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CALCULATION OF THE INSTANT MODEL OF SOLAR RADIATION DISTRIBUTION ON CURVED SURFACES IN HIGH-RISE BUILDINGS

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Abstract

The aim of research is to simulate the zones of solar radiation on the curved surfaces of the shells of high-rise buildings for the effective use of renewable solar energy. An urgent task is the development of tools that can substantiate the decision-making by designers about the location of solar thermal devices in the energy-efficient design of curvilinear high-rise buildings. The main attention is paid to high-rise buildings, is actively growing in modern megalopolises and requires a significant energy resource. To optimize the integration of solar thermal devices in high-rise buildings, it is important to take into account a set of design parameters, including parameters of surface shape and location in space. A feature of curved surfaces, considered in the study, is their aerodynamic properties, which provide them with the advantage of choosing among modern high-rise buildings. At the same time, the complexity of setting the parameters of a curved surface to determine the zones of solar radiation for the effective use of regenerative solar energy lies in providing reliable and convenient tools for optimizing decision-making.

The study proposes an application of the method based on a discrete geometric model of solar radiation input on the surface of the shells of high-rise buildings, described by compartments of curved geometric surfaces. As a result of modeling, let's obtain a family of lines of the same level of solar radiation on a certain curved surface for the given parameters of time and geographic location. As an example of simulation modeling, the performed calculations of the instantaneous model of the distribution of solar radiation on the compartments of the curved surfaces of an ellipsoid of revolution, hemisphere, hyperbolic paraboloid. On the basis of the proposed model for the distribution of solar radiation over curvilinear surfaces of buildings, the influence of factors arising in the design process is investigated: changes in the geometric parameters of the surface shape, orientation to the cardinal points, the formation of zones of its own shadow on surfaces. Calculations were performed and instantaneous solar radiation zones were constructed on the surfaces of a hemisphere, a hyperbolic paraboloid with various geometric parameters, taking into account different orientations relative to the cardinal points, and determining the zones of its own shadow.

At this stage of the study, the result is an algorithm for constructing zones of different levels of solar radiation on curved surfaces of high-rise buildings. The advantage of the algorithm is the ability to analyze the results of changes in the design parameters of the surface of a high-rise building when placing solar systems on them. The proposed approach will provide a basis for automating the modeling process, will help expand the scope of solar systems in high-rise construction and increase the efficiency of their work.

Keywords: regenerative solar energy, solar radiation, curvilinear geometric shells, high-rise buildings.

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1. Introduction

The 21st century is characterized by a global trend towards population growth, industrialization and urbanization. Modern megacities are built up mainly with high-rise buildings. A feature

of high-rise buildings is their high energy consumption in comparison with buildings with a lower number of storeys, which can be compensated by the integration of solar energy [1, 2]. This raises the problem of predicting a solar renewable resource.

The studies [3, 4] note the variability of solar energy in space, time and the complexity of modeling. As noted in [5], inaccurate forecasts can lead to significant economic losses and problems of the reliability of power systems. The variability of renewable solar energy is becoming an important factor for urban services that maintain grid stability, plan power distribution and manage the city's energy efficiency [6, 7]. Prediction of solar energy is carried out by various methods, taking into account the parameters of time, geographical latitude on flat surfaces [3–5].

The implementation of the advantages of solar energy in the design of modern high-rise buildings has its own difficulties associated, among other things, with the peculiarities of their shaping. At the present stage, the practical experience of using solar energy in skyscrapers is limited to the placement of photovoltaic panels on vertical, horizontal and inclined planes of walls and roofs (CIS Tower, Manchester, UK, TwentyRiverTerrace, New York, USA [8, 9]. There is practically no integration of solar panels on more complex aerodynamic curved surfaces of skyscrapers, which are able to perceive the increasing wind force with the height of buildings and provide a decrease in heat loss [10]. Integration of solar panels on such surfaces requires a search for appropriate methods for their design and optimization of solutions, and therefore it is an urgent scientific problem, the solution of which has significant economic, environmental and scientific potential. At the same time, the complexity of setting the parameters of a curved surface to determine the zones of solar radiation for the effective use of regenerative solar energy lies in ensuring reliable and convenient tools to optimize decision making. Consequently, *the aim of research* is to introduce an effective means of determining the zones of solar radiation on the curved surfaces of the shells used in modern high-rise architecture.

