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DEVISING A TECHNIQUE FOR DESCENDING THE ILLUMINATION ELEMENTS OF AERIAL VEHICLES

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The object of this study is the process of descending illumination elements equipped with a braking device in the form of two-bladed grills rotating in different directions. The classic parachute method does not provide the necessary speed of descent, it has low illumination parameters and significant drift of illumination elements by side wind.

To solve the tasks set, mathematical dependences were obtained for calculating the aerodynamic characteristics of the descent device with the illumination element and its delivery to the ejection point. The drag and lift force coefficients during the flow around the blades of a dual-rotor impeller with different Reynolds numbers were determined by the method of numerical modeling based on the ANSYS CFX software package. The optimal geometric characteristics of the profile satisfying the condition for the necessary speed of descent of the illumination element at the given weight of the descent apparatus were determined.

Reasonable requirements for illumination parameters and an improved composition of the flare have been proposed.

A mathematical model of the movement of a body of variable mass to the point of ejection of the illumination element was built.

The new design of the descent device makes it possible to reduce the speed of descent by 10–15 % and increase the weight of the payload by 20–30 %. The proposed illumination composition provides sufficient illumination of the object for 5 minutes with a light intensity of 2–2,5 million candelas and an average diameter of the illuminated area of 2000–2500 m. The mathematical model of the movement of a variable mass body to the point of the illumination element ejection makes it possible to determine with high accuracy the gun firing settings with illumination ammunition (30–40 % more accurate) and the time of ejection of illumination elements.

Results of the current research make it possible to solve the scientific problem of ensuring the maximum efficiency of illuminating the terrain at night

Keywords: drag force, dual-rotor impeller, descent speed, illumination time, light intensity, illumination radius

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1. Introduction

A known technique for descending the illumination elements from illumination aerial vehicles implies that after they are released from the illumination aerial vehicle, they move towards the earth's surface at a constant speed. They brake by using a parachute system of a certain design [1].

The disadvantages of the known technique for descending the illumination elements are, firstly, the high speed of descent of illumination elements (10 m/s); secondly, the short time of object illumination (40–50 s) and the insignificant radius of illumination (no more than 400 m). Also, there is a large dependence of parameters of the descending illumination element's trajectory on wind speed [1], as well as a large windage (wear) of illumination elements.

Therefore, it is a relevant task to carry out studies on devising a non-parachute technique for descending an illumination element equipped with a two-rotor impeller.

2. Literature review and problem statement

A lot of attention is paid in the scientific literature to the improvement of aerial vehicles (munitions) for main purpose [1–3]. At the same time, a small number of studies report research on the improvement of illumination aerial vehicles (munitions).

Design features of parachute-type illuminating ammunition are given in work [1]. But the issues related to increasing the time of the illumination element in the air, as well as keeping it above the place of illumination (preventing lateral wear) remained unresolved. To eliminate the shortcomings, a non-parachute technique for descending illumination elements with the use of an aerodynamic brake is proposed.

In [2], the chemical composition of illumination elements is considered, which, at present, no longer provide the necessary parameters for illuminating an area during rescue operations (conducting combat operations). A study was conducted to determine the increase in illumination of the area by improving the illumination element, to substantiate requirements for illumination parameters; an improved composition of the lighting torch was proposed.

Work [3] describes aircraft movement processes in a disturbed environment. At the same time, there are no dependences in the system of differential equations of motion for calculating the opening time of the carrier of illumination elements. An option to overcome this problem is to build a mathematical model of the movement of the body to the point of ejection of an illumination element.

The studies in [4] were carried out to identify the mechanism and the degree of influence of the loading of turbine profiles on their efficiency by means of numerical modeling of the flow in grids. However, the simulation of a group of gratings differing in the angle of entry (the angle of rotation of the flow) has not been carried out. It is necessary to consider configuration options, which would allow obtaining more effective profiles in the future.

