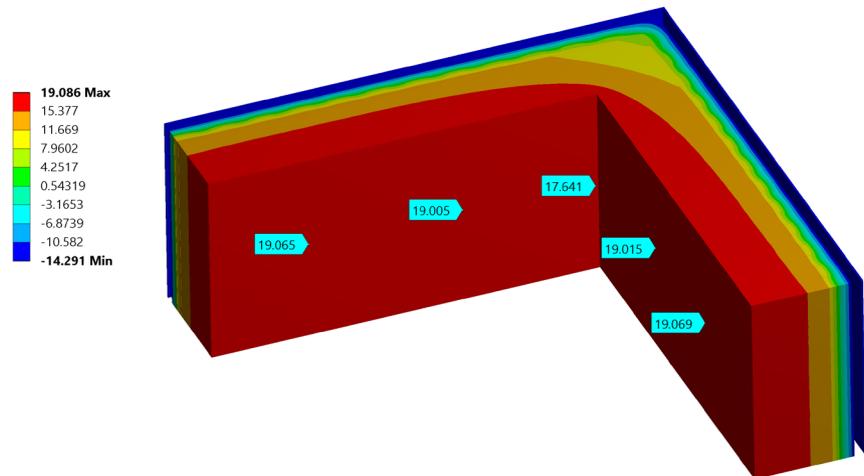


Fig. 7. Temperature field in the enclosure at an outside air temperature equal to the average temperature of the coldest five-day period with a probability of 0.92

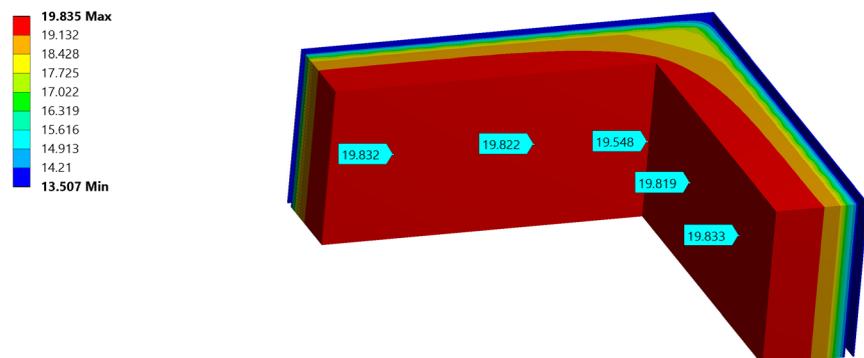


Fig. 8. Temperature field in the enclosure at an outside air temperature equal to the average April temperature

Analysis of our results reveals that, in the summer, taller buildings tend to have a more uniform temperature distribution within the building envelope. However, the magnitude of this effect remains insignificant and does not significantly affect the overall thermal conditions of the building envelope under the adopted boundary conditions.

Thus, the impact of changes in the building envelope geometry on the temperature conditions of the external walls is

examined. Fig. 6–12 show the temperature distributions within the building envelope under various external climatic conditions. Analysis of the results reveals that, in the corner zone, the temperature of the inner surface of the building envelope may differ from the temperature on the straight sections of the wall by 1–2°C, due to the spatial nature of heat transfer in the corner area. The observed unevenness in the temperature field is localized and rapidly attenuates with distance from the corner zone.

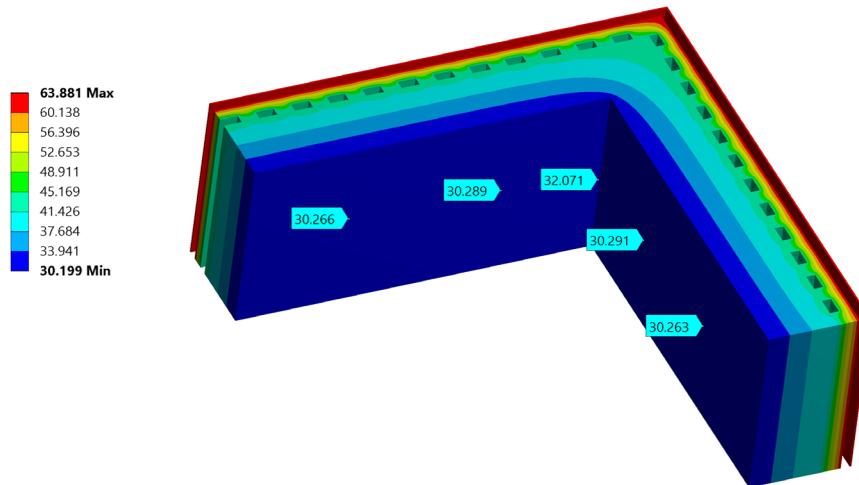


Fig. 9. Temperature field in the enclosure at the absolute maximum outside air temperature for a building 18 m high

