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Article

Assessment of thermal stability of external enclosing structures and justification of an effective structural solution

Nurlan Zhangabay[1], Sultan Bakhbergen[2,*], Arukhan Oner[3], Akmaral Utelbayeva[4], Ulzhan Ibraimova[2]

[1]Scientific Research Laboratory of Mechanical Engineering Problems, M. Auezov South Kazakhstan Research University, Shymkent, Republic of Kazakhstan
[2]Department of Architecture and Urban Planning, M. Auezov South Kazakhstan Research University, Shymkent, Republic of Kazakhstan
[3]Department of Building Materials and Technologies, Abylkas Saginov Karaganda Technical University, Karaganda, Republic of Kazakhstan
[4]Department of Chemistry, M. Auezov South Kazakhstan Research University, Shymkent, Republic of Kazakhstan
Correspondence: bahbergensultan@gmail.com

Abstract: This paper presents a study of the thermal stability of traditional external enclosing structures in hot climates, taking into account exposure to intense solar radiation. The objects of analysis are a wet facade and a mounted ventilated facade with an air space, widely used in the construction practice of the Republic of Kazakhstan. Calculations were performed for the climatic conditions of Shymkent city using a normative methodology to determine the amplitude of temperature fluctuations on the internal surface of the enclosure. It was found that, when exposed to extreme outdoor temperatures and solar radiation, the actual amplitude of temperature fluctuations exceeds the standard values, which leads to a decrease in thermal stability and an increase in heat gain into the premises. It is shown that the temperature of the external surface of the enclosures can reach 65-72°C, which significantly degrades the performance characteristics of traditional structures. Based on the conducted analysis, the use of the developed adaptive design of the external enclosure with an air space, ensuring increased energy efficiency and thermal stability, is justified. The simulation results showed that in winter, the internal surface temperature increases by 1.5-2.3°C, reducing heat loss by 12-18%. In summer, the external cladding temperature decreases by 3-5 °C, reducing heat gain by 8-14%. The results confirm the effectiveness of the proposed structural solution and can be used in the design of energy-efficient buildings in hot climates.
Keywords: building structure, thermal stability, hot climate, solar radiation, air space.

1. Introduction

Since ancient times, the outer case of a home has fascinated humanity, serving as the primary and most significant tool for protecting against the harsh climatic influences of the environment. Over the course of millennia, humans have evolved from the use of simple natural shelters and primitive structures to the construction of complex engineering systems that have become an integral foundation of modern civilization [1]. The outer case is one of the key elements responsible for significant heat loss, accounting for up to 35-40% of a building's total heat loss, as it occupies the bulk of the enclosure and forms the primary barrier to heat flow between the internal and external environments [2], [3], [4]. The evolution of external enclosing structures has been largely determined by the need to improve microclimate stability and reduce energy costs for their maintenance [5].

The issue of improving external wall enclosing structures has become particularly relevant and has attracted intense research at the international level in recent decades [6]. The development of highly efficient multilayer enclosing systems allows not only to expand the possibilities of developing various climatic zones (Figure 1), including regions with sharply continental and extreme conditions, but also to significantly reduce the anthropogenic load on the environment by reducing energy consumption [7].

a) Conventional wet facade of a high-rise building

b) Wall made of a three-layer panel

c) Wall made of a thermal panel

d) Ventilated facade

Figure 1 – Multilayer external enclosure systems [8]

Due to the significant diversity of natural and climatic conditions in different parts of the world, to ensure and sustainably maintain standard microclimate parameters in the internal premises of buildings, there is a need to develop and implement innovative structural and technological solutions aimed at adapting the building's outer case to the specific climatic realities of the area. Such solutions allow for temperature fluctuations, solar radiation levels, wind loads, and humidity conditions, and also help reduce inefficient energy consumption and prevent excess energy consumption during building operation. For example, the study [9] examined a wall structure with an integrated solar air collector and an additional intensively ventilated internal wall. The use of a dynamically adapted solution with two air layers made it possible to reduce heat loss through the enclosing structures by reducing thermal conductivity. The effectiveness of interlayer ventilation was further investigated in the study [10], where it was found that energy losses during air removal can be fully compensated for by an interlayer ventilation partition. In [11], an adaptive solution was proposed in the form of a solar dynamic buffer zone, which allows for the accumulation or removal of solar energy through air movement. As an adaptive solution for humidity control, [12] used internal air ducts in walls to dehumidify floor structures using heating cables in the air gaps. Similarly, the study [13] confirmed the energy-saving effectiveness of a solid air chamber in brick walls, revealing a close relationship between the temperature difference between inside and outside air and the air speed in the ventilation duct [8].