The system of differential equations of motion of various types of aircraft proposed in [5] was built by taking into account the influence of wind, rotation, and curvature of the Earth; it allows determining the opening time of illumination elements. At the same time, this system does not take into account the eccentricity of the traction force, aerodynamic eccentricity, eccentricity of the center of gravity, and other parameters that significantly affect the accuracy of delivery of illumination elements to the lighting area.

The issues considered in [6] refer to the clarification of the physical essence and nature of the emergence of aerodynamic forces, their dependence on the physical and mechanical properties and physical parameters of the environment, conditions of movement at different speeds. However, the proposed theoretical models for modeling the flow of liquid and gas around bodies do not make it possible to obtain the main operating characteristics of a two-rotor impeller.

The design parameters of the artillery projectile reported in [7] make it possible to significantly increase the flight range of the latter. But they do not allow delivery and ejection of illumination elements with sufficient accuracy over the lighting object.

All this gives reason to assert the expediency of conducting research aimed at overcoming existing problems related to the speed of descent and large lateral drift of the illumination element, as well as insufficient burning time of its torch and illumination radius. The use of illumination elements of an improved design will greatly facilitate search and rescue operations (conducting combat operations) at night or under conditions of limited visibility.

3. The aim and objectives of the study

The purpose of our research is to find alternative ways for descending the illumination elements, to design a descending apparatus that provides improved characteristics for descending and illuminating an area. This will make it possible to provide effective illumination of the area during rescue operations (conducting combat operations).

To achieve the goal, the following tasks were set:

– to calculate parameters for the aerodynamic brake of a non-parachute descent device;

– to improve the illuminating composition of the torch with the highest radiation intensity;

– to build a mathematical model of the movement of a body to the point of opening of illumination elements.

4. The study materials and methods

The object of our study is the process of descending the illumination elements of illumination ammunition, which are equipped with a braking device in the form of two bladed gratings rotating in different directions.

Research hypothesis assumes that the proposed structure makes it possible to create such kinematic flow characteristics at the exit from the first grid, which will significantly increase the efficiency of the next row of blades. Such a layout forms an aerodynamic brake that reduces the descending speed of illumination elements, thereby ensuring an increase in the time of illumination of terrain by these elements.

Accepted assumptions and simplifications:

– the density of the air flow that hits the blades of the aerodynamic brake grills is a constant value;

– acceleration of free fall along the path of descent of the illumination element is constant;

– the wind flow is continuous;

– drag coefficients C_x and resistance coefficient C_y are determined by numerical modeling.

The speed of lowering the illumination torch of existing illumination elements (parachute technique) [1] from a height of 400–600 m is, on average, 10 m/s. At the same time, the burning time of the lighting composition is 40–45 s, and the lighting radius is no more than 450 m. The specified parameters do not meet the current requirements for lighting the area under conditions of hitting targets with artillery fire or conducting rescue operations at night, as well as under conditions of limited visibility.

The parachute technique for descending the illumination elements, in addition, accepts a large drift (due to windage) of the torch from the target at a wind speed exceeding 10 m/s.

Underlying the proposed technique is the task to reduce the speed of descending the illumination elements, thereby ensuring an increase in the time of illumination by these elements of the terrain. The task is solved by introducing a new design solution that is radically different from the existing one (parachute descent), the main component of which is an aerodynamic brake [8, 9].

From the point of view of the design layout, the novelty of the aerodynamic brake under consideration is the use of two blade grills rotating in different directions. This design is used in aviation on helicopters and airplanes, as well as in wind turbines [10–13]. But it is used for the first time as an aerodynamic brake.

The advantage of this structure is the possibility of creating kinematic flow characteristics at the exit from the first grid that could significantly improve the efficiency of the next row of blades. Therefore, the efficiency of the proposed design with a counter-rotor structure increases at least 2.5 times [14, 15].

The aerodynamic forces of the blades do not slow down but on the contrary, induce impeller rotation due to the energy of the wind flow coming from below [16–19].

