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Review

Energy-Efficient Outdoor Fencing with Air Layers: A Review of the Effect of Solar Radiation on the Exterior Fencing of Buildings Made of Composite Material

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Abstract: In this study, the authors conducted a comprehensive review of the scientific and technical literature in the field of heat transfer in outdoor enclosures with an air layer of composite material, reviewing the effect of solar radiation on these areas. The review of the problem was carried out both at the national scale in the Republic of Kazakhstan and at the international level. It was found that an impressive number of scientists are involved in this topic, which is confirmed by the recent reviews, which analyzed more than 2700 relevant scientific and technical reports. The authors also reviewed the chronology of the development of hinged facade systems made of composite material on an international scale. Following the comprehensive review, a critical analysis was carried out on the most appropriate works, where a number of contradictions and discrepancies in the results were found. Taking into account these circumstances, the authors proposed to investigate the effects of climatic parameters considering barometric pressure. Using the regularity of the ideal gas equation, the dependences on the change in the volume of gas (air) when exposed to temperature loads and the influence of barometric pressure were determined. The results obtained will elucidate future research directions and can be taken into account in further studies of outdoor fences with an air layer considering solar radiation and territorial terrain.

Keywords: air layer; composite material; outdoor fencing; solar radiation; airflow; energy efficiency

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1. Introduction

The outer shell of housing has been of great interest to humankind since ancient times. The reliability of this structure ensures that inhabitants feel safe from various natural phenomena. The shells of buildings have changed quite dramatically as humankind has developed, from ordinary natural mountain stones [1], clay blocks [2], and wooden beams [3,4] to innovative modern claddings [5–7]. The problems related to the rapid development of the external shells of buildings have been particularly acute in recent decades at the international level in the study of traditional [8–10] and modern structures [11–13].

Scientists and builders use various types of cladding designs depending on the climatic features of the area. The main criteria for adopting a cladding design, for example, in climatic zones with cold temperatures [14], are the thickness of the structure and the efficiency of the insulation, which simplifies the problem of thermal protection. However, in climatic regions with a hot or mixed climate with moderate winters and hot summers [15], cladding design requires a special approach and a constructive solution [16]. Such constructive solutions include facades with a ventilated interlayer, which have shown their effectiveness throughout their development in different climatic conditions, gaining great popularity throughout the world [17,18]. Despite its relatively high cost [19], this design has the advantage of good thermal insulation properties and an aesthetically pleasing architectural appearance [20]. As studies of facade systems have shown, a ventilated interlayer can lead to significant energy savings depending on its design parameters and the characteristics of the thermal insulation material, regardless of climatic conditions. However, in the current design of any type of facade in the summer in characteristic (temperate winter and hot summer) climatic zones, due to the influence of solar radiation, rooms are prone to overheating. This destabilizes their microclimate, creating uncomfortable conditions for humans and subsequently leading to energy overspending. Unfortunately, this problem is also applicable to facades with a ventilated layer since the facade cladding overheats under the influence of solar radiation, which has a direct effect on the thermophysical processes occurring in the air layer and in the structural layer of the fence. The problem is aggravated by the fact that the effect of solar radiation is exponentially increased with the increase in the height of the building. This problem leads to the occurrence of different heat exchange processes at different levels of the building in the structure of the outer fence, which is not taken into account in the calculations. Additionally, I would like to note that this effect is also not considered in national standards since the design of the exterior fence of buildings is mainly calculated based on cold climatic parameters, which are based on the indicators of the degree–day heating period. This approach mainly takes into account the thermal protection of buildings, and thermal stability remains an unresolved issue, which in summer leads to problems such as the overheating of premises. Additional research is required given the high relevance of the use of ventilated facades as well as the described problem of studying the issue of overheating of rooms due to the influence of solar radiation on the facades of buildings with a ventilated layer. At the same time, according to previous studies, the issue of the influence of barometric pressure on the air velocity in the interlayer remains unresolved and may also have a significant effect on heat exchange in the enclosure when taking overheating into account. Considering this gap, the results of the conducted research will contribute to the correct assessment of the thermophysical processes occurring in the air layer of a ventilated facade.

2. A Literary Review and Justification for Conducting Research

2.1. Methodology of the Literature Review

Considering that the ventilated facade in its various manifestations has been the main optimal enclosure of buildings for several decades to the present, an extensive historical review of these structures was conducted in this study. It was found in this study that an impressive number of scientists are engaged in this topic, which is confirmed by modern reviews and studies (Tables 1 and 2), with 16 reviews presented over the past three years, in which more than 2700 scientific and technical works on the relevant literature were analyzed. At the same time, the authors present a detailed history of the development of hinged facade systems on an international scale since 1996, which covers 64 sources. In total, 105 relevant sources were considered in this review, which was carried out using modern national and international scientometrics databases and for which a methodology

for selecting the most appropriate systems was developed; see the methodology of the review in Figure 1 [21].

Table 1. The most important studies indicating the effectiveness of facade systems.

No.	Type/Period of Study	Climatic Conditions	Description of the Study	Efficiency of Using Ventilated Facades
[22]	Theory/ 1996	Summer	A comparison was made between the air gap thickness and its efficiency.	Increasing the air channels' thickness leads to energy recovery.
[23]	Theory/ 2002	Winter–summer	The effects caused by different air drain widths were investigated.	Comparisons showed that in summer, a noticeable solar cooling effect can be achieved when the air cavity width exceeds 7 cm. When the cavities expand, the cooling effect becomes stable. In winter, the thermal insulation provided by a closed ventilated facade is very important.
[24]	Experiment/ 2002	Summer	The time- and locally averaged overall heat transfer coefficients for turbulent mixed convective flows enhanced by solar radiation in transparent vertical channels were determined.	The average Nusselt numbers were obtained as a function of the average Archimedes number for several distances between gaps.
[25]	Theory/ 2003	Summer	A simple analytical method for calculating the energy savings achievable through the use of ventilated facades was considered.	It was established that the energy characteristics of such facades are greatly influenced by the air tube width.
[26]	Theory/ 2003	Winter–summer	The heating and cooling loads of the building with and without such a ventilated facade were calculated, and the impact of climate change on the performance of the buildings was investigated.	It was found that with the photovoltaic facade, the cooling load was marginally higher in all the rooms examined, while the facade effect on the heating load was highly dependent on the location.
[27]	Experiment/ 2004	Summer	The effectiveness of natural daytime ventilation was considered.	Wind speed and direction values were obtained.
[28]	Experiment/ 2004	Winter–summer	The wall element considered was a combination of a dynamic thermal insulation panel and a ventilated facade.	Results were obtained from tests carried out in a connected wall component under various pressure drop and air temperature conditions.
[29]	Experiment/ 2005	Summer	A comparison of heat loss of office buildings with single-layer and double-layer facades was carried out.	It was concluded that thermal energy consumption in double-skinned buildings is significantly reduced in winter conditions.
[30]	Theory/ 2005	Summer	The influence of plant-shaped facades on the thermal characteristics of the building was assessed.	It was established that plants can help create a comfortable indoor climate and save energy.
[31]	Experiment/ 2006	Summer	A comparison was made between two types of roofs, with and without a ventilated layer, and the air gap height parameter was taken into account.	It was established that the efficiency of a roof with a ventilated layer is significantly better.
[32]	Experiment/ 2006	Winter–summer	A wall with an integrated solar air collector and a highly ventilated inner wall was studied.	The accumulation of solar energy reduced the need for heat in winter and improved thermal comfort in summer due to air ventilation.

