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PHYSICAL PRINCIPLES OF GROUND-LEVEL WIND FORMATION AT THE BASE OF HIGH-RISE BUILDINGS

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Abstract

For almost two centuries, research into the causes of ground-level winds at the base of skyscrapers has failed to produce a consensus among scientists on how to diagnose and counteract them. The proposed hypothesis is based on fundamental physical laws and considers the process of ground-level wind formation as a consequence of the sun heating the building and the formation of areas of low and high pressure on its south and north sides, causing air movement around the building. The impact of the heat capacity of building materials on the degree of building heating is considered, and computer modeling of this process is carried out for the coordinates of London and New York on June 22 and December 22. For the obtained building surface temperatures, computer modeling of the temperature, speed, and volume of the upward flow forming a low-pressure zone on the south side of the building was performed. The characteristics of wind movement in a residential complex with a skyscraper in the center were obtained, and a method for reducing the intensity of ground-level winds was proposed.

Keywords: upward air flow, ground-level wind of high-rise buildings, computer simulation, air pressure.

Introduction

The issue of the environmental impact of high-rise buildings on urban climate conditions arose in the mid-19th century during the construction of the first skyscrapers in Chicago and was largely viewed negatively. This was manifested in the fact that hurricane-force winds arose at the bases of high-rise buildings, causing great inconvenience to pedestrians and even knocking them off their feet [1].

The growing awareness among the public of their right to a safe and comfortable living environment has led to considerable interest in studying the impact of high - rise buildings on wind conditions in cities. However, after almost two centuries, scientists have not been able to create a unified physical picture of the observed phenomenon and develop technical methods for its diagnosis and prevention. Therefore, the authorities of large megacities, which are particularly overloaded with skyscrapers, are forced to limit themselves to administrative measures in the fight against ground-level winds caused by high-rise buildings.

Administrative measures to counteract ground-level winds

This was reflected in the fact that, for example, in New York and Chicago, railings were built along sidewalks after an accident in 1903, when a cyclist was blown onto the roadway by the wind and hit by a car. In London, the government introduced strict restrictions on licenses for the construction of high-rise buildings [2] to ensure the safety of pedestrians and cyclists. After an accident in Leeds (England) in 2011, when a pedestrian on the sidewalk was crushed by a truck overturned by the wind [3], court hearings were initiated and a law was passed to suspend traffic on streets near the Bridgewater Place skyscraper when wind speeds at its base exceeded 20 m/s.

Japan made a special effort to combat ground-level winds due to the overpopulation of its cities. Starting in 1971, significant sums were spent on research, inviting European and American scientists [4]. However, even after that, Japan had to limit itself to administrative measures - after the construction of the 147-meter Kasumigaseki Building in 1968 and many years of public debate, it was only in 1981 that a law was passed requiring wind tunnel testing of models of all skyscrapers exceeding 100 meters in height. Since October 1978, Japan has had municipal regulations on state mediation in disputes between residents and developers. However, disputes often escalate into lawsuits that require developers to plant rows of artificial and natural trees, build canopies, windbreaks, wind protection panels, and handrails for pedestrians.

Hypotheses about the causes of ground-level winds

Analysis of all patterns of ground-level wind movement at the base of high-rise buildings is based on one well-known hypothesis: when wind hits a building, it splits into parts, one of which moves downward and increases its speed when it hits the street, moving along it [3]. However, this hypothesis contradicts the law of conservation of energy, since the wind loses some of its energy when it hits the building, and energy losses also occur due to the friction of the wind against the floors of the building as it moves downward. And hitting the street cannot be a source of additional energy for the wind, giving it acceleration.