In countries with hot climates, one of the priority tasks is to reduce the load on air conditioning systems [14]. In this regard, [15] simulated various enclosing structure options with voids under the climatic conditions of Qatar. The results obtained showed an increase in the energy efficiency of buildings by approximately 12% and a reduction in CO_2 emissions by 4%. A significant contribution to the development of adaptive ventilated facades was made in [16], where a facade with a double air chamber and adjustable airflow was proposed. The results showed a 38% increase in system efficiency in summer and up to threefold energy savings in winter compared to traditional ventilated facades [17]. In [18], an innovative ventilated facade using exhaust air from rooms during the heating season was studied. Modeling showed that such a facade has higher energy savings compared to facades with closed air cavities. In general, to achieve zero-energy buildings, scientific research is considering various options for climate-adaptive opaque facades [19], where the temperature difference between a traditional wall and a solar facade module can reach 0.5-9°C depending on the season and time of day [8].

In recent years, perforated and channeled facade systems have attracted increasing interest. [20] demonstrated that the use of ventilated air ducts effectively removes moisture from insulation: even with a relative humidity of approximately 70%, the insulation moisture content did not exceed 50%, ensuring high thermal insulation properties and leading to significant energy savings [21]. Furthermore, temperature stratification by height of up to 8-10°C was recorded in the ventilation ducts. [22] also demonstrated that the use of dynamic thermal insulation in opaque ventilated facades increases heat removal efficiency by 2.1-2.6 times compared to traditional systems [8].

Considering the widespread popularity of ventilated facade systems (Figure 2), the development of innovative solutions based on ventilated facade systems with an air space for the territories of Kazakhstan is highly relevant and, due to the simplicity of the design, economically feasible. Moreover, the housing market in the Republic shows active growth in the construction of high-rise residential buildings, where the rate of residential buildings commissioned over the past 10 years has increased by more than 2.1 times (Figure 3).

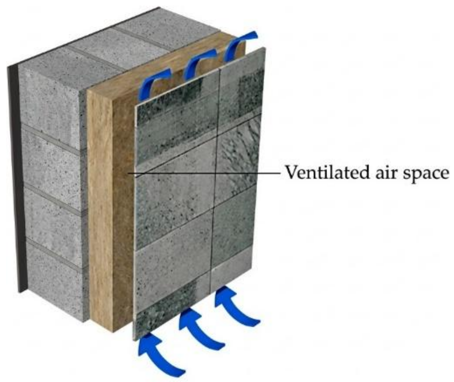


Figure 2 – Diagram of a traditional mounted ventilated facade [8]

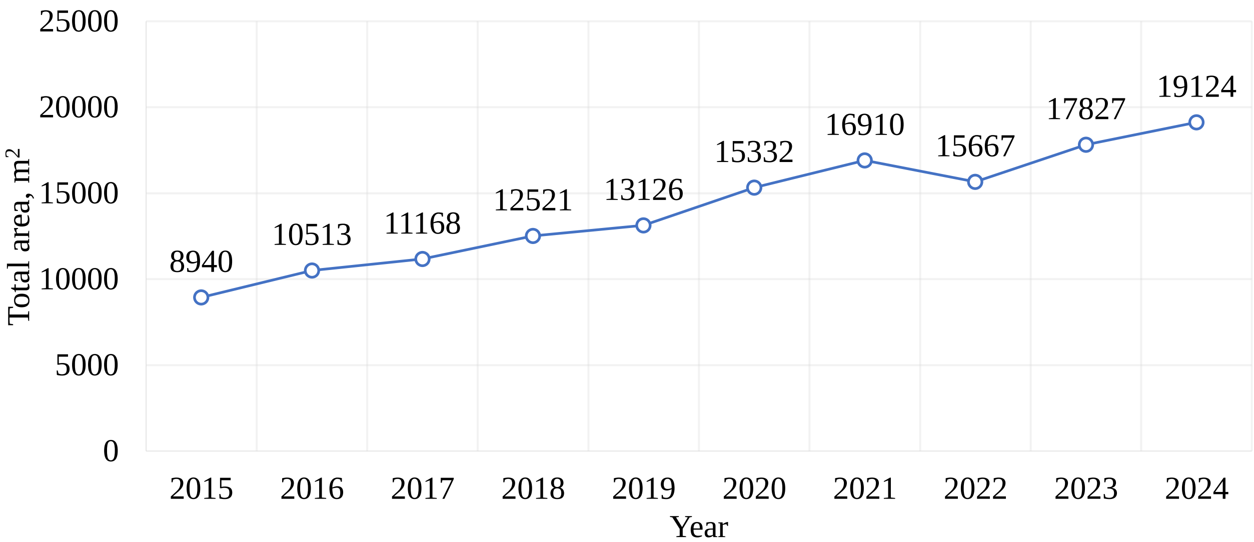


Figure 3 – Dynamics of the total area of residential buildings put into operation in Kazakhstan [8]