The drag coefficient C_x with the air flow around the blade with different Reynolds numbers *Re* was determined by numerical modeling based on the ANSYS CFX software package [4, 20–23]. A comparative analysis of the resulting graphical dependence with experimental data was carried out.

The proposed procedure makes it possible to obtain the basic operating characteristics of a two-rotor impeller by the method of numerical experiment with an error of 5–7 % compared to the experimental method of blowing in a wind tunnel [24, 25].

Since the main working body of a two-rotor impeller is a blade of a certain profile, in the given problem, in order to improve the aerodynamic characteristics of the impeller (C_x, C_y), there was a need to model the airflow around a separate blade. The goal is to obtain a pattern of the flow around the blade and to further modernize the geometric parameters of its profile [25].

Our calculations were performed by direct integration of the Navier-Stokes equation [26] using the Shear Stress Transport (SST) turbulence model. The calculations were carried out using the program developed at the Department of Applied Hydro-Aerodynamics, Sumy State University (Ukraine), by the method of numerical modeling of the working process of wind engines [17, 22].

In addition, the chemical composition of the torch of the illumination element was investigated. The hypothesis in this part of the study assumed that the improved pyrotechnic composition of the illumination element could increase the time, intensity, and diameter of the illumination of the area, which would improve the conditions for conducting rescue operations.

Accepted assumptions and simplifications:

– the technological process of mixing the pyrotechnic composition and pressing it into the shell does not change;

– the shape of the torch remains cylindrical;

– the inflammatory composition does not change.

The illumination elements [1] used in illumination aerial vehicle are located in the aircraft and are ejected at a given point of the trajectory under the action of a knockout charge. After being ejected, the ignited illumination elements descend and illuminate the area.

In order to overcome the low effectiveness of existing illumination pyrotechnic compositions, a study will be conducted to determine the requirements for the lighting parameters of objects in the area during search and rescue operations (conducting combat operations) under conditions of limited visibility. The necessary illumination parameters were determined: the diameter of the lighting spot, the duration (time) of illumination, the pyrotechnic composition of the torch of the illumination element.

The following general requirements are imposed on pyrotechnic compositions for illumination aerial vehicle [2]: maximum illumination effect with minimal consumption of the composition (at the same time, its density should be the highest). In this case, the illumination effect is achieved by such parameters as light intensity, radiation intensity in a given range of the visible spectrum, and other properties of the illumination composition.

The process of determining the opening point of the illumination projectile was also studied.

The hypothesis of the research in this part assumed that the opening point of the illumination projectile could be determined with high accuracy using a system of differential equations of motion of the aircraft in space.

Accepted assumptions and simplifications:

– the problem of the movement of a body in space is reduced to the problem of the movement of a system of particles;

– the system of differential equations does not take into account the eccentricity of the traction force, the aerodynamic eccentricity, and the eccentricity of the center of mass.

Model representations of a material point (particle) of a completely solid body, as well as a body of variable mass, are fundamental and, at the same time, the simplest concepts when studying the laws of movement of bodies in space.

In this sense, the problem of the motion of any body can be reduced to the problem of the motion of a system of particles.

Following the tradition of classical ballistics, a ballistic model of motion was used when compiling the equations of motion of a body of variable mass [3, 7]. When constructing the vector of the amount of movement $\sum_{i=1}^{n}\vec{F}_i$ the following factors were taken into account: the force of drag R_x; jet engine thrust P; gravitational force Q.

In addition, the influence of wind, rotation, and curvature of the Earth was taken into account in the system of differential equations.

The system of differential equations (SDE) was solved using fourth-order numerical integration applying the Runge-Kutta method.

Computer simulation of the aircraft movement along the trajectory to the point of ejection of illumination elements was carried out on the basis of a mathematical model of the movement of a body of variable mass. This makes it possible to determine, with high accuracy, installations for firing illuminating ammunition and the time of ejection of illuminating elements.