Research conducted at the Architecture and Construction University of Armenia has shown that ground-level winds around skyscrapers occur in full accordance with the fundamental laws of physics governing the movement of air masses from cold areas with high pressure towards warm areas with low pressure. These areas occur on both sides of a high-rise building facing south [5]. When the facade of a building is heated by the sun's energy across its entire height and width, a powerful upward air flow is formed, resulting in the formation of a low-pressure area at the base of the building, into which air is drawn from all nearby streets, primarily colder air from the north side of the building, where it has formed a large shaded area and retained the coolness of the night for a long time. This wind swirls around the building and moves precisely along the streets, as observed by many scientists, who explain this as the result of the vertical impact of the wind on the street [3,6].

It is evident that taller buildings have a larger surface area exposed to the sun and generate a more powerful upward air flow, which, according to the hypothesis, creates stronger ground-level winds. While well-known hypotheses explain the presence of stronger winds at the base of the tallest buildings by the fact that stronger winds prevail at high altitudes [6], which, after colliding with the building, direct a large flow of air downward. However, in this case, such a flow would have to overcome the resistance of many floors before reaching street level.

The correctness of the proposed hypothesis and the contradictions of the well-known concept are also supported by the fact that the wind blowing at the level of the upper floors of the city collides with all of its buildings. However, ground-level wind is formed only near some of them, while there are taller buildings in the city, which the well-known hypothesis does not explain. At the same time, the proposed hypothesis asserts that ground-level winds arise only near buildings that have a non-standard architectural layout, with their wide side facing north to south, which is usually associated with the characteristics of the territory provided to the developer.

The influence of the heat capacity of building materials on ground-level winds

The validity of the new hypothesis is also confirmed by the fact that the strongest winds are formed at the base of buildings whose cladding contributes to their strong heating, resulting in a more powerful upward air flow, the volume of which determines the speed of the wind drawn into its place. An example of this is the Bridgewater Place skyscraper (Fig. 1), which has a distinctly decorative architectural style of office buildings, based on cladding all window-free surfaces with aluminum, which has a lower heat capacity coefficient than concrete (Tab. 1) and heats up more from solar energy than the facades of standard residential buildings.

This effect is clearly evident in the Walkie Talkie skyscraper (Fig. 2), which is more problematic from a wind perspective. Its design is dominated by glass edged with steel frames, which have a lower heat capacity coefficient than aluminum (Tab. 1). In addition, the thickness of the glass, steel frames, and sheet aluminum used to clad the buildings is 3-5 mm, which means that their mass, converted to a unit of sun-heated surface area, is significantly lower than that of concrete walls 10-20 cm thick. This explains the severe overheating of such buildings in accordance with the definition of heat capacity as the amount of energy required to heat 1 kg of a substance by 1^0 C (tab. 1).

Table 1

Thermal capacity of building materials

material	joule / kg * ^{0}C	material	joule / kg * ^{0}C
concrete	1000	glass	840
aluminum	920	ceramic tile	840
limestone	900	steel	470
terracota	880	iron	400
brick	880	copper	380
armored concrete	840	gold	120

Fig. 1 Bridgewater Place Skyscraper

Fig. 2 Walkie Talkie Skyscraper

These properties are also evident in the UN Secretariat building in New York (Fig. 3), whose main entrance, according to its employees, is littered with broken umbrellas in rainy weather [1], which scientists explain by the fact that “the building catches the prevailing westerly winds and directs them downward.” In fact, the reason for this lies in the building's technical specifications published on the UN website: height - 154 m, orientation - north to south, materials - reinforced concrete, glass, steel, the combined effect of which leads to severe overheating of the building's facade and creates wind at its base in accordance with the hypothesis outlined above.

The example of the aforementioned Kasumigaseki Building (Fig. 4) is very illustrative. Numerous studies of the causes of winds at its base led to the adoption of a law on testing models of high-rise buildings in a wind tunnel, which was based on scientists' belief that ground-level winds were formed as a result of the collision of buildings with winds blowing over the city. And from the point of view of the new version, models should be built to diagnose ground-level winds, allowing the process of their formation to be simulated as a result of buildings heating up under the influence of solar energy [5].