At the same time, the Republic of Kazakhstan's housing stock is characterized by a significant volume and a high degree of physical deterioration: there are more than 80,000 multi-apartment residential buildings in the country, of which approximately 18,000 require major repairs. Multi-apartment buildings account for approximately 70% of the total housing sector, which determines their key role in shaping the overall energy balance of residential development in the country. Given Kazakhstan's sharply continental climate, heating costs for buildings are the dominant item of operating expenses, reaching an average of approximately 65% of utility bills [23].

Therefore, within the framework of this study, it seems appropriate to focus on a comparative analysis of wet facade and traditional ventilated facade designs in terms of thermal stability during hot periods, as well as to explore the applicability of the newly developed structural solutions for reducing heat gain into premises during hot periods, taking into account the degree-day indicator of the heating season. The solution to this problem on a national scale is relevant for climatic zones IB, IIIA, IIIB, IVA, IVG on the territory of the Republic of Kazakhstan [24].

2. Methods

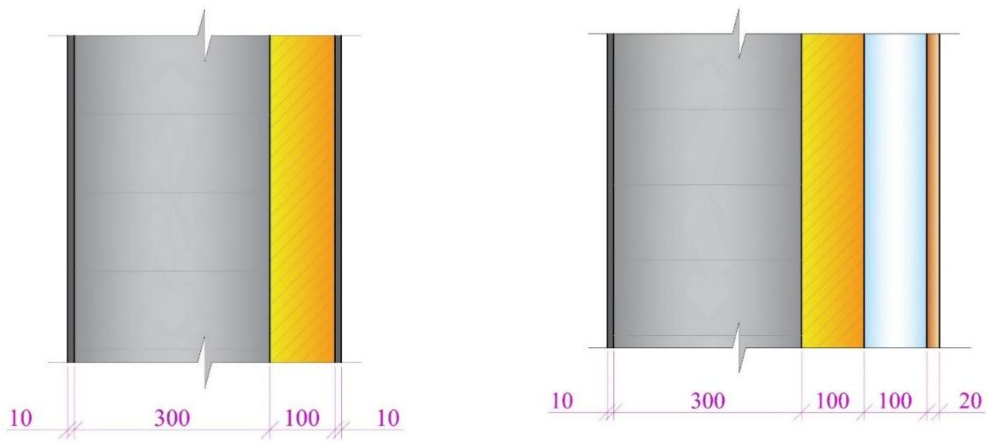
The thermal stability analysis of traditional building enclosures was conducted based on national regulations [25], and climatic parameters were adopted in accordance with [24]. Since Shymkent city is characterized by high outside temperatures and intense solar radiation in the summer, calculations were conducted for this specific area. Climatic values for the relatively hot period for Shymkent city are presented in Table 1.

Table 1 – Standard and extreme climatic parameters for Shymkent city [24]

Parameter	Standard values	Extreme values
t_{ext}	+26.4 °C	+65 °C
A_{tn}	+23.7 °C	+37 °C
I_{max}	758 W/m^2	900 W/m^2
I_{avg}	175 W/m^2	175 W/m^2
ρ	0.45	0.45
υ	1.3 m/s	1.3 m/s

Note: t_{ext} – average monthly outdoor air temperature in July, °C; A_{tn} – maximum daily amplitude of outdoor air temperature, °C; I_{max} and I_{avg} – maximum and average values of total solar radiation, W/m^2; ρ – solar radiation absorption coefficient of the outer surface; υ – wind speed, m/s.

In the thermal stability analysis, two types of structural solutions were considered as traditional external enclosure structures: a traditional wet facade (Figure 4a) and a traditional ventilated facade (Figure 4b).



a) Traditional wet facade (design 1) b) Traditional ventilated facade (design 2)

Figure 4 – Traditional designs of external building enclosing structures

The main geometric characteristics and thermophysical exponents of the external enclosures are presented in Tables 2 and 3.