2. Materials and methods

The use of solar energy in modern high-rise buildings, formed from the compartments of curved surfaces, leads to the formulation of the problem of determining the efficiency of placing solar thermal devices on such surfaces. So, the target object of research is high-rise buildings and their elements, where it is planned to place a solar receiver to obtain solar energy at different stages of the life cycle of a high-rise building, both during new construction and during the reconstruction of a high-rise building. The issues of optimizing the placement of a solar receiver on the surface of a high-rise building should be determined in conjunction with other architectural, structural, technological and urban planning parameters of the building and included in the design as a subsystem taking into account various influencing factors. For a preliminary analysis of the location of solar thermal devices on high-rise buildings, we define the following influencing factors:

– the geometry of the surface of the construction object is determined in accordance with functional, structural, space-planning solutions and urban planning requirements [10, 11];

– macro, meso and microclimatic characteristics are determined in accordance with the location of the high-rise building [12, 13];

– the type of solar thermal devices is determined taking into account the requirements for the need for appropriate power supply of the architectural object, economic feasibility, technical capabilities and efficiency of work for the given building conditions [14].

So, the design of solar thermal devices on high-rise buildings depends on many factors that require additional clarification when setting tasks, namely the possibility of:

– control of the shape of a high-rise building, which determines adjustments to the level of solar radiation entering the building surface without changing the position in space;

– control of the position of a high-rise building in space, solves the problem of optimal orientation of the building to the cardinal points without changing its shape;

– location of solar control devices on a complex surface of a skyscraper, taking into account solar – radiation zones, rational for placing a solar system;

– control of the position and shape of an object, taking into account its falling into its own shadow or shading from protruding structural elements of the objects themselves.

The next design stage is the analysis of the model of solar radiation input to the surface with the possibility of determining zones on it, the maximum amount of solar radiation is obtained during a given period of time (day, month, season, year). In this case, two main components are taken into account that determines the effective solar radiation zones – this is the surface of a high-rise building object and the model of a set of sun rays (cone of sun rays).

The geometric model of the surface of a high-rise building is an ordered two-dimensional point wireframe of sufficient freedom over a rectangular plan. The geometric model in the form of a sunbeam cone with apex at the irradiated point is adopted as the model of the set of sunbeams. The parameters of the sunbeam cone for a given latitude of the area change depending on the season. A geometric model of the diurnal cone of sunbeams was proposed for insolation calculations in [15], where the Sun is taken as a point source, which at each moment of time gives ∞^2 congruence of practically parallel rays. A complex of ∞^2 rays is formed per day. If we assume that the Earth is in orbit at one point during the day, then this is a complex of the 2nd degree. Then any point separates from this complex a daily circular cone of sun rays, the axis of which is parallel to the axis of the Earth. It is the guide for all sunlight per day. The angle of inclination of the axis of the cone to the horizontal plane is equal to the latitude of the terrain. The angle φ is the angle between the axis of the cone and its generatrix, which varies throughout the year from 66°, 33′ to (180°–66°33′). The hour generators of the cone are located in axial planes taken from the midday plane every 15°. Consequently, the determination of the magnitude of solar radiation energy on the house surface is primarily associated with modeling the movement of the Sun, taking into account the azimuth of the Sun and the altitude of the solstice, latitude, the value of time in hours, days, and the like. In solar architecture, the thermal indicators of solar radiation are also determined.

Let's consider the principles of basic modeling of the process of determining the zones of solar radiation on the surfaces of the shells of a high-rise building. In [16, 17] it is shown that the value of the intensity of solar radiation S_H on the surface normal to the direction of the sun's rays for latitudes 38–64 °C is determined by the ratio:

$$S_H = \frac{S_0 \sin h}{\sin\ h + C}, \tag{1}$$

where S_o – solar constant equal to 7.527 W/cm×min; h – solstice height; C – coefficient characterizing the transparency of the atmosphere.

The coefficient is determined according to [18] by the formula:

$$C = \frac{1-P}{P}, \tag{2}$$

where P – transparency coefficient (provided that the sun's rays pass the atmosphere along the normal) is taken 0.7–0.8 for a cloudless time of day.