Fig. 3 UN Secretariat Building (154 m) in New York

Fig. 4 Kasumigaseki Building (147m) in Tokio

In terms of analyzing the thermal characteristics of materials used in construction, the Flatiron Building (Fig. 5) is particularly noteworthy. Built in 1902 in Manhattan, it has become a New York City landmark not only because of the hurricane-force winds at its base, but also because of its unique triangular shape, which was a necessary measure dictated by the fact that the developer was given a triangular plot of land at the intersection of Broadway and Fifth Avenue. The architects designed a steel frame for the building to ensure its stability and used advanced technologies for its thermal insulation - the entire surface of the building was clad with limestone and glazed terracotta (Tab. 1), which not only gave the building a rich golden-brown hue, but also, in accordance with the properties of ceramic materials, created a thermal shell for the building, preventing the penetration of cold and solar heat [7]. However, this advantage had a downside: all the sun's energy was concentrated on the facade of the building and overheated it significantly. In addition, for decorative reasons, all the window frames were clad with copper (Fig. 5), which has a very low heat capacity (Tab. 1).

Fig. 5 Flatiron Building (87m) in New York, top view and fragment of facing

As a result, hurricane-force winds formed at the base of the Flatiron Building, the strongest ever recorded in the history of ground-level wind observations - they knocked pedestrians off their feet and tore newspapers from their hands. Their strength allowed experts to make a very valuable observation: columns of dust, debris, and cardboard boxes rose up along the wall of the building. However, this observation did not allow scientists to draw correct conclusions about the physical nature of this wind and the updraft that formed it - all studies continued to be based on the concept that the wind first moves down along the building and then rises after hitting the street.

The heat capacity of building materials was not taken into account in the case of the Lefcourt Colonial Building, known for its winds, built in New York in 1930. Advertisements for office space in this building specifically stated that "the offices have floor-to-ceiling glass walls and an impressive conference room made entirely of glass." These glass structures occupy the entire central part of the building (Fig. 6) with crossbars between floors made of bluish steel beams (Tab. 1). The New York building database "Buildings DB" indicates that the first six floors of the building are clad in limestone, while the rest are clad in brick (Tab. 1) and porous corrugated stone, which are easily heated by the sun. The upper part of the building is clad in blue terracotta and decorated with spires (Fig. 7) covered with gold, which has the highest heat capacity (Tab. 1). Each of the materials used contributes to the upward air flow on the building's facade in accordance with its thermal characteristics.

Fig. 6 Lefcourt Colonial Building (164m) in New York

Fig. 7 Fragment of Lefcourt Colonial Building

Thus, it can be stated that the upward air flow in each building is the result of the combined effect of the heating temperature of each of its structural elements facing the sun. It is obvious that the predominance of glass, metal, and ceramic surfaces in building architecture will have a dominant effect on the degree of their heating. Therefore, to diagnose the power of the upward flow and the speed of the ground-level wind of a particular building, it is necessary to take into account the ratio of its surfaces covered with certain materials.

Computer modeling of the formation of ground-level winds

Undoubtedly, studying the problem of ground-level winds from the perspective of the proposed concept of their formation will require the efforts of many scientists from fields related to architecture. However, computer modeling allows us to take a first look at the observed phenomenon from the perspective of fundamental physical laws and to identify the direction, methodology, and basic principles of subsequent research and experimental work.

To simulate the process of heating a building facade under the influence of solar energy, a generalized case of a building clad with 4-millimeter sheet aluminum over its entire surface was considered, which has the lowest heat capacity compared to all the buildings considered and the building materials used in their construction. The simulation was performed using the "Flow Simulation 2024 SP2.0.Build: 6320" version of the SOLIDWORKS computer program for London coordinates at two extreme points of solar activity: June 22 and December 22.