Table 1. *Cont.*

No.	Type/Period of Study	Climatic Conditions	Description of the Study	Efficiency of Using Ventilated Facades
[33]	Theory/ 2007	Winter–summer	The issue of a waterproofing membrane for hinged wall systems was studied.	The technical characteristics and basic requirements for materials of this class were presented.
[34]	Experiment/ 2007	Summer	A two-layer facade was investigated.	The results of the most effective orientation in the specified climatic conditions were presented.
[35]	Theory/ 2008	Summer	A zonal approach for modeling currents of air and temperature in ventilated facades was investigated.	It was found that the temperature difference between the inlet and outlet increased with the increase in altitude but decreased with the increase in air speed.
[36]	Theory/ 2008	Summer	Various thermal comfort parameters were investigated for different configurations of double facades.	It was found that significant energy savings can be achieved by using natural ventilation with a double-layer facade.
[37]	Theory/ 2009	Summer	To obtain detailed characteristics of the ventilated double-layer facade, a simulation of an office building was carried out.	It was proven that careful facade design can play an important role in buildings with high levels of glazing and provide potential for improved energy efficiency.
[38]	Experiment/ 2009	Summer	The energy efficiency of a double-skinned office building facade under Hong Kong climate conditions was investigated.	It was established that the two-layer facade system provides annual energy savings for cooling the building of approximately 26% compared to a conventional single-layer facade.
[39]	Review/ 2010	Winter–summer	The existing basic methods for studying the thermal characteristics of ventilated facade systems were described.	The possibility of applying hinged facades as an effective way to solve the problem of sustainable building design in China was proposed for commercial buildings in hot summer and cold winter areas.
[40]	Theory/ 2010	Winter–summer	The thermal characteristics of three different types of ventilated facades were investigated.	An analytical method for selecting the most suitable ventilated facades in the case of forced and natural convection was proposed.
[41]	Theory/ 2011	Summer	The phenomena occurring in a ventilated facade with an open joint and a sealed air cavity were investigated.	It was established that ventilated facades with open joints can help achieve significant energy savings in climates with hot summers and mild winters.
[42]	Experiment/ 2011	Winter–summer	The study was carried out on walls with different air drain heights (6 m and 12 m) with controlled indoor air temperature, where air movement speed was monitored.	It was found that on sunny days, the temperature of the outer surface, the temperature in the air cavity and the air speed in the gap were significantly higher for a 12 m wall.
[43]	Theory/ 2012	Winter–summer	The dependence of energy costs for maintaining a standardized thermal regime inside buildings on the effect of solar radiation and heat losses of claddings with ventilated layers was investigated.	An optimal temperature regime for the moving current of air was established, ensuring a reduction in heat loss from claddings.

Table 1. *Cont.*

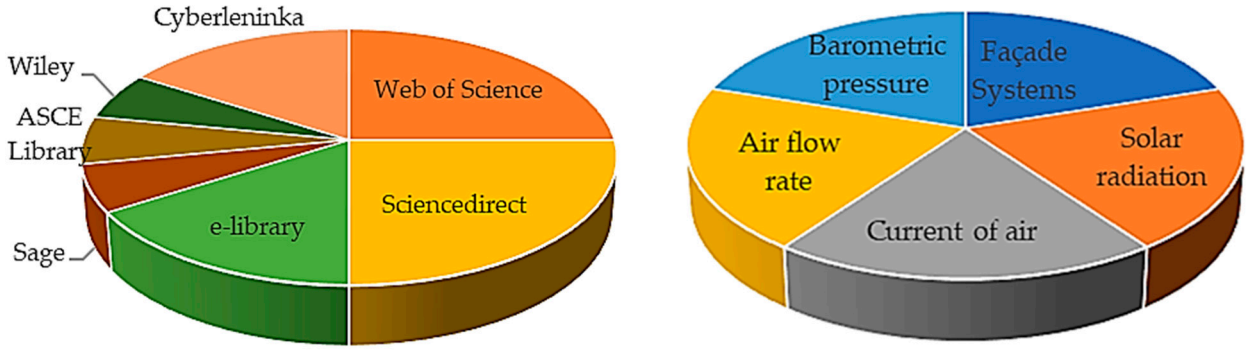
No.	Type/Period of Study	Climatic Conditions	Description of the Study	Efficiency of Using Ventilated Facades
[44]	Theory/ 2012	Winter–summer	An innovative approach to DSF analysis taking into account energy consumption was investigated.	A method of analytical solution was obtained considering the speed and temperature associated with the geometry of the facades and the distance between them.
[45]	Experiment/ 2013	Winter–summer	The use of heat-retaining materials in ventilated facade systems was investigated.	It was established that the efficiency of using phase transition material in ventilated facades was improved by 10–12% compared to traditional ones.
[46]	Experiment/ 2013	Summer	The tested laboratory model of the facade was a panel structure 0.825 m high and 0.3 m wide, consisting of four panels and five corresponding horizontal joints 5 mm in thickness. The air cavity was 40 mm wide.	The results showed that an upward flow with the same flow pattern was created inside the air cavity, regardless of the solar radiation falling on the facade.
[47]	Experiment/ 2014	Winter–summer	A new thermal insulation system for facades of newly constructed and reconstructed buildings based on thermal insulation panels with ventilated channels was investigated.	It was established that the considered configuration of ventilated channels is capable of providing low moisture content and good thermal insulation properties of walls.
[48]	Experiment/ 2014	Winter–summer	Loam brick used for external cladding of ventilated facades was investigated.	It was established that in order to improve thermal insulation properties, it is not recommended to increase the pores, as this leads to the destruction of the system.
[49]	Review/ 2015	Winter–summer	Several types of facade systems were considered: traditional facade, plaster-insulated facade, and ventilated facade.	The advantages of each facade were identified and compared.
[50]	Review/ 2015	Winter–summer	A type of design for a hinged wall system was investigated.	The design diagram and its advantages were presented, and the factors influencing the moisture removal from the air gap of the facade were investigated.
[51]	Theory/ 2016	Summer	The thermal behavior of a nontransparent facade with natural ventilation on summer days was studied, taking into account wind conditions.	It was established that the ventilated facade reduces peak loads and provides energy savings in the range of 47% to 51% depending on the climate.
[52]	Theory/ 2016	Winter–summer	The efficiency of using non-ventilated facades with air gaps for thermal insulation in hot climates was investigated.	It was established that facades with air gaps as thermal insulation may be more effective in areas where the heating season is longer than the cooling season.
[53]	Review/ 2017	Winter–summer	Regulatory documents defining the criteria for the applicability of hinged wall systems were reviewed.	The criteria for the applicability of ventilated hinged walls were obtained.
[54]	Experiment/ 2017	Winter–summer	An experimental module of a nontransparent ventilated facade was investigated at full scale.	The results showed a 58% reduction in heat load. Experimental measurements were used to calibrate the simulation results.