The value of the amount of solar radiation (intensity) S_γ, which enters the plane perpendicular to the direction of the sun's rays is directly proportional to the cosine of the angle between the normal to the plane and the direction of the sun's rays, is written by the formula:

$$S_\gamma = S_H \cos\gamma. \tag{3}$$

Let's consider the process of constructing an instant model of the distribution of solar radiation over the section of the coating surface (the section of the surface with a family of lines of equal amount (intensity) of solar radiation applied to it). On a given surface, let's apply a regular grid (for example, 11×11 nodes) to determine the parameters of the tangent planes at the grid nodes. Set the normal to the surface at each node of the mesh. Determine the angle between the normal to the surface and the vector opposite to the direction of the sun's rays using the well-known formula:

$$\cos\gamma = \frac{a_x\bar{a}_x + a_y\bar{a}_y + a_z\bar{a}_z}{\sqrt{\bar{a}_x^2 + \bar{a}_y^2 + \bar{a}_z^2}\sqrt{a_x^2 + a_y^2 + a_z^2}}, \tag{4}$$

where $\bar{a}_x$, $\bar{a}_y$, $\bar{a}_z$, a_x, a_y, a_z are the cosines of the vector of the opposite direction of the sun's rays and the direction cosines of the normal.

Having linked the direction of the cosine of the vector facing the direction of the sun's rays with azimuth, solstice altitude and time angle, the values $\bar{a}_x$, $\bar{a}_y$, $\bar{a}_z$ will be written in the following expressions:

$$\bar{a}_x = \text{tg}\varphi\cos\tau\sin\delta - \cos\delta,\ \ \bar{a}_y = \text{tg}\varphi\sin\tau,\ \ \bar{a}_z = \text{tg}\varphi\cos\tau\cos\delta + \sin\delta, \tag{5}$$

where δ – inclination angle of the Earth's axis to the plane of the horizon, equal to the latitude of the terrain, τ – hour angle, φ – angle between the Earth's axis and the direction to the Sun, are determined using the daily cone of solar rays according to [15].

For each of the fixed points on the surface of the building with an interval of one hour, we find the value for $\bar{a}_x$, $\bar{a}_y$, $\bar{a}_z$ and a_x, a_y, a_z.

Substituting these values in (4), let's determine the arrays cosγ for each fixed point, and then we substitute the value cosγ in (3) and determine the amount of solar radiation entering the calculated point at the nodes of the surface. As a result, we can obtain the value of the instantaneous intensity of solar radiation at each fixed point of the node for a given fixed position of the Sun. Considering N fixed positions of the Sun during the day, we will assume that the daily intensity of solar radiation at a fixed point of the node (A_{ij}), excluding shading, is equal to the sum S_γ of instantaneous values of the amount of solar radiation referred to the number of calculated points N. Summing up the instantaneous intensities at each calculated point, let's obtain daily intensity.

$$S_{\gamma\,daily} = \frac{1}{N}\sum_{i=1}^{N} S_\gamma i. \tag{6}$$

This will make it possible to build a picture of the distribution of solar radiation over the surface and determine the zones of maximum intensity and possible shading zones during the day. The indicated analytical provisions are applicable for modeling the distribution of solar radiation over the compartments of various curved surfaces used for shaping in high-rise buildings.

3. Research results

As noted above, to reduce the wind load on high-rise buildings, curved surface compartments are used in their design. This is due to the aerodynamic properties of curved surfaces. For example, the sections of the surface of the ellipsoid of revolution define the shape of the famous skyscraper 30 St Mary Ax, Greater London ENG United Kingdom, 179.8 meters high, architect Norman Foster (**Fig. 1**). The applied form is aerodynamic, which significantly reduces the wind pressure on the high-rise building (**Fig. 2**).

Let's present the modeling of the distribution of solar radiation over the surface of the compartment of the ellipsoid of revolution, will provide an opportunity to further determine the feasibility and locations of solar panels on the surface of a high-rise building. On the ellipsoid, let's take a surface section bounded by planes that pass through the foci of the ellipsoid and are parallel to the axis and planes passing at a distance of the focal parameter from the y-axis (**Fig. 3**).