Calculations of the building facade temperature TF were performed at 1-hour intervals in the time range from sunrise to solar noon, for which the angle of elevation of the sun above the horizon α^0 for each hour and the temperature of the air surrounding the building TA at that time, referred to in forecasts as the "temperature in the sun," which, according to data from the UK National Meteorological Service (Met Office),"exceeds" the temperature "in the shade" Ts, officially published in weather forecasts. For real-time physical calculations, the temperature data "in the shade" published in the "by the hour" section is used, since the "by the month" and "by the day" sections often give the average temperature for daytime or nighttime intervals.

The results of computer modeling at two calculation points are shown in Fig. 8 and Fig. 9, where the side view of the building shows the color spectrum of the temperature of its facade TF and inside the structure itself, as well as the temperature of the air surrounding the building TA and the temperature in its shadow Ts according to the temperature scale. Calculations show that on June 22, the maximum heating of the building occurs at 11 a.m. at an angle of elevation of the sun of 53.4^0, and as the sun continues to move towards its zenith of 61.9^0, the temperature begins to drop due to the decrease in the angle of the sun's rays hitting the building. On December 22, the sun rises to a zenith of only 15.1^0, so in this case the phenomenon described above is not observed, and the maximum temperature of the building is reached at the zenith at 11:59. Calculations also show that in winter, at lower building heating temperatures, a higher difference with the temperature in its shadow is formed, which determines the speed of its ground-level wind, which moves from the shadowed area of the building to its facade. This explains the observations of scientists who have noted that ground-level winds intensify in winter [1].

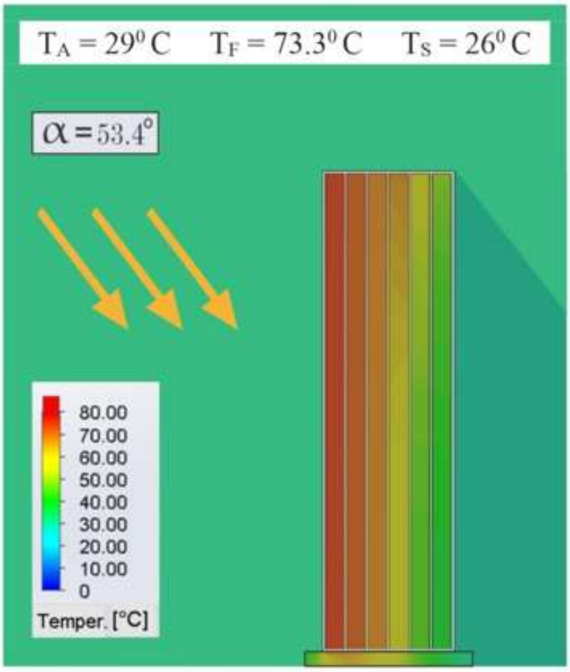

Fig. 8 Simulation of the heating of a high-rise building by the sun on June 22 in London

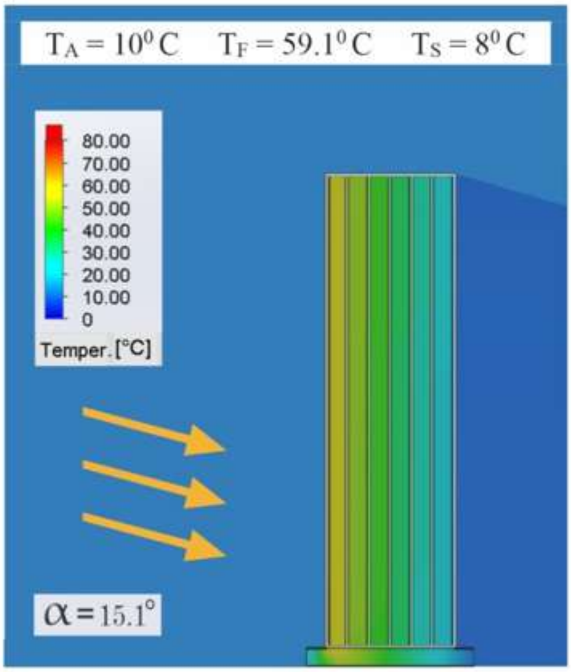

Fig. 9 Simulation of the heating of a high-rise building by the sun on December 22 in London