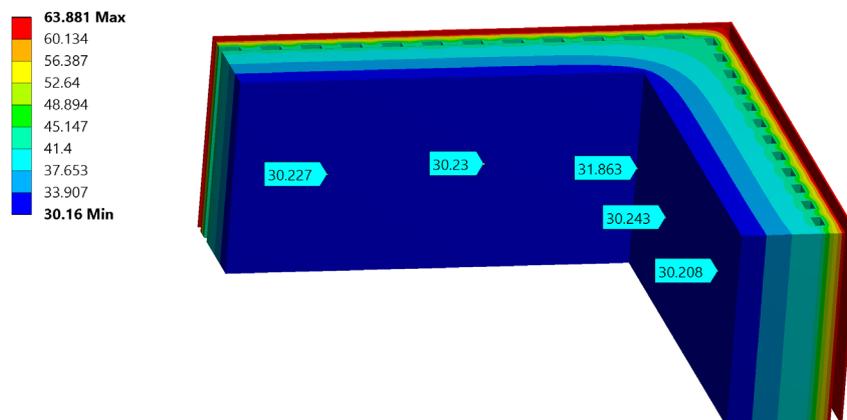


Fig. 10. Temperature field in the enclosure at the absolute maximum outside air temperature for a building 48 m high

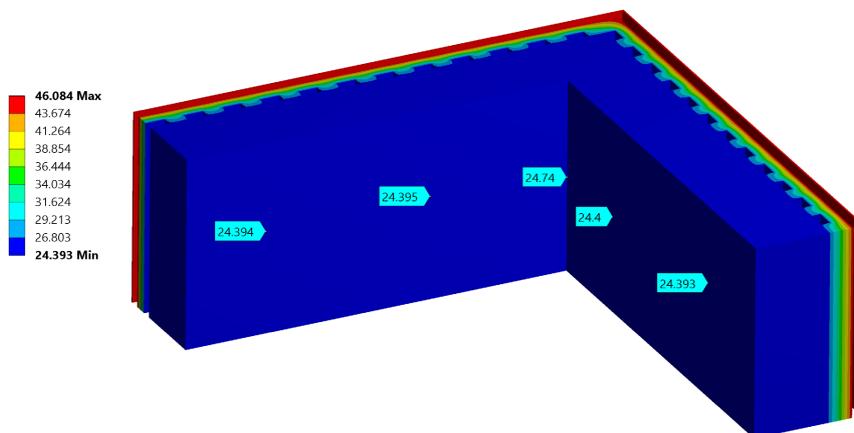


Fig. 11. Temperature field in the enclosure at an outside air temperature equal to the average July temperature for a building 18 m high

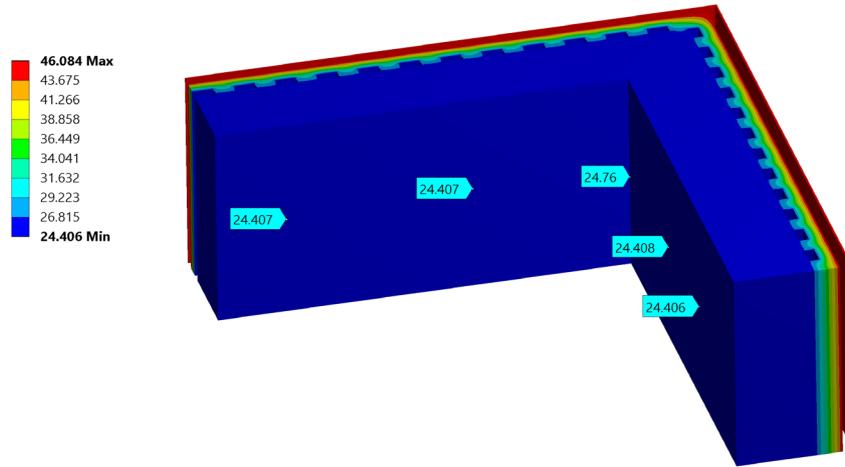


Fig. 12. Temperature field in the enclosure at an outside air temperature equal to the average July temperature for a building 48 m high

5. 2. Moisture analysis of the corner zone of a building using additional air ducts and a heat-reflecting screen

Based on the calculated temperature fields, an analysis of the building’s moisture regime was performed in the enclosing structure’s control sections, as shown in Fig. 5. The assessment was conducted for sections located opposite the air duct and opposite the continuous insulation zone, which allowed us to identify the influence of the building’s geometry and design features on moisture accumulation.

Fig. 13 shows the relationship between the difference in partial water vapor pressure and saturated vapor pressure ($E-e$) across the building’s enclosing structure’s thickness.