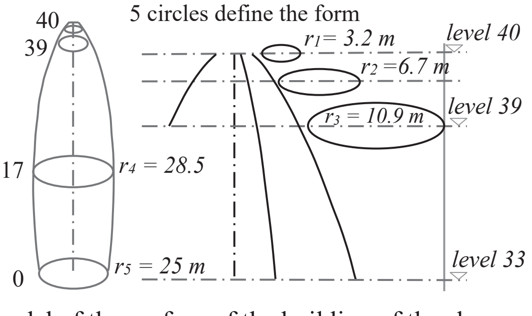


Fig. 1. Geometric model of the surface of the building of the skyscraper 30 St Mary Ax, Greater London, UK, 179,8 m [19]

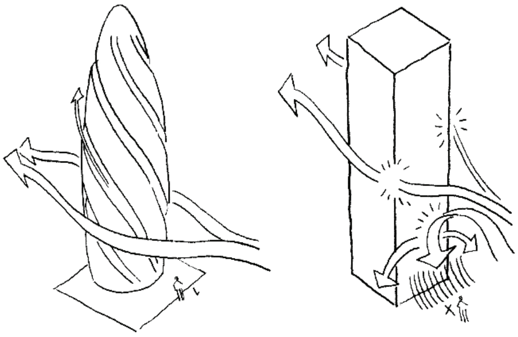


Fig. 2. Comparison of the distribution of wind flows of curved and prismatic surfaces of high-rise buildings [20]

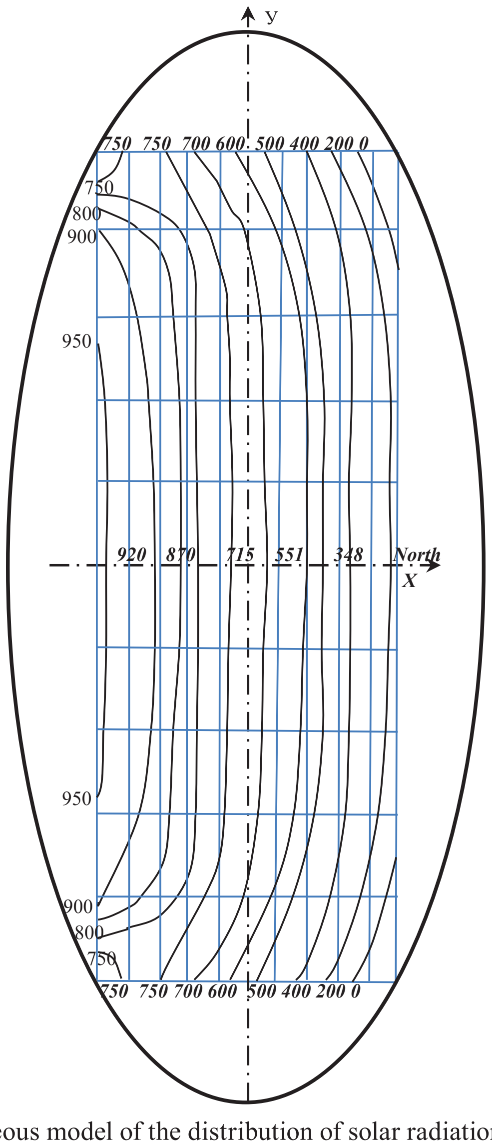


Fig. 3. Instantaneous model of the distribution of solar radiation over the section of the ellipsoid surface

Let's set the initial data:
The semi-major axis of the ellipsoid $a=10$ (coincides with the axis y).
The middle semi-axis of the ellipsoid $b=5$ (coincides with the axis x).
The semi-minor axis of the ellipsoid $c=5$ (coincides with the axis z).

Let's determine the focal length:

$$F_1F_2 = \sqrt{a^2+b^2} = \sqrt{100+25} = \sqrt{75} = 8.6. \quad (7)$$

Let's define the focal parameter p:

$$p = \frac{b^2}{a^2} = \frac{25}{100} = 2.5. \quad (8)$$

The ellipsoid equation will be written:

$$\frac{x^2}{25} + \frac{y^2}{100} + \frac{z^2}{25} = 1. \quad (9)$$

Let's split a regular grid of 11×11 nodes on the surface of the ellipsoid compartment.