Table 1. *Cont.*

No.	Type/Period of Study	Climatic Conditions	Description of the Study	Efficiency of Using Ventilated Facades
[55]	Experiment/ 2018	Summer	The solar radiation effect on a naturally ventilated facade was investigated.	It was established that a facade with natural ventilation helps to reduce the temperature inside the layer since it suppresses direct solar radiation.
[56]	Review/ 2018	Winter–summer	Two types of facades were studied: wet and ventilated.	Positive and negative criteria for each type of facade were shown.
[57]	Experiment/ 2019	Summer	The energy benefits of nontransparent ventilated facades compared to lining facades in multi-story residential buildings located in nine Brazilian climate zones according to the Köppen–Geiger classification were investigated.	This study found that ventilated facades improve the passive cooling performance of a building compared to lining facades, delivering energy savings of up to 43% per year in the hottest cities.
[58]	Experiment/ 2019	Winter–summer	The performance characteristics of a secondary school building renovated using prefabricated ventilated facade elements were investigated.	It was found that changing the cladding to hinged wall systems had a positive effect on the internal microclimate of the school.
[59]	Experiment/ 2020	Winter–summer	The influence of ventilated channels of facade panels on the state of moisture thermal insulation was studied.	It was established that even with indoor air humidity of 70%, the relative air humidity in the insulation material did not exceed 50%, which ensured good thermal insulation properties of the panels.
[60]	Experiment/ 2020	Winter–summer	A comparison of the thermal characteristics of a nontransparent ventilated facade and a conventional non-ventilated facade was carried out taking into account two control days for the winter and summer periods.	The results of this study showed that the ventilated facade guarantees energy savings in the range of 20 to 55%, with the highest figure observed on a summer day in eastern and western orientations.
[61]	Theory/ 2021	Winter–summer	A numerical study of the heat and humidity state of a brick wall of a building, insulated with panels with ventilated channels, in a long-term operating cycle was conducted.	It was found that two characteristic peaks of relative moisture content were observed in the panel insulation material. One of them corresponded to the end of summer–beginning of autumn, and the second peak corresponded to the winter–beginning of spring.
[62]	Experiment/ 2021	Winter–summer	A comparison was made between the thermal characteristics of a ventilated facade and a conventional wall and a wall with vacuum-insulated panels.	It was established that the proposed system has good inertial properties and causes a temperature drop of more than 10 °C during the sunniest hours in summer.
[63]	Experiment/ 2022	Winter–summer	The ventilated facade was studied taking into account different climatic conditions.	It was found that the efficiency of using a ventilated facade was up to 81%. However, it was also shown that solar radiation has a significant impact.
[64]	Experiment/ 2022	Winter–summer	The influence of design parameters on thermal conductivity was studied, such as the internal wall and design features of the facade, including the coefficient of joint opening, the color of the external cladding, and the width of the air gap.	Optimal design configurations for summer and winter use were proposed, which made it possible to reduce energy consumption by 11.4% and 6.5% compared to a conventional facade, respectively.

Table 1. *Cont.*

No.	Type/Period of Study	Climatic Conditions	Description of the Study	Efficiency of Using Ventilated Facades
[65]	Theory/2023	Winter–summer	The current of air through a 1 m-wide and 13.7 m-high facade with a ventilated gap and its influence on the year-round thermal balance of this facade were investigated.	It was established that controlling the current of air through a ventilated gap in winter and especially during the transitional period of the year reduces the heat flow by an average of 25–30% and, on the contrary, increases heat transfer by 20%.
[66]	Theory/2023	Winter–summer	The use of phase transition material in ventilated facades was investigated.	It was established that the use of phase transition material further increases the efficiency of ventilated facades.
[67]	Theory/2024	Summer	A parametric energy analysis of the design parameters of a ventilated facade with window openings was carried out.	It was established that a ventilated facade significantly reduces heat flow by up to 32%.
[68]	Theory/2024	Winter–summer	The application of dynamic insulation in ventilated facades, where ambient air can penetrate beyond the insulation layer, was studied, which resulted in a reduction in the thermal load on enclosing structures during hot (daytime) times.	It was established that the efficiency of heat dissipation was 2.1–2.6 times higher than that of conventional ventilated facades.



(**a**) (**b**)

Figure 1. Methodology of the review: (**a**) scientometrics sources; (**b**) keywords.

Table 2. List of modern review studies on the solar radiation effect on the building envelope.

No.	Year of Study	Construction Element	Description of the Study	Number of References	Type of Study
[7]	2023	Double facade	Effect of solar heating on the facade	136	Review
[69]	2022	Thermal and hydrodynamic characteristics for different geometric parameters	Effect of solar heating on the facade	257	Review
[70]	2023	Phase transition materials in facades	Effect of solar heating on the facade	161	Review
[71]	2023	Measures to reduce overheating of buildings	The impact of solar heating on buildings in urban environments	327	Review

Table 2. *Cont.*

No.	Year of Study	Construction Element	Description of the Study	Number of References	Type of Study
[72]	2023	Shape and orientation of buildings	Effect of solar heating on the facade	168	Review
[73]	2023	Building cooling measures	Effect of solar heating of a building	137	Review
[8]	2024	Double facade	Effect of solar heating on the facade	95	Review
[10]	2024	Double facade	Effect of solar heating on the facade	135	Review
[74]	2024	Self-shading facade	Effect of solar heating on the facade	234	Review
[75]	2024	Dynamic facade	Effect of solar heating on the facade	143	Review
[76]	2024	Passive photovoltaic systems on facades	Effect of solar heating on the facade	114	Review
[77]	2024	Photovoltaic enclosure systems	Effect of solar heating on the facade	248	Review
[78]	2024	Passive cooling with phase change material	Effect of solar heating on the facade	225	Review
[79]	2024	Cold roof system for cooling a room	Effect of solar heating on the facade	124	Review
[80]	2024	Dynamic facade	Effect of solar heating on the facade	165	Review
[81]	2024	Thermal characteristics of facades	Effect of solar heating on the facade	96	Review

The relevance of each research area is emphasized by the word cloud, which was compiled based on the research keywords in the field of ventilated facades; see Figure 2.

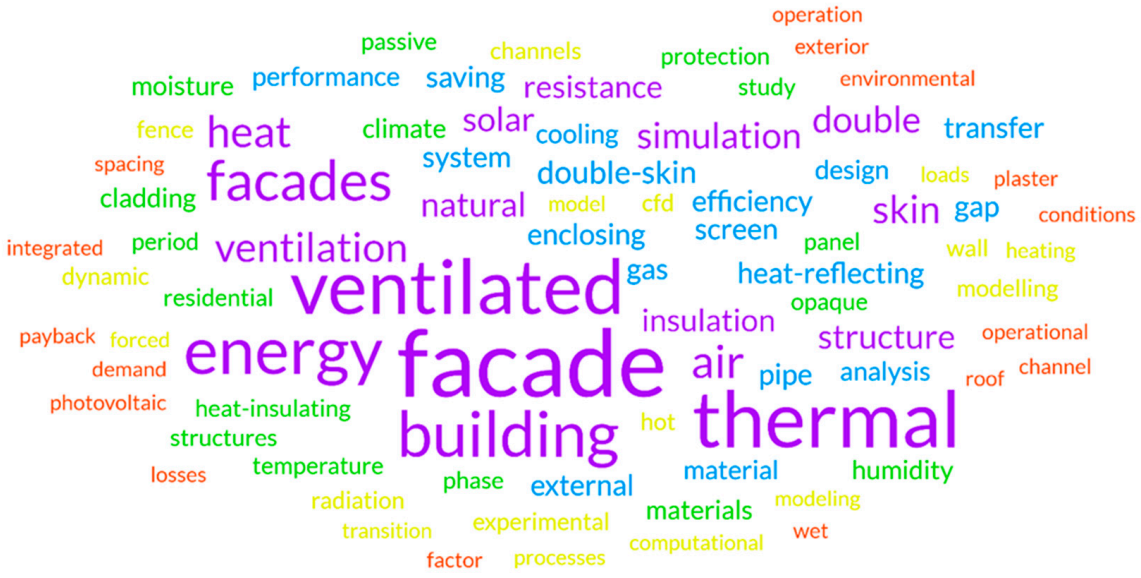


Figure 2. Word cloud depicting keywords.

An analysis of the scientometrics databases presented in Figure 1 showed that since 1996, the number of studies in the field of ventilated facades published in well-known international scientific journals has increased by more than 30-fold; see Figure 3.