To more clearly identify this and other patterns of solar heating of buildings, computer modeling of this process was also carried out for New York coordinates, which are characterized by a higher angle of elevation of the sun at the zenith points. To this end, by analogy with London, the temperature of the air surrounding the building TA and the temperature in its shadow Ts were entered into the program in accordance with data from the US National Weather Service (NWS). It should be noted that the modeling was carried out only up to the zenith point due to the fact that in terms of solar radiation intensity, the process is mirrored until sunset, but processes are identified whose degree of influence on the phenomenon under study requires the development of a special methodology. In particular, the temperature “in the sun” begins to decrease immediately after the sun reaches its zenith, while the temperature “in the shade” continues to rise for 1.5-2 hours, depending on the time of year, due to the inflow of air from surfaces heated by the sun into the shaded area.

The results of the program calculations shown in tab. 2 more clearly demonstrate the process of reducing the intensity of building heating due to the fact that the angle of elevation of the sun corresponding to the beginning of this process is further from the zenith than was observed for London. For the conditions adopted in this simulation, the noted angle is reached between 10 and 11 a.m., but the calculation of its exact value cannot be considered a universal characteristic of this phenomenon, since it can vary significantly for each building and the conditions associated with it. At the same time, the calculation of this time for a particular skyscraper, taking into account the reflective properties of its surface, the heating of neighboring structures, cloud cover, and the degree of sunlight scattering, may be the subject of separate studies and serve as a basis for taking administrative measures or warning citizens about increased wind speeds near the skyscraper.

Table 2

Simulation of the heating of a high-rise building by the sun on June 22 in New York

June 22	α^0	T_A (^0C)	T_F (^0C)	T_S (^0C)	$T_F - T_S$
12:58	72.74	34	78.9	29	49.9
12:00	68.82	33	80.4	28	52.4
11:00	59.81	31	82.7	27	55.7
10:00	49.04	29	83.2	26	57.2
9:00	37.75	27	80.1	24	56.1
8:00	26.43	26	75.0	23	52.0
7:00	15.41	24	64.1	22	42.1
6:00	4.91	22	31.9	21	10.9
5:25	0	20	20	20	0

A comparison of tab. 2 and tab. 3 confirms the pattern identified for London, whereby a greater difference between the temperature of the building facade and the temperature in its shadow occurs during the winter period.

Table 3

Simulation of the heating of a high-rise building by the sun on December 22 in New York

Dec 22	α^0	T_A (^{0}C)	T_F (^{0}C)	T_S (^{0}C)	$T_F - T_S$
11:54	25.96	11	72.0	9	63.0
11:00	24.55	9	71.2	7	64.2
10:00	20:48	6	67.6	5	62.6
9:00	14.06	4	56.8	3	53.8
8:00	5.84	2	24.7	1	23.7
7:17	0	1	1	1	0

The calculations of the building facade's warm-up temperature allow us to simulate the upward flow of the building, heated to 60^0 C, which is achieved by 10 a.m. in both summer and winter. For the simulation, the dimensions of Bridgewater Place were used: width - 30 m, length - 80 m, height - 112 m. Fig. 10 shows the results of modeling the upward flow of the building with the distribution of temperature inside it, which, according to the temperature scale, decreases with distance from the building and has a width of 15.3 meters at the point where it decreases to the ambient air temperature. Fig. 11 shows the characteristics of the upward flow velocity, which in the widest section has a velocity of 9.428 m/s and a volume of air moved of 8 954.5 m ^{3}/s (Tab. 4).