Direction cosines of $\bar{n}\{\bar{a}_x\ \bar{a}_y\ \bar{a}_z\}$ normal and generators of cosines $\bar{r}\{a_x\ a_y\ a_z\}$ will be:

$$\bar{n}\{\cos 45°\ \sin 0°\ \sin 45°\},\quad \bar{r}\left\{8.6; 2.5; 5 - x - \frac{y}{2}\right\}. \quad (10)$$

Let's set a normal at each node of the grid. Next, let's determine the angle between the normal and the vector opposite to the direction of the sun's rays (4), substituting the value of the cosines of the normal and generating cosines, let's obtain the data array cosγ for each nodal point of the frame (A_{ij}). After that, substituting the values cosγ (3), let's obtain the amount of solar radiation arriving at the calculated point of the surface at a given time. Let's determine for each nodal point of the frame (A_{ij}) the values of the amount of solar radiation at this point. Interpolating the obtained data arrays, let's plot lines with the same values of the amount of solar radiation S_γ (W/cm×min) on the surface of the ellipsoid compartment. As a result, let's obtain an instant model of the distribution of solar radiation over the surface of the ellipsoid compartment. Summing up the instantaneous intensities according to formula (6), let's obtain the daily amount (intensity) of solar radiation arriving at a given surface. This will enable the designers, based on the amount of solar radiation arriving at the surface and the energy requirement for a given high-rise object, to draw a conclusion about the possible placement of the solar system.

The design of solar systems in high-rise buildings depends on many factors that require additional clarification. The above geometric model of the distribution of solar radiation over the curved surfaces of the enclosing structures makes it possible to analyze the influence of factors arising in the design process:

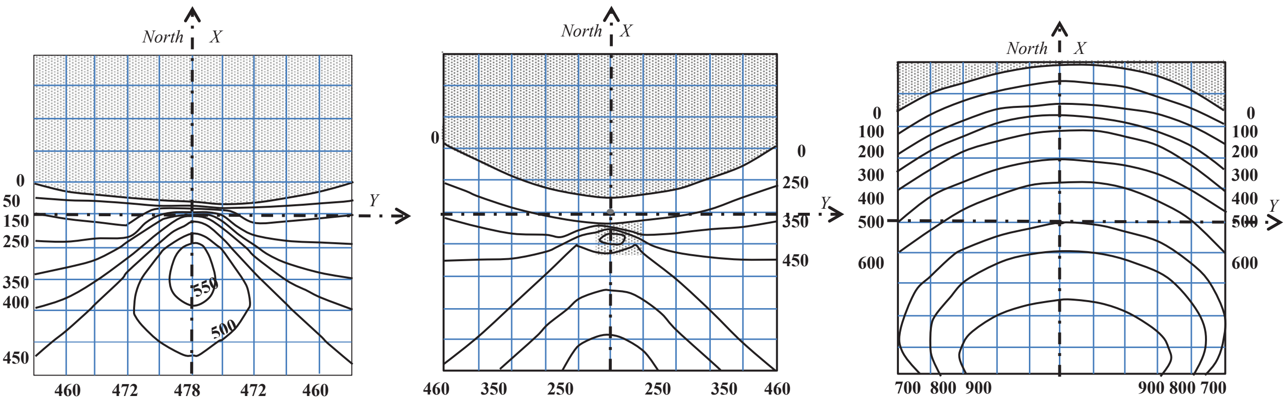
– taking into account the position and shape of an object when it enters its own shadow, considered by the example of modeling the surfaces of a hemisphere and a hyperbolic paraboloid (**Fig. 4–6**);

– changes in the geometric parameters of the surface shape, considered by the example of modeling a hemisphere and a hyperbolic paraboloid (**Fig. 4–6**);

– changes in the orientation of the curved surface relative to the cardinal points, considered by the example of modeling a hyperbolic paraboloid (**Fig. 5, 6**).

As a result of the specified geometric modeling, conclusions have been drawn. On the example of modeling hemispheres with different geometric parameters of the shape with a constant orientation to the cardinal points, it has been determined determined that the use of such surfaces is not always economically feasible. Since the amount of solar radiation entering such surfaces will be insignificant due to the large area of zones in their own shadow. It has been determined that the regulation of the geometric parameters of the hemisphere shape makes it possible to regulate the zone of its own shadow and the intensity of the distribution of solar radiation. (**Fig. 4**).

The influence of changes in the geometric parameters of the shape of a hyperbolic paraboloid is investigated for surface sections with flat and strongly curved edges.