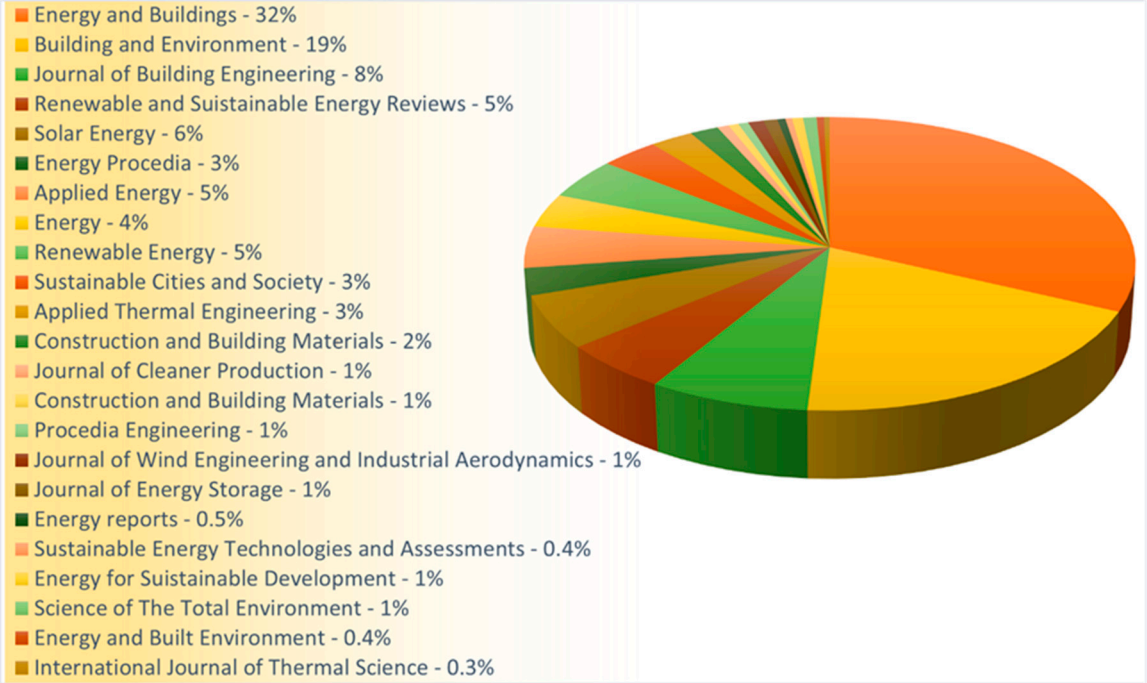


Figure 3. Pie chart of scientific journals in the field of adaptive dynamic facades.

2.2. Research Analysis

This study reviewed the literature on the influence of a climatic parameter, such as solar radiation, on thermophysical processes occurring in air layers. At the same time, the chronology of the studies conducted on outdoor fences with air layers, mainly in hot climates, over the past three decades was analyzed. A critical analysis of the most important studies was conducted, as presented in Tables 1 and 2.

The conducted review of works shows that the problem of overheating of the building envelope due to the solar radiation effect has been actively studied in recent years. The considered reviews provide a sufficient number of references (Table 2), and from the reviews it is possible to note the following scientifically similar studies: Balocco C. [23] considered the issue of the influence of the ambient temperature on the current of air, determining the most effective width of the air channel as 7 cm in the summer. The issue of the influence of solar radiation on the flow rate was not considered. Zöllner Z. et al. [24] in their work additionally studied turbulent flows in layers with a width of 0.3, 0.6, and 0.9 m in order to determine the most effective heat transfer coefficient, taking into account solar heating of the air. Ciampi, M. et al. in their work [25] established that in addition to the width of the air cavity, the energy performance of buildings is greatly influenced by the distribution of insulating material, the intensity of solar radiation, the thermal resistance of the outer surface of the wall and the roughness of the slabs limiting the air cavity. However, the air flow velocity as a function of ambient pressure was not considered. Dimoudi, A. et al. [28] investigated the issue of energy efficiency in hot climates using dynamically active double-facade systems, which showed their efficiency in reducing the temperature by up to two times in almost all cases. At the same time, this study did not assess the thermophysical changes in the air layer during heat exchange due to the influence of climatic parameters such as solar radiation and atmospheric pressure. Similar issues using dynamically active facades were studied in the works [47,63,68] and reviews [71,80]. Jiru T. et al. [35] conducted a study of the effect of temperature differences in the current of air at the entrance and exit, where special attention was paid to the sun's effect on the air speed. As a result, it was found that the temperature difference increased with the increase in height and

decreased with the increase in air speed [7,8,10]. A similar observation was also made in the work [42], where it was determined that under sunny conditions, the air speed was higher in the higher wall. Wong, P.C. et al. [36] in their study compared various configurations of double facades to determine the effective type of configuration considering the natural ventilation of high-rise buildings under the solar radiation effect [39,79,81]. Similar studies were conducted by Lin, Z. et al. [64]. Using the integration of optimal solutions in ventilated facades, they proposed the most effective system, which leads to energy savings in the summer period of up to 6.5%. The results of the above-mentioned works exhibit variation, which requires additional research. Domínguez-Torres C. et al. [67] conducted an analysis of the reconstruction of an old building from a traditional facade and its replacement with a ventilated one, taking into account the windows. The study showed that the heat flow inflow during the hot period is reduced by up to 32%. Patania F. et al. [40], based on the complete thermofluid-dynamic analysis of a ventilated air duct, presented an analytical method for design applications that can provide all the useful criteria for selecting the most suitable ventilated facades both in the case of forced convection caused by the action of a fan and natural convection. In this case, the most optimal temperature regime of the moving current of air was established in the work [43]. It should be noted that in these works, climatic parameters such as the influence of solar radiation and barometric pressure on the degree of increase in air volume in the layers were also not considered, though they can have a significant impact. Sanjuan C. et al. [41] studied the thermohydrodynamic characteristics of ventilated facades with thin seams on the siding and concluded that ventilated facades with open joints can help achieve significant energy savings in a climate with hot summers and mild winters. Sánchez M. et al. [46] conducted five experiments in a study with different Rayleigh numbers for panel structure parameters of 0.825 m and 0.3 m in height and width and an air gap of 40 mm in width and showed that an upward flow with the same flow pattern is created inside the air cavity, regardless of the solar radiation falling on the facade [55]. Gagliano, A. et al. [51] studied the thermal behavior of a nontransparent facade with natural ventilation using computer simulation and found that the thermodynamic performance assessment shows an improvement in terms of passive cooling of the building compared to a non-ventilated facade since it allows for a reduction in peak load and provides energy savings ranging from 47% to 51% depending on the climate. In this study, the authors showed that solar radiation does not affect the flow of the rising sun, which may be contrary to other works [7,8,10,35,42,47,63,68,71,80]. This finding requires additional comprehensive research. In addition, Gagliano, A. et al. in a subsequent work [60] conducted an analysis of the impact of energy savings in the summer period. They found that due to air ventilation, energy savings from 20 to 55% can be achieved, mainly observed for the sunniest facades facing east and west. De Masi F. et al. [62] aimed to determine energy efficiency and evaluate the thermal characteristics of ventilated facades based on natural experiments. They came to the conclusion that in winter, this type of facade has good inertial properties, and in summer, it helps to lower the temperature in the room by 10 °C on the hottest days. Matour S. et al. [82] conducted full-scale test experiments and came to the conclusion that the most important factor influencing the risk of cavity overheating is the air speed inside the cavity. Tao, Y. et al. [83] conducted a study of the influence of air speed on the angle of incidence of solar rays using three cities as an example: Shanghai, Melbourne, and Chicago. As a result of their research, it was established that the critical angle of incidence, which has the maximum effect on natural ventilation, is 75°. A theoretical model was developed in [84] that facilitates the calculation of natural convection in a channel from the external conditions, and the developed model replaces labor-intensive numerical modeling. This result [82–84] confirms the assumption about the influence of significant solar radiation; however, atmospheric pressure was not considered.