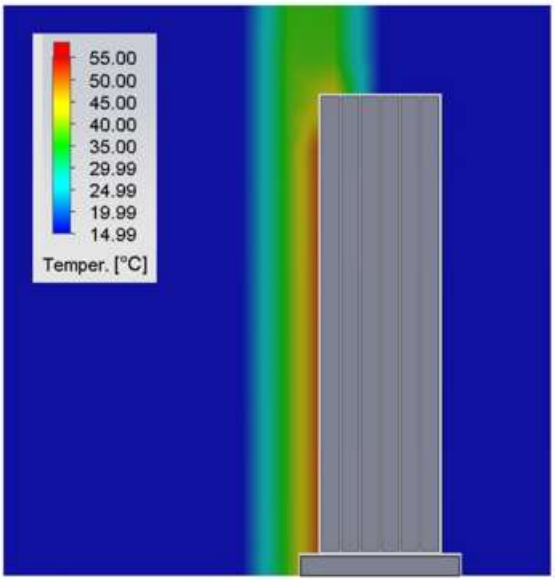

Fig. 10 Computer model of temperature distribution in an updraft

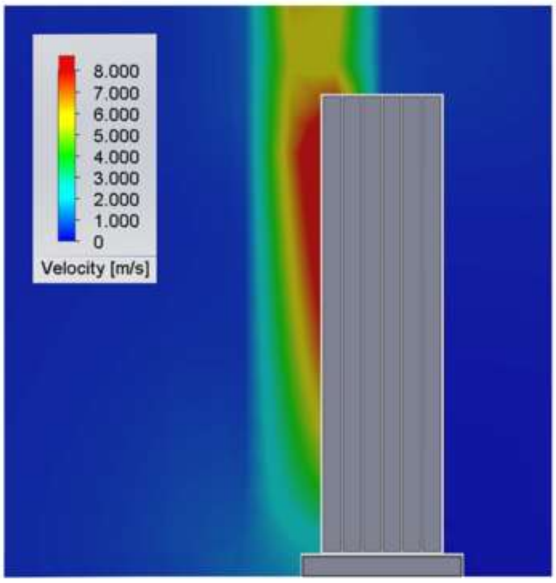

Fig. 11 Computer model of the updraft velocity of a high-rise building

The upward movement of such a volume of air forms an area of low pressure at the base of the building, into which the same volume of air is drawn from all nearby streets and from the shadow area of the building, where, due to its large size, a mass of cold air has formed with a pressure exceeding the pressure in the shadow areas of neighboring houses (Fig. 12).

Table 4

Value of the updraft of a high-rise building

Goal Name	Unit	Value
SG Surface temperature	[°C]	60,102
SG Volume Flow Rate	[m^3/s]	8954,537
SG Velocity Flow Rate	[m/s]	9,428
SG Width Flow Rate	[m]	15,3