5. Results of studies on the determination of alternative ways for descending the illumination elements

5. 1. Results of the calculation of parameters of the aerodynamic brake of a non-parachute descent device

It is proposed to land the illumination elements with the help of a two-rotor impeller, which has blades set at a certain angle. Such a layout enables the generation of a lift aerodynamic force, which makes it possible to reduce the speed of the descending illumination elements and helps prolong the time of illuminating an object.

After the illumination aerial vehicle reaches the required point of the trajectory (opening point) above the illumination area, the controlling element (remote tube) is activated, which ignites the knockout charge. Gases formed during the combustion of the powder of the knockout charge generate the necessary pressure, under the action of which the thread of the bottom of the aerial vehicle is cut through the diaphragm and half-cylinders in which the illumination element assembly is placed. At the same time, under the action of centrifugal forces, the bottom moves away from the trajectory of the latter and clears the way for the ejection of the illumination element. In this case, the force of the flame of the knockout charge through the apertures of the diaphragm ignites the pyrotechnic illumination composition of the torch of the illumination element.

After leaving the body of the aircraft, the half-cylinders fly in different directions, releasing the assembly of illumination element (Fig. 1).

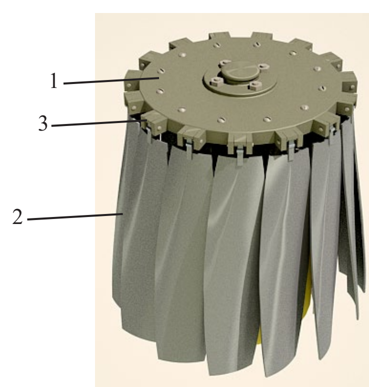

Fig. 1. The assembly of illumination element in the transport position: 1 – the base of the impeller; 2 – impeller blade; 3 – blade stop

Under the action of high-speed air pressure and the initial impulse of the elastic stoppers (item 4 in Fig. 2), the impeller blades are opened, which are moved to the working position, limited by stops 3 of the base (Fig. 1). In the extended state, the stopper also prevents involuntary folding of the blades.

General appearance of the illumination element with a two-rotor impeller in the working position is shown in Fig. 3.

The rotation of the impeller relative to the housing of the illumination element is enabled by the incoming air flow, which creates a lift force, which allows for the descent of the entire structure at the calculated speed and for illuminating the area for a given time.

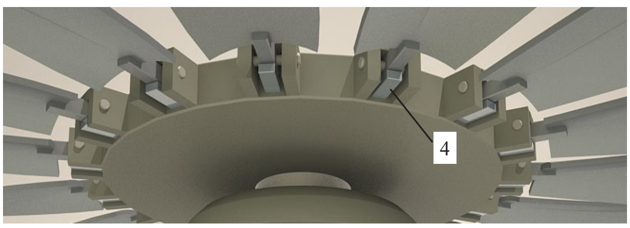

Fig. 2. Spring-loaded stopper of the impeller base: 4 — spring stopper

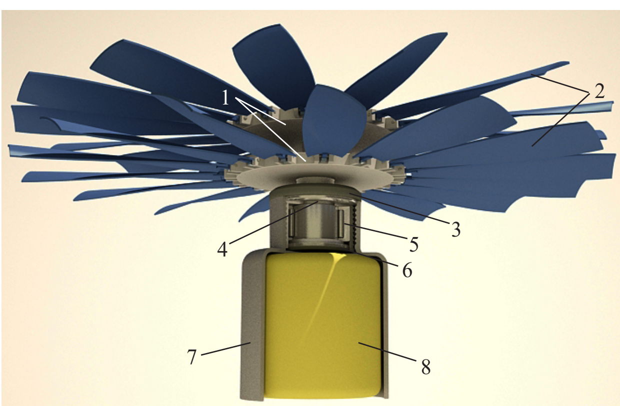

Fig. 3. Illumination element with two-rotor impeller: 1 — upper and lower base of the impeller; 2 — impeller blades; 3 — housing of the connecting device; 4 — sleeve; 5 — bearing device; 6 — cover; 7 — housing of the illumination element; 8 — illumination composition

Our calculations showed that equipping the illumination element with a two-rotor impeller makes it possible to effectively use the energy of the wind stream coming from below and to reduce the speed of descent of the illumination element by 1.5–2 times compared to parachute descent.