Zhao, X. et al. [10] conducted a study of various forms of ventilated facades with natural ventilation, such as passive, manual, active, non-automatic hybrid, and automatic control systems. As a result, the required shape was determined for different climatic zones, and the efficiency was shown to be 27.3–47.9%. Król A. et al. [85] conducted experimental and numerical studies of the sun's influence on the air current in the air gap of a 55 m-high building, where the significant influence of the sun on the air flow rate was also confirmed. At the same time, atmospheric pressure was not considered.

The conducted analysis of historical and modern research on the solar radiation effect shows that research in this area is ongoing, which is confirmed in the research reviews (Table 2). According to these reviews, it can be understood that there is currently no single scientifically substantiated consensus, and many studies of individual cases show discrepancies in their results, which complicates the assessment of heat exchange through ventilated facade structures. This indicates the need for further study in order to elucidate and reduce the indicators of such discrepancies. At the same time, many additional solar factors affecting heat exchange in ventilated facade structures are worthy of further exploration.

A review of the popularity of hinged wall systems with air gaps showed that research in this area has been actively conducted since the end of the 20th century. This research has been carried out at an increasing pace and has solved a large number of modern problems (Table 1) arising mainly from the climate features, the development of new building materials, and the effectiveness of their use. The authors of [86–90] also contributed to the development of this area on a national scale in the Republic of Kazakhstan using modern software packages, calculation methods, and experimental standards, contributing to the further development and solutions to modern problems in this area. The relevance of the study of this problem on a national scale is exemplified by the fact that more than half of the country's territory is exposed to solar radiation [91] during the hot period (summer), an issue that is not regulated by national regulatory documents for the design of claddings [92–95]. The need for long-term development of solutions to this problem is additionally due to the annual warming of the climate in the Republic of Kazakhstan [96,97]. The study of the effect of solar radiation on outdoor fences in the climatic conditions of the Republic of Kazakhstan is therefore necessary. The new results obtained in the form of a calculation methodology that takes into account environmental parameters on air flow in air layers and heat exchange in general can also be used internationally when designing buildings in similar climatic conditions since there is currently no single scientifically sound answer in the research in this field on the effects of solar radiation. Many studies also show discrepancies in the results, which makes it difficult to assess heat transfer through ventilated facade structures. Such a circumstance indicates the need for further study in order to understand and reduce such discrepancies. At the same time, there are no studies on the effect of barometric pressure on the air flow rate in ventilated air layers. Such circumstances indicate the need for additional research on these issues.

2.3. Design Features of the Ventilated Facade

The design of the hinged facade system with an air gap mainly consists of several elements with several types of material. For example, the siding can be made of natural stones or modern composite materials [97]. In turn, the hinged system can be designed from different materials, such as aluminum, steel, or corrosion-resistant steel [98]. Hinged system solutions also have a different design; at present, according to the type of fastening, the most popular are horizontal–vertical, vertical, and interfloor [99]. The number of cold bridges, the strength, and the economic feasibility are considered by designers of energy-efficient systems.

As was covered in Section 1, ventilated facades are currently the most widely used due to their efficiency and solution to many problems in creating a more favorable indoor microclimate (Table 1). However, due to the climatic features of the southern regions of the Republic of Kazakhstan, this type of enclosure faces the problem of overheating due to solar radiation, which plays a huge role in the heat exchange of the ventilated structure in the summer (Figure 4).

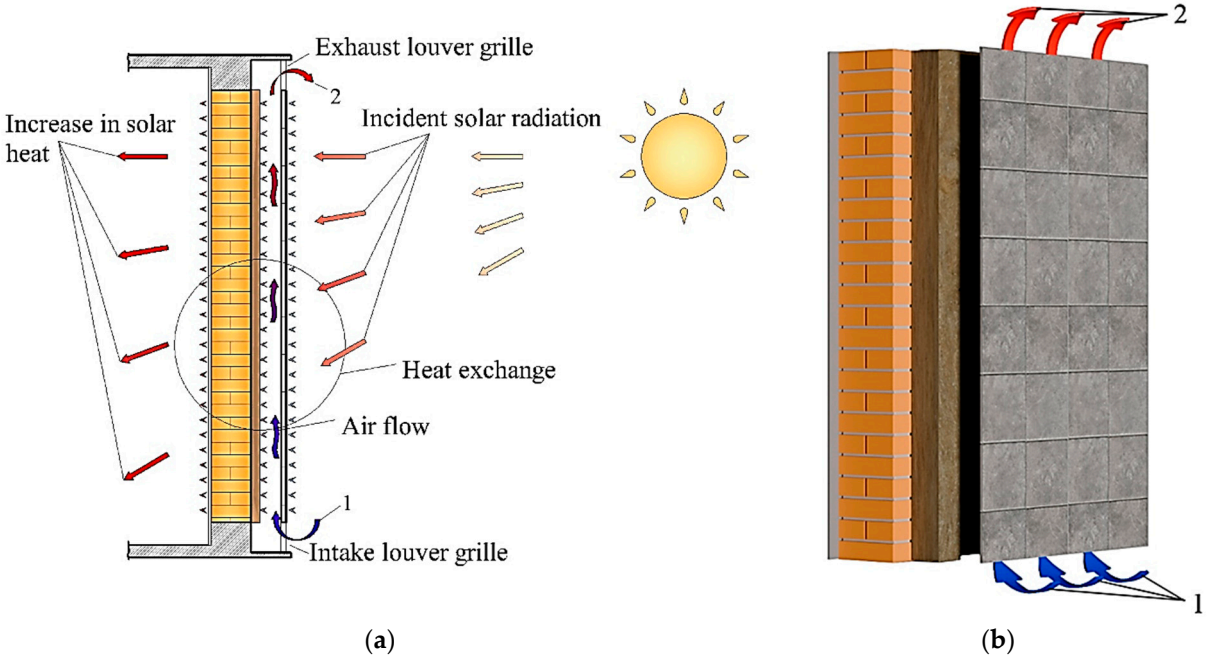


Figure 4. The solar radiation effect on the heat exchange of an enclosure with a ventilated layer: (**a**) heat exchange; (**b**) current of air in the layer: 1—current of air; 2—current of air heated by solar radiation.

In general, the effect of solar radiation on the enclosing structures of buildings has been investigated in certain works, including studies of facade systems with air gaps, but the problem of changing the air flow and the effect of the changed air flow on heat exchange with the indoor air of the room, taking into account the height of the building, are insufficiently illuminated. In addition, the problem of the influence of atmospheric pressure on the flow of air in the air gap has not been studied at all. Considering these unresolved problems, scientists are currently conducting research in this direction, which is confirmed by the review works carried out over the past two years, indicated in Table 2.

2.4. Climate Justification of Research on a National Scale

As discussed above, the relevance of studying this problem on a national scale is due to the fact that more than half of the country's territory is exposed to solar radiation [91] during the hot period (summer). This area includes the southern, southeastern, and southwestern parts of the territory, the classification of which is given in Table 3 in the context of existing densely populated cities.

The territorial units presented in Table 3 are located between the coordinates 42.3 and 47.1 N, where the southernmost metropolis is Shymkent, with a maximum temperature reaching 50.7 °C and a minimum temperature of −30.3 °C. The climatic values, which are presented in Figure 5, are based on current data [100,101].

Table 3. Regions of the Republic of Kazakhstan with a hot climate [91].