Positive values of this difference indicate the potential for water vapor condensation in the corresponding zones. The results show that during the cold season, condensation can form in both the cross-section with the air duct and the cross-section with continuous insulation; however, the quantitative and spatial characteristics of this process differ significantly.

The estimated amount of condensed water vapor during the cold season is approximately 13.5 g/year in the cross-section with the air duct and approximately 4 g/year in the cross-section with continuous insulation.

Moreover, the estimated drying time for the accumulated condensate does not exceed two days, indicating the absence of conditions for prolonged moisture accumulation and satisfactory moisture exchange within the structure as a whole.

At the same time, it was found that in the corner zone of the building, the position of the condensation zone in the cross-section with the air duct shifts compared to the enclosure sections located further from the corner. In this case, condensation occurs predominantly within the enclosed air duct, due to changes in the temperature field and a localized temperature drop in the corner area. This effect highlights the sensitivity of the humidity regime to the spatial geometry of the building envelope.

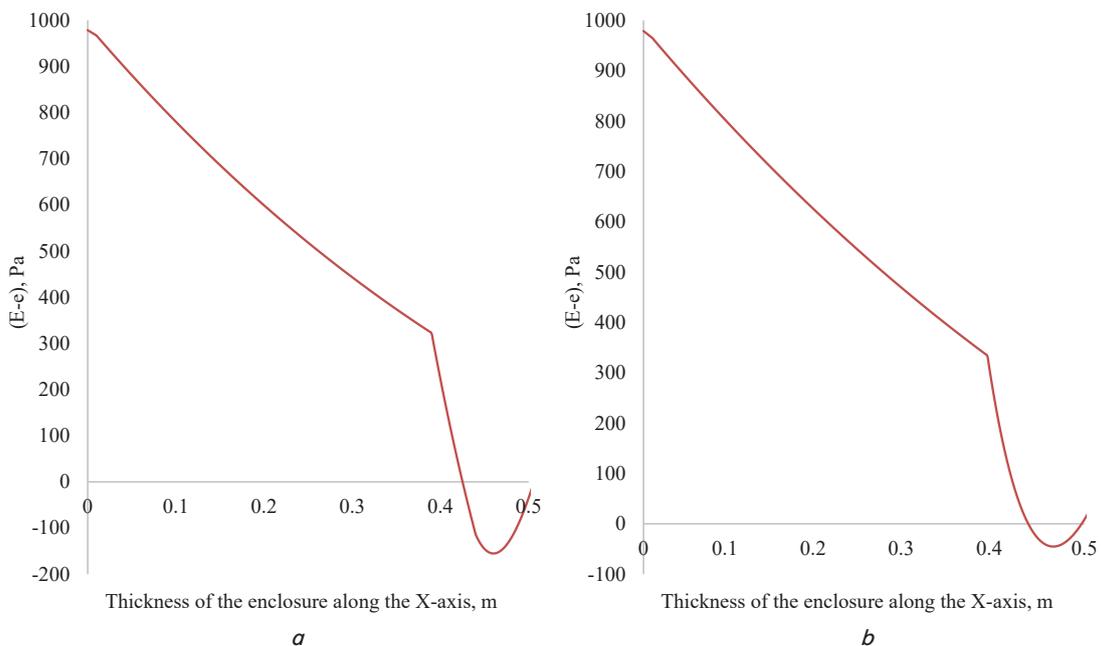


Fig. 13. Dependence of the difference in partial pressure of water vapor and saturated vapor pressure in the thickness of the enclosure, Pa: a – in the channel section; b – in the section of the solid insulation

From an engineering perspective, our results indicate the advisability of limiting the use of air ducts near the corner areas of external walls. In these areas, the use of a continuous layer of insulation is preferable, thereby reducing the risk of localized moisture accumulation and increasing the reliability of the building envelope under conditions of pronounced seasonal temperature gradients.

6. Discussion of results based on the study of a building's corner element using additional air ducts

The results of our study confirm the hypothesis that significant energy efficiency can be achieved by using additional air ducts and a heat-reflecting screen in corner elements. To assess the impact of the corner zone of the external wall on the thermal and humidity conditions of the building envelope, characteristic temperature control zones of the internal surface of the building envelope were identified in the calculation model (Fig. 5).

Simulation confirmed that building corner elements are most susceptible to heat loss and are among the most vulnerable areas of the external enclosure. Since the external surface area of the corner element exceeds the internal surface area, this leads to a 7–12% decrease in the internal surface temperature of the building envelope in the variable climate of Kazakhstan (Fig. 6–8). A comparative analysis reveals that increasing the building's height leads to a slight decrease in temperature in the corner zone of the building envelope, where the relative temperature decrease is only 0.65%. At the same time, the temperature in the rest of the building envelope decreases by an average of 0.3% (Fig. 9, 10). This difference may be due to changes in the geometric conditions of heat transfer and the redistribution of heat flows in the spatial formulation of the problem, caused by an increase in the height of the computational domain and a corresponding change in the length of the external surfaces involved in heat exchange with the environment.