Table 2 – Thermophysical characteristics of layers for the designs in Figure 4a

Layer material	Layer thickness, mm	Thermal conductivity coefficient λ, W/(m·°C)	Heat absorption coefficient S, W/(m·°C)	Thermal inertia D
Cement and sand mortar	10	0.76	9.6	0.126
Gas block	300	0.41	6.13	4.487
Mineral wool insulation	100	0.045	0.74	1.643
Cement and sand mortar	10	0.76	9.6	0.126

Table 3 – Thermophysical characteristics of layers for the designs in Figure 4b

Layer material	Layer thickness, mm	Thermal conductivity coefficient λ, W/(m·°C)	Heat absorption coefficient S, W/(m·°C)	Thermal inertia D
Cement and sand mortar	10	0.76	9.6	0.126
Gas block	300	0.41	6.13	4.487
Mineral wool insulation	100	0.045	0.74	1.643
Air space	100	-	-	-
Ceramic granite cladding	20	2.85	22.86	0.16

To adhere to the requirements for thermal protection in degree-days of the heating period, the composition of the multilayer structures presented in Tables 2 and 3 (Figure 4) was adopted based on the minimum value of the required heat transfer resistance, which, for Shymkent city, is 2.25 m^2·°C/W [25].

Next, to assess the thermal stability of the presented structures, let's use a calculation method based on determining the amplitude of temperature fluctuations on the internal wall surface under the influence of variable climatic factors [25].

The basic method for analyzing the thermal stability of building enclosures during hot periods is presented in Figure 5.

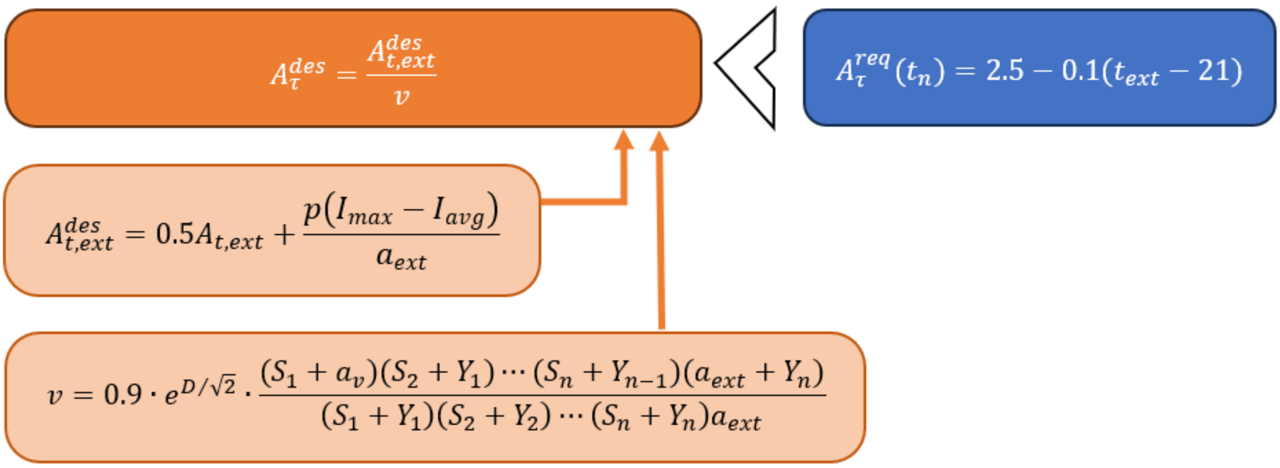


Figure 5 – Method for analyzing the thermal stability of building enclosing structures during hot periods [8], [25]

The thermal stability of the external enclosing structures during the hot period was assessed in accordance with [25]. The calculation procedure is schematically presented in Figure 5 and includes the following main steps and equations.

The standardized amplitude of temperature fluctuations of the internal surface of the enclosure is determined as:

$$A_\tau^{req}(t_n) = 2.5 - 0.1\,(t_{ext} - 21), \quad (1)$$

where: t_{ext} is the average monthly outdoor air temperature in July, °C.

The design amplitude of outdoor air temperature fluctuations, taking into account solar radiation, is calculated by the formula:

$$A_{t,ext}^{des} = 0.5A_{t,ext} + \frac{p(I_{max} - I_{avg})}{a_{ext}}, \quad (2)$$

where: $A_{t,ext}$ is the maximum daily amplitude of outdoor air temperature, °C; ρ is the solar radiation absorption coefficient of the outer surface; I_{max} and I_{avg} are the maximum and average values of total solar radiation, W/m^2; a_{ext} is the heat transfer coefficient of the outer surface, W/(m^2·°C).

The thermal inertia of the multilayer wall is determined as the sum of the thermal inertias of individual layers:

$$A_{t,ext}^{des} = \sum R_i S_i = \sum \left(\frac{\delta_i}{\lambda_i} \cdot S_i\right), \quad (3)$$

where: $R_i = \frac{\delta_i}{\lambda_i}$ is the thermal resistance of the *i*-th layer, m^2·°C/W; S_i is the heat absorption coefficient of the material of the *i*-th layer, W/(m^2·°C).