No.	Climatic Subregion	Major Cities	Barometric Pressure, mm Hg	Average Monthly Air Temperature in January, °C		Average Wind Speed for Three Winter Months, m/s	Average Monthly Air Temperature in July, °C		Description of the Climate
1	IIIB	Almaty Taldykorgan	695 710	−5	−14	-	21	25	Cold winters and hot summers
2	IVA	Kyzylorda	740	−10	2	-	28	28	Hot summers and warm winters
3	IVG	Aktau Atyrau Taraz Shymkent	760 765 706 714	−15	0	-	25	28	

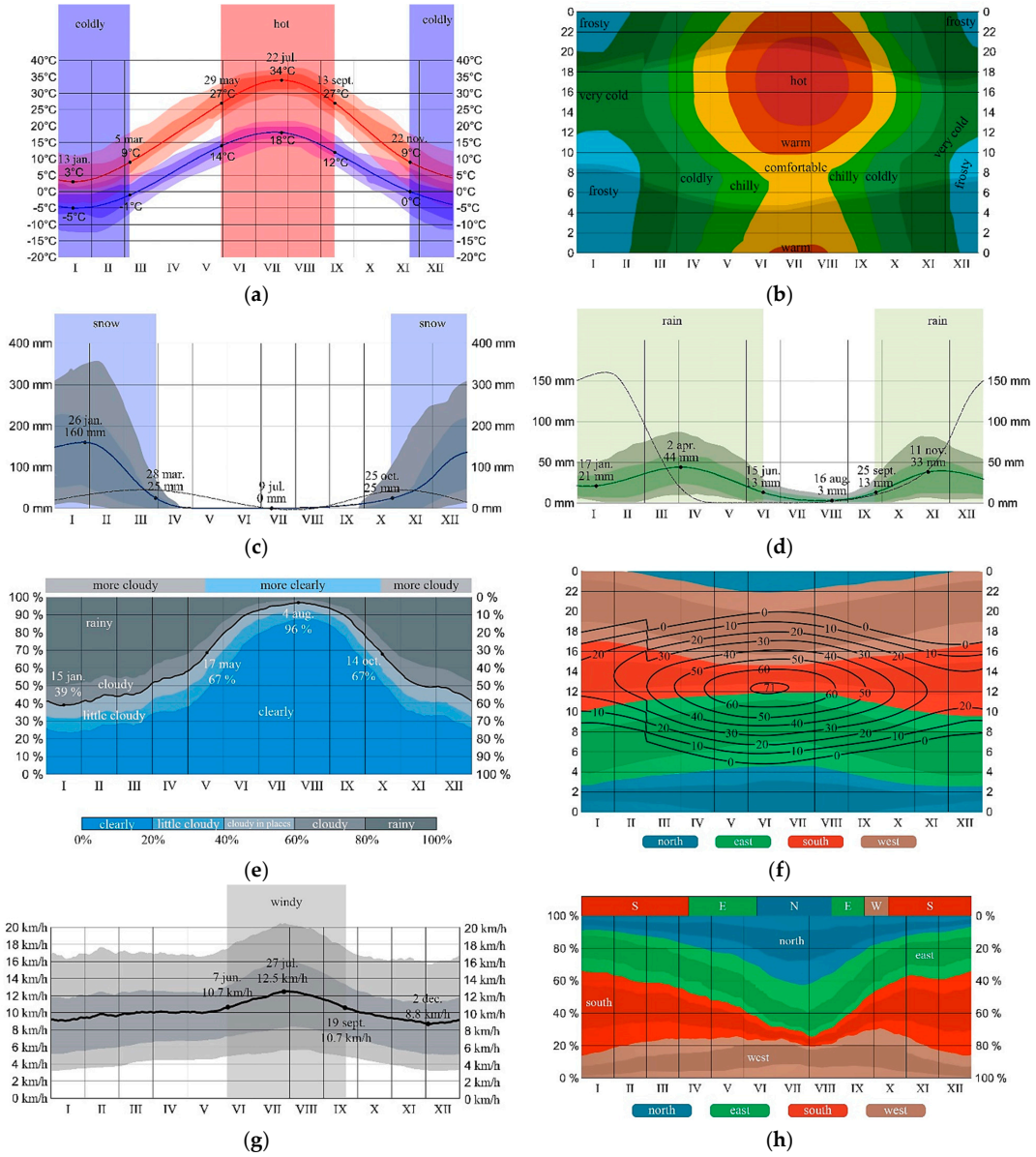


Figure 5. Climatic parameters of Shymkent [100,101]: (**a**) average maximum and minimum temperature; (**b**) average hourly temperature; (**c**) average monthly snowfall; (**d**) average monthly rainfall; (**e**) cloud category; (**f**) sun altitude and azimuth; (**g**) average wind speed; (**h**) wind direction.

Analysis of the climatic parameters of Shymkent shows that the period from April to October is exposed to solar influence. This is a sufficient reason to study solar radiation on the building envelope since the correct calculation solutions for the heat exchange of hinged facade systems taking into account the period of solar influence can lead to significant energy savings. In this regard, Figure 6 shows an engineering and climatic calculation with a favorable indicator considering the orientation of facade structures [102–105].

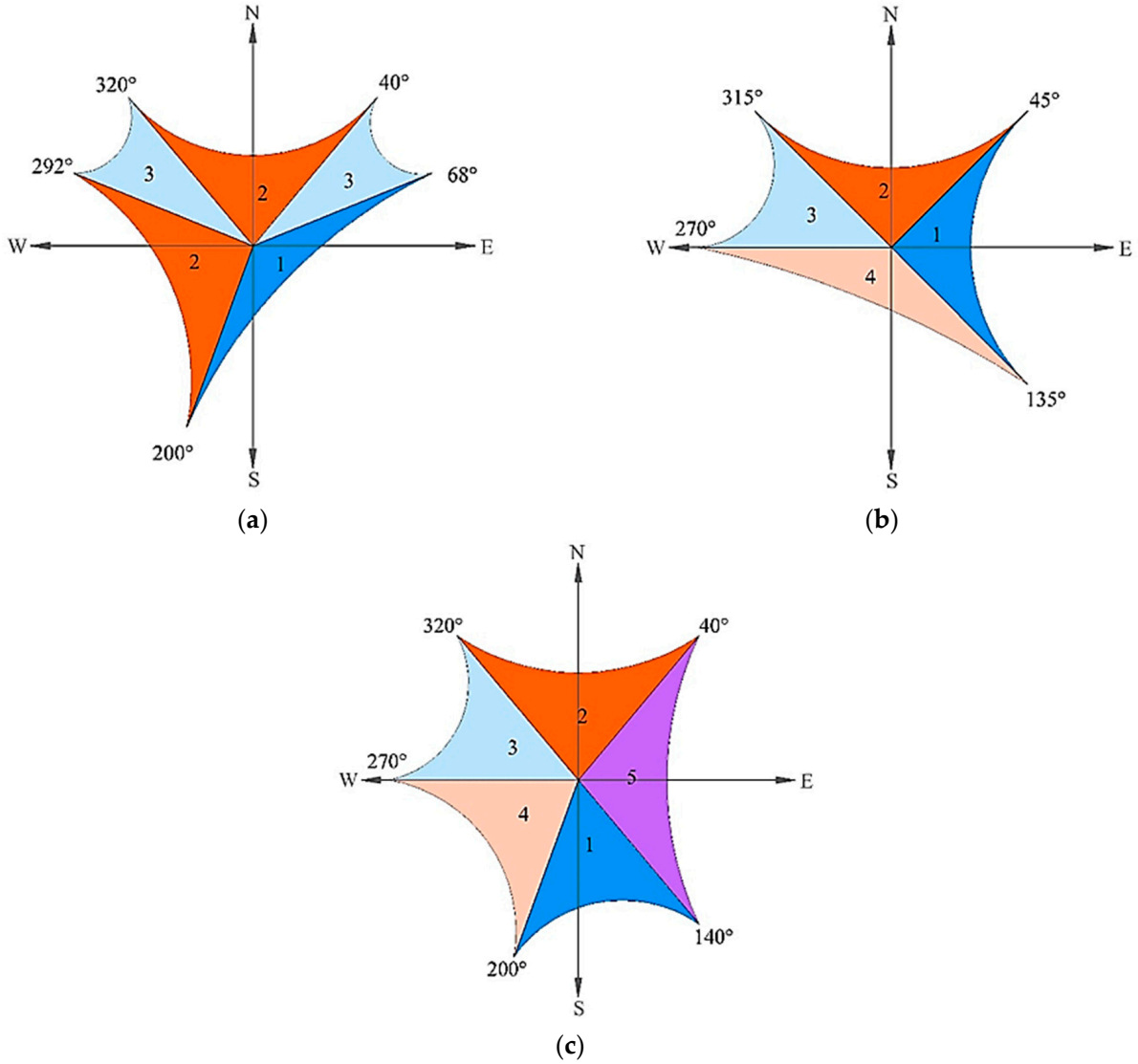
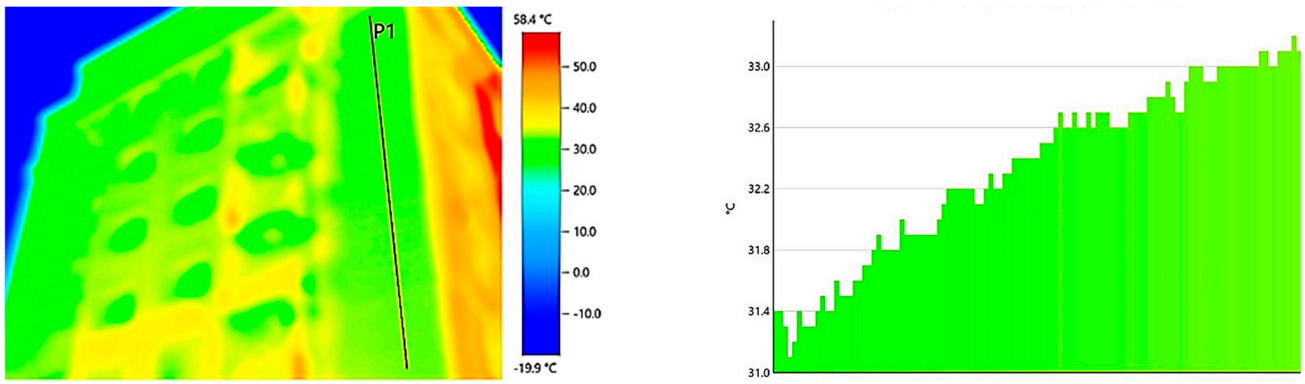