Similar temperature field calculations were performed at an outside air temperature corresponding to the average July temperature (Fig. 11, 12). The modeling results show that increasing the building height from 18 to 48 m has virtually no effect on the calculated temperature values, either in the corner zone of the building envelope or in the wall sections remote from the corner. Only a slight increase in temperature is observed in the corner zone, the value of which does not exceed 1.5%.

Positive values of this difference indicate the potential for water vapor condensation in the corresponding zones. Our results demonstrate that, during the cold season, condensation can form both in sections with an air duct and in sections with continuous insulation; however, the quantitative and spatial characteristics of this process differ significantly. Moreover, the estimated drying time of the accumulated condensate does not exceed 2 days, indicating the absence of conditions for long-term moisture accumulation and indicating satisfactory moisture exchange in the structure as a whole (Fig. 13).

It should be noted that the numerical model is in satisfactory agreement with the fundamental provisions of the international standard governing the accuracy of calculating the temperature fields of the enclosure. Furthermore, a comparison of the results in our study agrees well with those reported in [30, 31], where the discrepancy was no more than 5%, indicating the adequacy of the selected calculation grid. The use of a heat-reflecting screen and humidity regime, as well as the effectiveness of this solution, are also confirmed in [32].

The proposed model could be used by the scientific and technical community in the design of buildings and the development of energy performance certificates, as regulated by national norms and standards. Our research results show that the application of these solutions also demonstrates a margin of operational reliability in extreme outdoor environments [33, 34], which might also be further expanded in the study of industrial structures.

A limitation of this study is that it did not take into account airflow turbulence in the air ducts and the interlayer caused by gusty winds, which may require certain adjustments. Furthermore, a drawback of the work is the durability of the heat-reflective surface, which requires long-term full-scale testing.

Future research could include studying transient conditions, taking into account various climatic loads, and considering thermal bridges in the form of various fastenings when analyzing the thermal and humidity conditions.

7. Conclusions

1. Due to their geometric features, corner elements of a building are particularly vulnerable, with temperature differences ranging from 7–12% relative to straight sections of the external enclosure. Temperature field calculations at the absolute maximum outdoor temperature are presented for buildings 18 and 48 m tall, respectively. A comparative analysis reveals that increasing building height leads to a 0.65% decrease in temperature in the corner zone. Meanwhile, the temperature in the rest of the enclosing structure decreases by an average of 0.3%. However, an increase in temperature of just over 5% is observed in the corner zone. Similar temperature field calculations were performed at an outdoor temperature corresponding to the average July temperature. The modeling results show that increasing building height from 18 to 48 m has virtually no effect on the calculated temperature values, either in the corner zone of the enclosing structure or in the wall sections remote from the corner. Only a slight increase in temperature is observed in the corner zone, the value of which does not exceed 1.5%. Analysis of our results reveals that taller buildings tend to have a more uniform temperature distribution within the building envelope during the summer. Thus, the results show that in the corner zone, the temperature of the inner surface of the envelope may differ from the temperature on the straight wall sections by 1–2°C, due to the spatial nature of heat transfer in the corner area.

2. Analysis of the humidity regime reveals the absence of conditions for prolonged moisture accumulation and indicates satisfactory moisture exchange within the structure as a whole. The estimated amount of condensed water vapor during the cold period is approximately 13.5 g/year in the cross-section containing the air duct, and approximately 4 g/year in the cross-section with a continuous insulation layer. The analysis revealed that moisture condenses in the air duct at a rate more than 3.3 times higher than in the insulation layer. Moreover, the estimated drying time for the accumulated condensate does not exceed two days, indicating the absence of conditions for prolonged moisture accumulation and satisfactory moisture exchange within the structure as a whole. However, it was found that in the corner area of the building, the position of the condensation zone in the cross-section with the air duct shifts compared to sections of the enclosure further from the corner.

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, as well as the results reported in this paper.

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Data availability

The manuscript has associated data in the data warehouse.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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Authors' contributions

Nurlan Zhangabay: Conceptualization, Methodology, Investigation, Data curation, Writing – original draft preparation, Writing – review and editing, Supervision, Project administration, Funding acquisition; **Ulzhan Ibraimova:** Conceptualization, Methodology, Writing – review and editing; **Timur Tursunkululy:** Writing – review and editing, Supervision; **Bolat Duissenbekov:** Conceptualization, Methodology, Writing – review and editing; **Bagdaulet Urmashiev:** Supervision, Methodology; **Akmaral Utelbayeva:** Supervision, Methodology; **Shugyla Shayakmet:** Writing – review and editing.

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