The attenuation coefficient of temperature fluctuations is calculated according to this equation:

$$v = 0.9 \cdot e^{D/\sqrt{2}} \cdot \frac{(S_1 + a_v)(S_2 + Y_1) \cdots (S_n + Y_{n-1})(a_{ext} + Y_n)}{(S_1 + Y_1)(S_2 + Y_2) \cdots (S_n + Y_n) a_{ext}}, \quad (4)$$

where: Y_i are the heat absorption coefficients of the outer surfaces of the layers; a_v is the heat transfer coefficient of the internal surface of the enclosure.

Finally, the actual amplitude of temperature fluctuations of the internal surface is determined as:

$$A_{\tau}^{des} = \frac{A_{t,ext}^{des}}{v}, \quad (5)$$

The thermal stability requirement is considered satisfied if $A_{\tau}^{des}(t_n) \leq A_{\tau}^{req}(t_n)$ according to [26].

The calculation method includes determining the following parameters [25]: Standardized amplitude of temperature fluctuations on the internal surface of the enclosure; Calculated amplitude of outside air temperature fluctuations; Thermal resistance of individual structural layers; Thermal inertia of a multilayer wall; Temperature fluctuation attenuation; Temperature amplitude of the internal surface of the enclosing structure.

3. Results and discussion

To verify compliance with the thermal protection requirements for the heating season, the total thermal resistance R_0 of the considered structures was calculated according to this equation:

$$R_0 = R_{int} + \sum R_i + R_{ext}, \quad (6)$$

where: $R_{int} = 1/a_{int}$ is the internal surface resistance, $R_{ext} = 1/a_{ext}$ is the external surface resistance, and $\sum R_i$ is the sum of the thermal resistances of the structural layers.

The calculation results are presented in Table 4.

Table 4 – Thermal resistance of the considered external enclosure designs

Design	$\sum R_i$ of layers, m^2·°C/W	R_{int}, m^2·°C/W	R_{ext}, m^2·°C/W	R_0, m^2·°C/W	Required minimum, m^2·°C/W
Design 1	2.98	0.115	0.043	3.14	2.25
Design 2	2.97	0.115	0.093	3.18	2.25

Both designs meet the minimum required heat transfer resistance of 2.25 m^2·°C/W established for Shymkent conditions, as specified in [25].

The results of the thermal stability analysis of the traditional building enclosing structure designs examined, as described in Section 2, are presented in the diagrams below. Figures 6 and 7 present the thermal stability analysis results for traditional wet and ventilated facades under various external solar exposures, taking into account the heating of the enclosure surface. The design’s thermal stability assessment was based on a comparison of the standardized amplitude of internal surface temperature fluctuations (A_τ^{req}) and the actual amplitude of internal surface temperature fluctuations (A_τ^{des}).