Figure 6. Engineering and climatic calculation of Shymkent: (**a**) indicator of favorable and unfavorable orientation to the cardinal points; (**b**) indicator of architectural analysis of wind conditions; (**c**) indicator of favorable (1), unacceptable (2), acceptable (3), unfavorable (4), and optimal (5) orientations based on a and b.

2.5. Rationale for This Study

The facade of a building, depending on the height of the building, heats up from solar radiation. The higher the building, the more the upper part of the building heats up, and the temperature difference reaches impressive values [7]. A similar phenomenon was also recorded by the authors during thermal imaging surveys of buildings carried out in Shymkent during the hot period [104,106]; see Figure 7.



(**a**) (**b**)

Figure 7. Graph of temperature change by height on the surface of the southern-facing facade at 9:00 a.m.: (**a**) thermogram of the surface of the ventilated facade of the upper five floors of a nine-story building; (**b**) diagram of temperature values of line P1 on the surface of the facade.

From the conducted studies [104], it was found that the temperature difference on the surface of the ventilated facade on the fifth and ninth floors was more than 2.5 °C, which is an impressive difference for this altitude distance. In the case when the height of the heated facade of buildings exceeds 50 m or 20 floors [99], the difference between the first and last floors is more than 10–15 °C. Taking into account these circumstances, the influence of the sun on the air in the layer is noticeable. It is also assumed that solar radiation on the facade has an effect of a different nature; for example, in [5,46], it was found that the velocity is the same at different heights and does not change as a result of heating by the sun. On the contrary, in the work [35], the authors found that the temperature difference increased with height and decreased with the increase in air flow velocity, which was also established in [42]. Considering these circumstances, regardless of how the ventilated air behaves in the facade layer, the temperature of this air significantly affects the heat exchange in the cladding [96]. It is necessary to conduct a theoretical justification to analyze the behavior of gas (air) under the influence of solar radiation (heating).

It is necessary to use the equation of state of an ideal gas [107] to justify the change in the behavior of gases due to the influence of temperature changes, and all parameters affecting the volume of gas must be taken into account; see Figures 8 and 9.

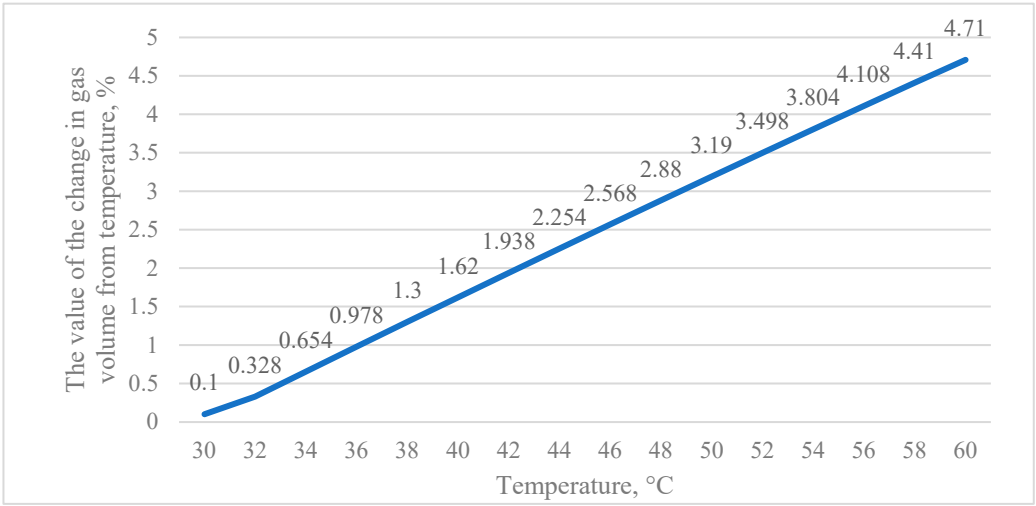


Figure 8. The value of the change in gas volume with the increase in temperature.

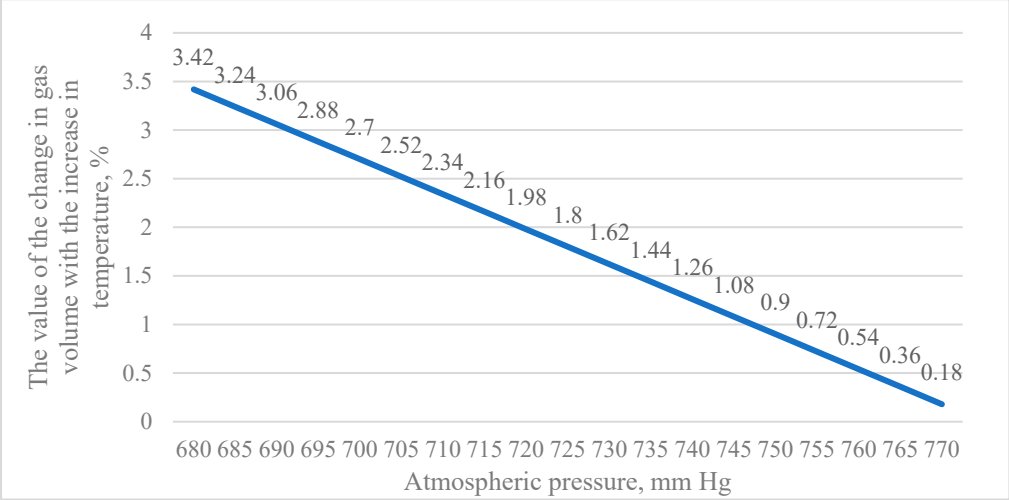


Figure 9. The value of the change in volume of gas (air) with the increase in temperature.