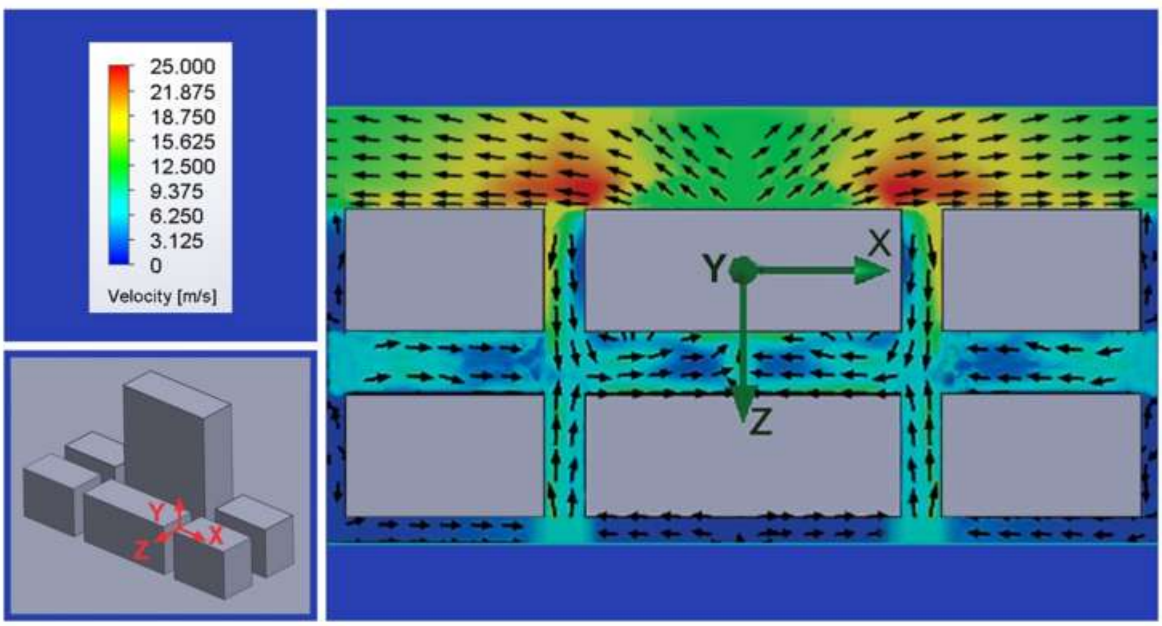

Fig. 12 Models of the residential complex and ground-level wind movement within it (top view)

Because of this, the strongest ground-level wind, about 25 m/s (red zone), occurs in the shadowed part of the building and decreases in speed as it moves towards the facade of the building, where it combines with weaker winds from neighboring streets and compensates for pressure losses at the base of the skyscraper. The assessment of the ground-level wind speed conducted for Bridgewater Place is comparable to a speed of 20 m/s, above which the Leeds authorities prohibit traffic near this skyscraper. In the computer model of the residential complex shown in Fig. 12, the buildings adjacent to the skyscraper are included in the program only to perform the function of directing the wind flows caused by the skyscraper itself, since the impact of all buildings in the microdistrict is the subject of more long-term research, the results of which must be tested on models of microdistricts in which directional heating of structures is applied with the fixation of air flows by means of smoke or micro-sensors [5].

Method of counteracting ground-level winds

The analysis of the causes and patterns of ground-level winds can be of considerable assistance to architects in the design of high-rise buildings and the assessment of their interaction with the environment. At the same time, the hypothesis considered allows us to propose a technical method of counteracting ground-level winds for already constructed skyscrapers, based on providing cold air with a shortened corridor from the shaded part of the building to its facade by means of pipes laid from north to south in the technical floors of the building [5,8]. This technical solution prevents the movement of ground-level winds along the entire perimeter of the building, as the cold air that forms these winds is able to move towards the sun-warmed facade of the building via a shorter route. Consideration of this method from the standpoint of the physical theory of air mass movement is based on the fact that the cold air entering through the pipes compensates for the pressure loss at the base of the southern wall of the building caused by the upward flow of heated air, which leads to a reduction in the pressure difference between the sides of the building and a decrease in wind speed. It should be noted that a complete cessation of wind movement around the building would only be possible if the pipes offered zero resistance to air movement.

Pipes should enter the building from the area of highest pressure at the base of its northern wall and exit at the level of the second floor of the southern wall so as not to interfere with pedestrians and traffic. The pipe outlets can be designed as portholes or other decorative structures. A numerical assessment of the characteristics of this method should be based on the optimal selection of the number and diameter of pipes, their internal resistance, and the resistance of the entire pipe route associated with the configuration of their passage inside the building. Preliminary calculations show that the air flow at the pipe outlets can have a speed of 20-30 m/sec and be ejected up to a distance of 40 meters. Therefore, for the safety of nearby buildings, the pipes should be directed upwards at an acute angle to the building, which will further contribute to reducing the temperature of its facade and the upward flow.