The shape and dimensions of the impeller blades are set based on the design and weight of the payload; for this study, they take the form shown in Fig. 4.

The aerodynamic forces of the blades do not slow down but on the contrary, generate the rotation of the impeller due to the energy of the wind flow coming from below [16–19]. Since in this case the wind flow is continuous (Fig. 5), the particles of the flow flowing around the profile from above must travel a longer distance over the same time than the particles flowing around the profile from below.

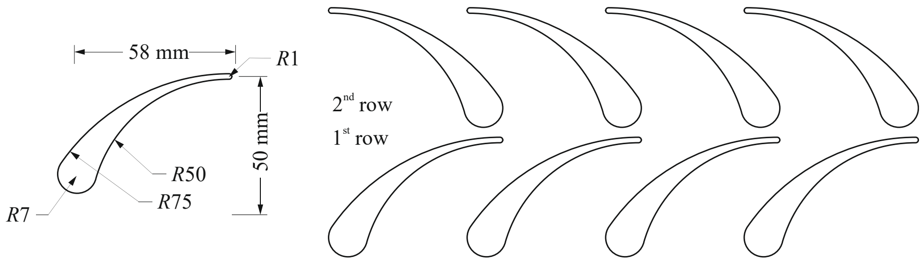

Fig. 4. Basic parameters of the impeller blade, mm: *R*1 — radius of the leading edge of the blade; *R*7 — radius of the leading edge of the blade; *R*50 — radius of the lower forming blade; *R*75 — radius of the upper forming blade; 58 — projection of the blade on a plane perpendicular to the oncoming flow; 50 — projection of the blade onto a plane parallel to the oncoming flow

Therefore, according to Bernoulli's law, on the lower surface of the airfoil, where the flow velocity is lower, the air pressure is greater than on the upper surface. The pressure difference on the surfaces creates a drag force R_x (Fig. 6) (in the given case, it will be a lift force).

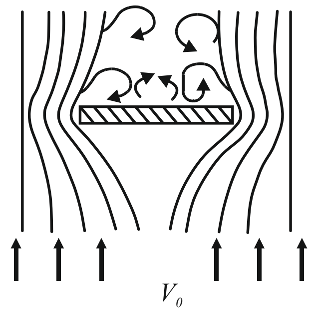

Fig. 5. Air flow around the blade of the impeller

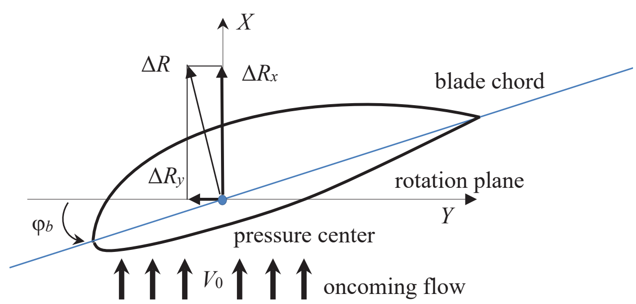

Fig. 6. Kinematic parameters and aerodynamic forces of the blade profile

The equilibrium condition of a system is determined by Newton's second law:

$$F = R_x - Q, \tag{1}$$

where R_x is the force of drag; Q is the force of gravity.

If the body is moving at a constant speed, its acceleration is $a=0$. Then:

$$R_x = C_x \frac{\rho V_0^2}{2} brn, \tag{2}$$

$$Q = mg,$$

where m is the mass of a two-rotor impeller; g – acceleration of free fall; ρ – air density; b – blade width; r – blade radius; V_0 is the speed of the incoming air flow; n – number of blades (1st row – 10 blades, 2nd row – 10 blades).