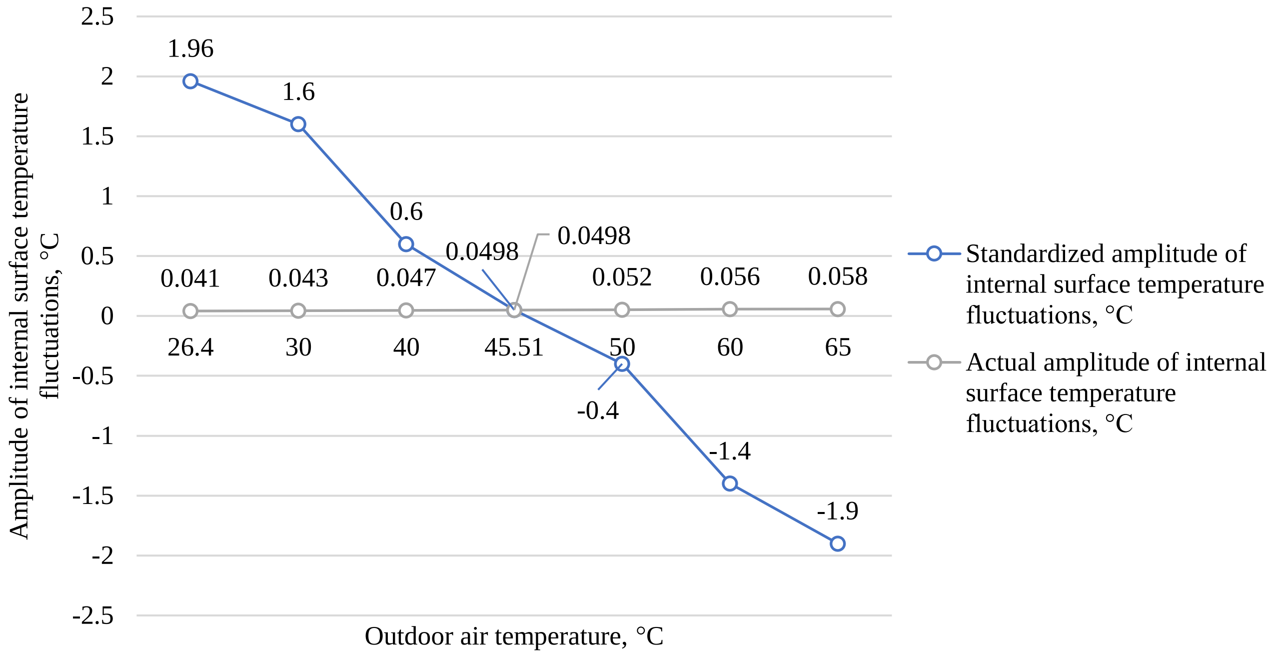


Figure 6 – Dependence of the standardized (A_τ^{req}) and actual (A_τ^{des}) amplitude of internal surface temperature fluctuations for the wet facade

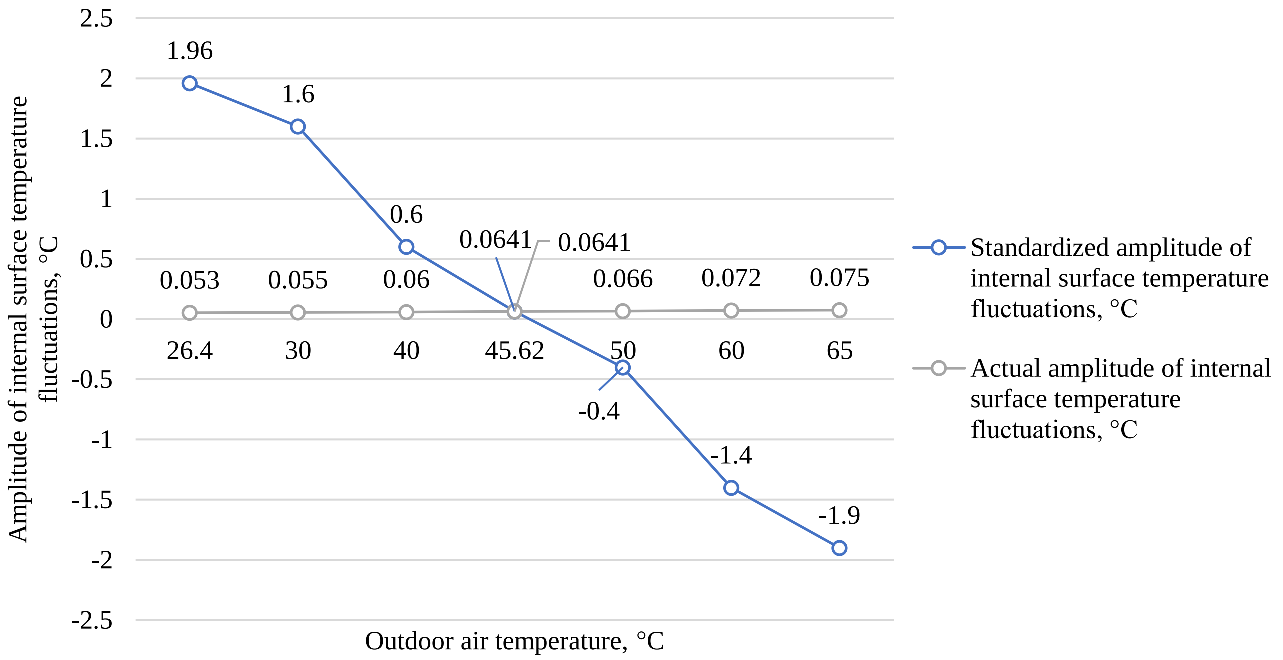


Figure 7 – Dependence of the standardized (A_τ^{req}) and actual (A_τ^{des}) amplitude of internal surface temperature fluctuations for the ventilated facade

The analysis revealed that the highest temperature fluctuations are observed for both the traditional wet facade and the traditional ventilated facade. The boundary values for the amplitude of temperature fluctuations on the internal surface of the building enclosure for the two designs are shown in Figure 8.