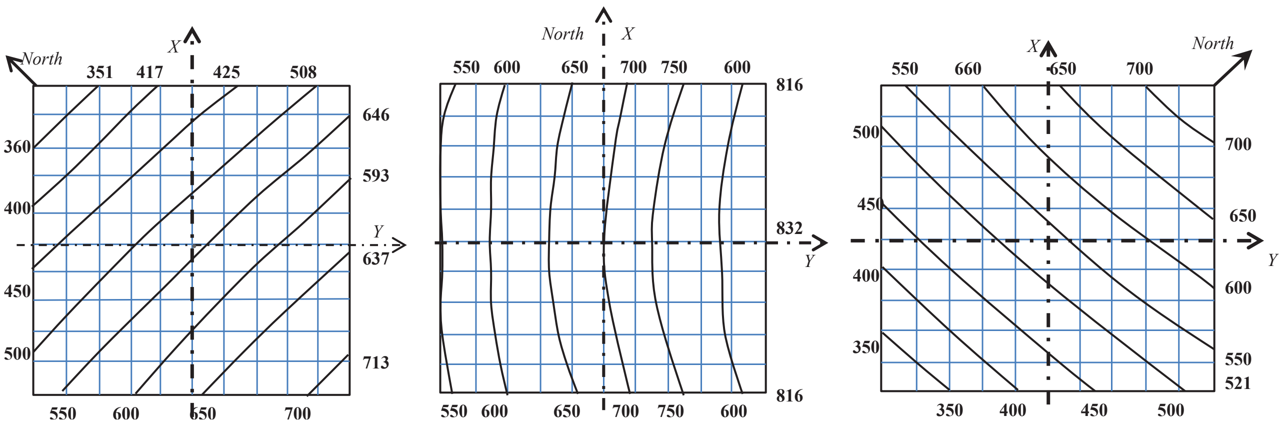
a *b* *c*

Fig. 4. Instantaneous model of solar radiation distribution over the section of the hemisphere surface for a given orientation and changes in the geometric parameters of the shape described by the equations: $a - x^2+y^2+z^2=600$; $b - x^2+y^2+z^2=255$; $c - x^2+y^2+z^2=50$

The geometric shape of a hyperbolic paraboloid with shallow edges is given by the equation:

$$0.4_{xy} + 20_z = 0. \tag{9}$$

Modeling of the distribution of solar radiation has shown that such a surface shape excludes the formation of its own shadow zones on it with different orientations to the cardinal points. The distribution of solar radiation over the surface is fairly uniform and changes insignificantly when the orientation of the surface compartment changes to the cardinal points (**Fig. 5**). Although this simplifies the architectural expressiveness and partially the aerodynamic properties of high-rise buildings.



a *b* *c*

Fig. 5. Instantaneous model of the distribution of solar radiation over the surface of the compartment of a hyperbolic paraboloid with shallow edges, described by equation (9) with different orientations relative to the cardinal points

The geometric shape of a hyperbolic paraboloid with curved edges is given by the equation:

$$0.4_{xy} + z = 0. \tag{10}$$

In compartments of hyperbolic paraboloids with curved edges, the geometry of the shape is more complex. Has the best architectural expressiveness for a high-rise building and aerodynamic properties. Modeling the distribution of solar radiation showed that the sections of the surface of a hyperbolic paraboloid with curved edges have a smaller area of solar radiation zones. This is due

to an increase in surface areas that are in their own shadow, and reduces the total amount of solar radiation entering the surface. The distribution of solar radiation over the surface is uneven and changes greatly when the orientation of the surface compartment changes to the cardinal points (**Fig. 6**).

Thus, the proposed method for modeling radiation zones is a means for preliminary design analysis of the efficiency of the location of solar systems on curved surfaces used in the formation of high-rise buildings. The proposed method makes it possible to analyze the influence of the design parameters of the change in orientation, the geometric shape of buildings, zones of dullness on the distribution of solar radiation over the surface of buildings.