Conclusion

The correctness of the proposed hypothesis is confirmed by comprehensive explanations of all known manifestations of ground-level wind properties, as well as by the regularity of their clearly pronounced intensification near office buildings with characteristic cladding, which is most susceptible to heating by the sun. Studies have shown that in the summer months, the highest surface temperature of a building is reached within 11 hours, as the angle of contact between the sun's rays and the building decreases as the sun moves further towards its zenith. In the winter months, at lower building surface temperatures, a greater difference with the temperature in its shadow is formed, which contributes to the formation of stronger winds at this time of year. Computer modeling confirms all the aspects of the hypothesis and determines the methodology for more in-depth research in each of the areas considered. A numerical assessment of the characteristics of the method of counteracting ground-level winds should be based on the optimal selection of the number and diameter of pipes, their internal resistance, and the resistance of the entire pipe tract associated with the configuration of their passage inside the building. Analysis of the causes and patterns of ground-level wind formation can be of considerable assistance to architects in the design of high-rise buildings and the diagnosis of their interaction with the environment.

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Մ. Վ. Մարկոսյան, Հ.Հ. Այվազյան
Երևանի կապի միջոցների ԳՀԻ ՓԲԸ

Գետնամերձային քամիների առաջացման ուսումնասիրությունները արդեն մոտ երկու հարյուրամյակ չեն ձևավորում գիտնականների մոտ ընդհանուր կարծիք նրանց ախտորոշման և կանխարգելիչ միջոցների վերաբերյալ: Առաջարկվող վարկածը հիմնավորված է ֆիզիկայի ֆունդամենտալ օրենքների վրա և դիտարկում է գետնամերձային քամիների առաջացումը որպես շենքի երկու կողմերում արևից տաքանալու շնորհիվ տարբեր ճնշման գոտիների ձևավորվելու հետևանք, ինչը առաջացնում է օդի շարժում շենքի շրջագծով: Դիտարկված են շինանյութերի ջերմակլանման գործակցի ազդեցությունը շենքի արևից տաքանալու վրա, կատարված է այդ երևույթի համակարգչային մոդելավորում Լոնդոնի և Նյու Յորքի կոորդինատների համար հունիսի 22-ին և դեկտեմբերի 22-ին: Ստացված ջերմաստիճանների համար մոդելավորված են վերընթաց օդի հոսքի արագության և ծավալի արժեքները: Արված է բնակելի թաղամասի տարածքում գետնամերձային քամու շարժման մոդելավորում, առաջարկված է այդ քամու նվազեցման տեխնոլոգիա:

Բանալի բառեր՝ օդի վերընթաց հոսք, բարձրահարկ շենքերի գետնամերձային քամի, համակարգչային մոդելավորում, օդի ճնշում:

ФИЗИЧЕСКИЕ ОСНОВЫ ФОРМИРОВАНИЯ ПРИЗЕМНЫХ ВЕТРОВ У ОСНОВАНИЯ ВЫСОТНЫХ ЗДАНИЙ

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Изучение причин возникновения приземных ветров у основания небоскрёбов уже почти два столетия не приводит учёных к единому мнению об их диагностике и мерах противодействия. Предложенная гипотеза основана на фундаментальных физических законах и рассматривает процесс возникновения приземных ветров как следствие прогрева здания солнцем и формирования на его юге и севере зон пониженного и повышенного давления, вызывающих движение воздуха вокруг здания . Рассмотрены вопросы воздействия теплоёмкости строительных материалов на степень прогрева зданий, проведено компьютерное моделирование этого процесса для координат Лондона и Нью-Йорка 22 июня и 22 декабря. Для полученных температур поверхности здания проведено компьютерное моделирование температуры, скорости и объёма восходящего потока, формирующего зону пониженного давления на южной стороне здания. Получена характеристика движения ветра в жилом комплексе с небоскрёбом в центре, предложен метод снижения интенсивности приземного ветра.

Ключевые слова: восходящий поток воздуха, приземный ветер высотных зданий, компьютерное моделирование, давление воздуха

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