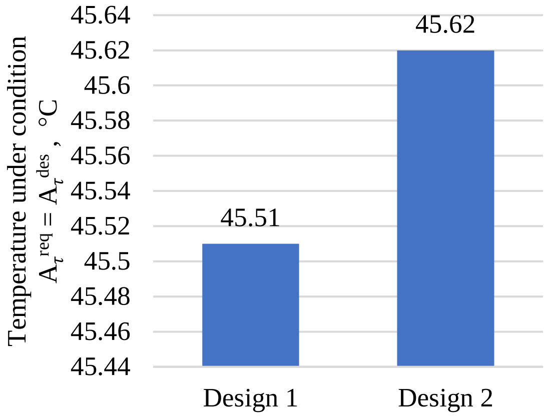


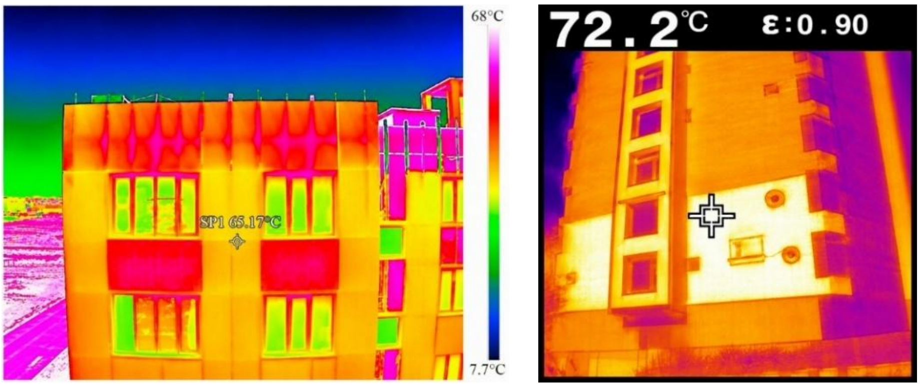
Figure 8 – Outside air temperature (t_{ext}) at which the actual amplitude of fluctuations in the temperature of the internal surface reaches the boundary value ($A_\tau^{req} = A_\tau^{des}$)

The boundary outdoor air temperature at which the actual amplitude of temperature fluctuations of the internal surface reaches the standardized value was determined by solving the equality:

$$A_\tau^{des}(t_n) = A_\tau^{req}(t_n), \quad (7)$$

where: $A_\tau^{req}(t_n) = 2.5 - 0.1\ (t_n - 21)$ according to [25], and A_τ^{des} is calculated as the ratio of the design outdoor temperature amplitude to the attenuation coefficient υ.

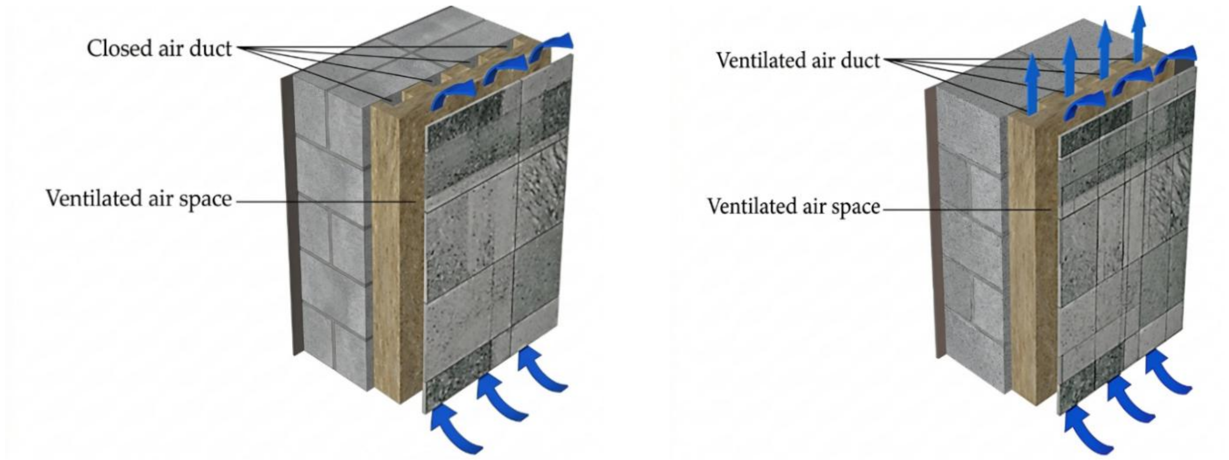
For the traditional ventilated facade (Design 2), this intersection occurs at t_n = 45.62°C (see Figure 8). This temperature represents the upper limit of outdoor air temperature under which the considered enclosure still satisfies the thermal stability requirements. When the outdoor temperature exceeds this value (which is typical for Shymkent during the hot period under intense solar radiation), the actual amplitude A_τ^{des} becomes higher than the standardized limit, indicating a decrease in the thermal stability of the structure. Analysis of Figure 8 shows that the boundary conditions corresponding to the regulatory conditions, taking into account the heating of the external enclosure surface of buildings in Shymkent city is equal to 45.62°C. However, the authors' full-scale experimental studies have established that, under the conditions of Southern Kazakhstan, the external enclosure surface can exceed 65°C due to the influence of intense solar radiation [8], [26], [27], which will lead to excessive heat gain into the room and energy consumption for cooling (Figure 9).