According to Figures 6 and 7, the volume of gas (air) is subject to change with the increase in the temperature value, with a difference of 4.71% over a range of 30 °C. The volume of gas (air) is also subject to change with the change in barometric pressure, which changes the volume of gas (air) with a difference of 3.42% over the range of 680–770 mm Hg. It should be noted that with such changes in gas (air) parameters, the air flow in the ventilated air gaps of the facade system is necessarily subject to change [108].

Figure 10 shows the nature of the change in air volume in the same geometric parameters of the ventilated layer, taking into account territorial affiliation according to Table 3.

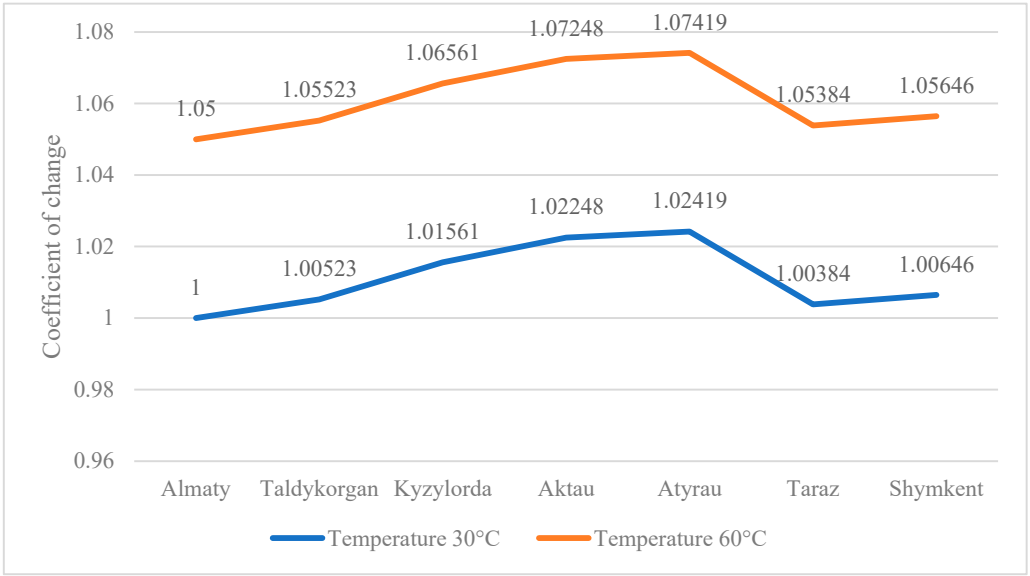


Figure 10. Volume change of air at different temperatures and barometric pressures according to Table 3.

After analyzing the data in Figures 8–10, it can be concluded that the temperature of the heated air and the atmospheric pressure of the environment have a certain effect on the air parameters. Consequently, a change in certain parameters entails a change in the air velocity in the air gap of the ventilated facade, and at different air flow speeds, the inner surface of the facade heats up in different ways, which entails variance in heat exchange.

3. Discussion

A review of research in the field of ventilated facade systems and the influence of climatic parameters on them was conducted in this work based on international scientometrics databases and keywords of the unresolved problem (Figures 1–3). The emphasis was mainly on a hot climate. As a result of the conducted review study, it was found that there is no single scientific consensus, and many studies show discrepancies in the results (Section 2.2), which complicates the assessment of heat transfer through ventilated facade structures (Tables 1 and 2). Such a situation indicates the need for further study to understand and reduce such discrepancies. At the same time, there are many additional factors affecting heat transfer that are worthy of further study considering the solar effect on the structures of ventilated facades, which were also analyzed in this study. This problem is aggravated on a national scale by the fact that the territory of the Republic of Kazakhstan has complex climatic indicators (Figures 5 and 6), and the standards for designing structures of external fences do not take these circumstances into account (Table 3). As noted in Section 1, external fences are adopted for the cold period, where the main indicator is the value of the degree–day heating period, which leads to overheating of the premises in the summer. To solve the problem of overheating, among other issues, many engineers and scientists have recommended ventilated facades, which have shown their effectiveness in solving a number of tasks to create comfortable conditions in residential premises. However, as shown by the authors' own observations [109,110], a ventilated layer in an external fence does not fully solve the problem of overheating in a room under the influence of solar radiation. Thus, due to the overheating of the facade at various building heights, the temperature on the surface of the facade cladding layer differs; that is, relative to the height of the building, the temperature increases, which is confirmed by full-scale thermal imaging surveys by the authors, the thermogram of which is shown in Figure 7. Consequently, the heat exchange in the design of the exterior fence is different at varying building heights and is not stipulated in national standards [88,89]. According to the author, this phenomenon contributes to the overheating of buildings. Preliminary observations show that the temperature increase is characterized by a change in the properties of the gas (in our case, the air in the facade layer) in the form of an increase in volume, which is described by the ideal gas equation. The degree of change in air volume with temperature is shown in Figure 8. According to the authors, barometric pressure also affects the volume of gas (air), as this indicator is present in the ideal gas equation, which is reflected in Figure 9. Consequently, the geographical area directly influences the processes occurring in the ventilated layer of the outer fence. Using the obtained dependencies, the authors showed, according to Table 2, how much the volume of gas can change under the influence of a certain temperature or barometric pressure (Figure 10). Evidence of an unresolved problem in the analysis of thermophysical processes is clearly observed, which highlights the need to develop a solution to this problem in the future. Using the obtained values, it is necessary to conduct comprehensive studies with theoretical and experimental checks since the results obtained can positively complement the scientific conclusions drawn earlier by other scientists (Tables 1 and 2), which are to promote the correct representation of heat transfer in the design of ventilated facade structures.

4. Conclusions

The main purpose of this literature review was to study the application of ventilated facade systems from the 20th century to the present, and the main focus was on the effects of solar radiation and barometric pressure on structures. The influence of solar radiation on the thermophysical processes occurring in the intermediate layer is considered the main

direction of research on ventilated facades. The authors obtained the following key results from this comprehensive review:

- A historical overview of the relevance of the use of ventilated facade systems on national and international scales is presented.
- The design features of ventilated facade systems are presented, as is modern research conducted to date.
- Studies are presented in which there is no consensus and there are a number of discrepancies in assessing the effect of solar radiation on ventilated facade systems.
- The current engineering and climatic calculations on a national scale are presented for the Republic of Kazakhstan, a territory with a hot climate. These calculations confirm the relevance of the research for this region as well as for similar territories on an international scale.
- A thermogram of temperature changes on the surface of ventilated facade systems is presented and provides a justification for further research.
- Using the ideal gas equation, the dependences on the change in the volume of gas (air) under the influence of temperature loads and the influence of barometric pressure were obtained.

The results of this review may have a positive impact on further studies of ventilated facade systems, taking into account solar radiation and barometric pressure. Thus, preliminary results have shown that both criteria have a certain effect on the air flow velocity in ventilated layers, which definitely affects heat transfer through external fences in such structures. The authors found that to study these criteria, additional comprehensive studies are required, which in the future will directly affect the accurate assessment of the heat transfer and energy efficiency of fences and ultimately lead to the minimization of environmental damage. As a limitation of this work, it can be noted that this study mainly considered only traditional types of ventilated facades with the correct air gap shapes. However, these limitations do not reduce the value of the study, as the authors plan to develop the task under study in the future and conduct research on various types of modern facades.

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