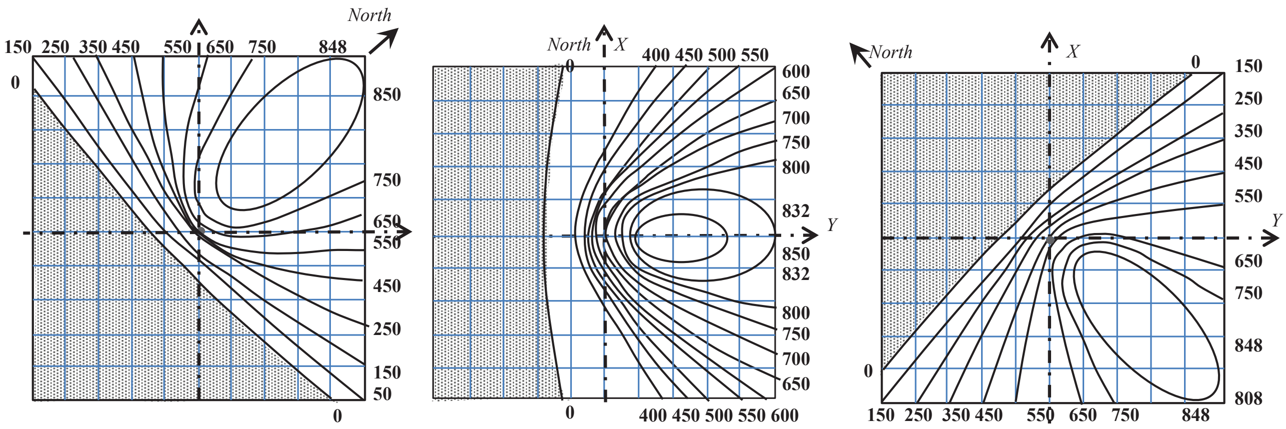


Fig. 6. Instantaneous model of the distribution of solar radiation over the surface of a hyperbolic hyperboloid with strongly curved edges described by equation (10) at different orientations relative to the cardinal points

4. Discussion

The search continues for efficient ways to use solar energy as a reliable source of renewable energy in high-rise buildings. So, in [21], based on a review of information sources, formalized, generalized and descriptive recommendations for integrating solar energy systems into high-rise buildings are presented. In [22, 23], various aspects of geometric modeling of the shape of high-rise buildings are described when determining the energy supply strategy. But in these studies, the problems of geometric modeling of high-rise buildings are considered when using only passive form of solar energy (accumulation of solar heat and light). In [24], analytical dependences of calculating the values of total solar radiation for the use of heliosystems on horizontal and vertical planes are presented, without the possibility of effective modeling of the solar radiation input on the surface of buildings with a curvilinear geometric shape. Thus, the problems of multifactorial optimization of the integration of solar systems on the curved surfaces of high-rise buildings are not presented by methods for analysis.

The aim of the presented research is to provide designers with a means of modeling the distribution of solar radiation on curved surfaces for the effective location of solar thermal devices on them. The curved surfaces used in the design of modern high-rise buildings to reduce the influence of wind pressure are taken for consideration. The proposed tools are based on geometric modeling of the representation of the process of interaction between the parameters of variable sunlight and the geometric parameters of the shape of a curved surface. This approach makes it possible to simulate the change in the geometric parameters of the shape of a curved surface, its orientation relative to the cardinal points and the formation of zones of its own shadow when determining effective solar radiation zones for placing solar systems on the curved surface of a high-rise building.

The expected practical significance of the research results is:

– application of the proposed algorithm for further automation of the process of optimizing the placement of solar systems on curved surfaces of high-rise buildings;

– providing scientifically sound decision support based on the analysis of the results of calculating the intensity of solar radiation on models of curved surfaces.

5. Conclusions

To implement the concept of creating an energy efficient and environmentally safe environment for a modern metropolis, it is important to integrate systems from renewable energy sources, including solar energy, into high-rise buildings. The algorithm proposed in the study can be applied for efficient placement of solar control devices on curved geometric surfaces, which are widely used in modern architecture of skyscrapers.

The introduction of solar energy into high-rise construction and the urban energy grid requires the development of automated software tools to implement targeted design of energy efficient high-rise buildings.

The application of the proposed algorithm for constructing an instant model of the distribution of solar radiation has an analytical and geometric basis for further automation of the process of optimizing the parameters of the placement of solar systems on curved surfaces of high-rise buildings.

At this stage, the study of the problem of multifactor optimization when integrating solar systems on the curved surfaces of high-rise buildings requires further development. The proposed modeling algorithm can form the basis of such development.

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