a) t = 65.17°C b) t = 72.2°C

Figure 9 – Thermograms of a building's external enclosure surface in Shymkent during summer [26], [27]: SP1 – marking of the fence surface point; ε – Radiation coefficient of the fence surface

The current situation requires the development of an additional structural solution that will simultaneously meet thermal protection requirements for the heating season's degree-day conditions and thermal stability in hot climates. Based on this objective, the authors developed an external enclosure design (Figure 10) that ensures compliance with both conditions [28], [29].



a) Wintertime b) Summertime

Figure 10 – Developed design of external enclosure based on a mounted facade system with an air space [8], [28], [29]

The results of the studies showed [8], [28], [29] that in winter, the proposed Design 3 (Figure 10) increases the temperature of the internal surface of the enclosure by 1.5-2.3 °C compared to the basic diagram, which leads to a decrease in the heat flow through the enclosure by 12-18%. In summer, the temperature of the external cladding in the adaptive diagram is lower by 3-5 °C, which reduces heat inflow into the room by 8-14% and reduces the load on the air conditioning.

Thus, the developed design of the external enclosure solves both problems (Figure 10): thermal protection and thermal stability, which can significantly optimize the boundary conditions corresponding to the regulatory conditions, taking into account the heating of the external enclosure surface, that is, the ratio of the standardized (A_τ^{req}) and actual (A_τ^{des}) amplitude of fluctuations in the temperature of the internal surface [25].

4. Conclusions

This paper examines the thermal stability of traditional external enclosing structures, taking into account the climatic conditions of a hot region and exposure to intense solar radiation. It was found that for both wet facades and ventilated facades, extreme temperature fluctuations on the internal surface exceed permissible values, indicating insufficient thermal stability of these structures during the summer.

It was shown that the actual temperature of the enclosure’s external surface can reach 65-72°C, significantly exceeding regulatory limits and leading to increased heat gains in the premises and higher energy costs for air conditioning.

Based on the analysis, the use of the developed adaptive air-space external enclosure design, which provides improved thermal performance, was justified. It was established that the proposed solution increases the internal surface temperature in winter by 1.5-2.3°C and reduces heat loss by 12-18%, while in summer it reduces the external cladding temperature by 3-5°C and reduces heat gain by 8-14%. Thus, the proposed design simultaneously meets thermal protection and thermal stability requirements, making it promising for use in energy-efficient construction in hot climates.

Prospects for further research include experimental validation of the proposed model, consideration of non-stationary aerodynamic processes in the airspace, and optimization of the facade system’s structural parameters.

Acknowledgments

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Information about the authors:

Nurlan Zhangabay – PhD, Associate Professor, Scientific Research Laboratory of Mechanical Engineering Problems, M. Auezov South Kazakhstan Research University, Shymkent, Republic of Kazakhstan, nurlan.zhanabay777@mail.ru

Sultan Bakhbergen – MSc, Department of Architecture and Urban Planning, M. Auezov South Kazakhstan Research University, Shymkent, Republic of Kazakhstan, bahbergensultan@gmail.com

Arukhan Oner – PhD Student, Department of Building Materials and Technologies, Abylkas Saginov Karaganda Technical University, Karaganda, Republic of Kazakhstan, arukhanoner@mail.ru

Akmaral Utelbayeva – Doctor of Chemistry, Associate Professor, Department of Chemistry, M. Auezov South Kazakhstan Research University, Shymkent, Republic of Kazakhstan, mako_01-777@mail.ru

Ulzhan Ibraimova – PhD, Department of Architecture and Urban Planning, M. Auezov South Kazakhstan Research University, Shymkent, Republic of Kazakhstan, ibraimova_uljan@mail.ru

Author Contributions:

Nurlan Zhangabay – concept, methodology, interpretation.
Sultan Bakhbergen – data collection, testing, modeling.
Arukhan Oner – editing, funding acquisition.
Akmaral Utelbayeva – analysis, visualization.
Ulzhan Ibraimova – resources, drafting.

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