The drag force coefficient C_x was determined according to the following dependence [3]:

$$C_x = -\frac{4m}{\rho S_{cs}} \frac{\frac{t_2}{t_1}x_1 - x_2}{\frac{t_2}{t_1}x_1^2 - x_2^2} \left(1 + \frac{2}{3} \frac{\left(\frac{t_2}{t_1}x_1 - x_2\right)\left(\frac{t_2}{t_1}x_1^3 - x_2^3\right)}{\left(\frac{t_2}{t_1}x_1^2 - x_2^2\right)^2} \right), \quad (3)$$

where S_{cs} is the cross-sectional area of a two-rotor impeller; x_1, x_2 – distance to speed measurement points; t_1, t_2 – flight time of the device descending to the points of the trajectory x_1, x_2.

Numerical simulation determined the drag coefficient C_x when the air stream flows around the blade with different Reynolds numbers Re on the basis of the ANSYS CFX software package [4, 20–23]. A comparative analysis of the obtained graphical dependence with experimental data was carried out. The results are shown in Fig. 7.

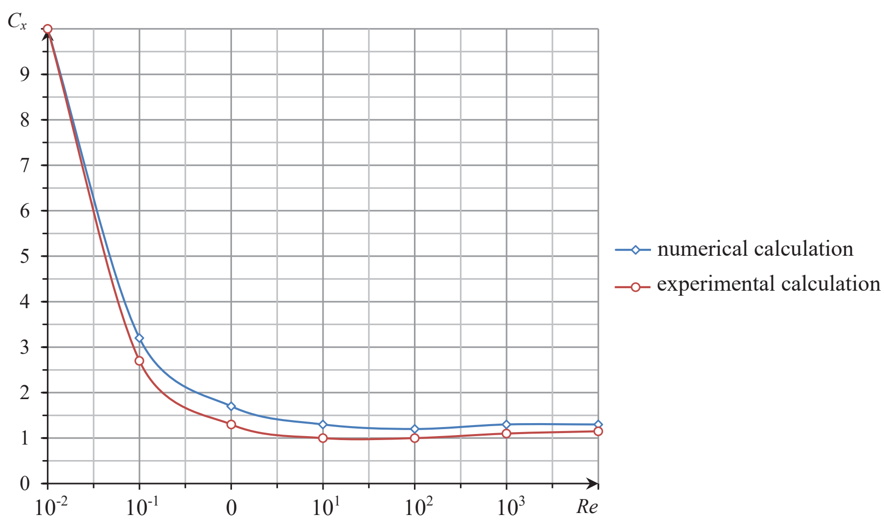

Fig. 7. Comparative characteristics of the experimental and numerical simulation-derived dependence $C_x = f(Re)$ for the projected blade

Our procedure makes it possible to obtain basic operating characteristics of a two-rotor impeller by the method of a numerical experiment with an error of 5–7 % compared to the experimental method of blowing in a wind tunnel [24, 25].

The descending speed of the illumination element with a two-rotor impeller can be determined from the expression:

$$V = \sqrt{\frac{2mg}{C_x \rho b r n}}, \quad (4)$$

the mass – from expression (4):

$$m = \frac{C_x \frac{\rho V^2}{2} b r n}{g}. \quad (5)$$

In addition to the drag force R_x, a rotational resistance force occurs on each element of the blade, which generates a torque on the impeller shaft:

$$M_\tau = R_y r_1, \quad (6)$$

where R_y is the resulting force of resistance to rotation (Fig. 8); r_1 is the radius from the axis of rotation to the center of pressure:

$$R_y = C_y \rho \frac{V_0^2}{2} r l n, \quad (7)$$

where l is the blade length; C_y is the aerodynamic force coefficient R_y, which is determined from the following expression [3]:

$$C_y = \frac{2 q r_m \left(1 - \sqrt{\sigma}\right)^2 a^2}{d l 10^3 V_0^2 \delta_{\max}}, \quad (8)$$

where q is the weight of the descent device; r_m – amplitude of nutational oscillations; σ – coefficient of gyroscopic stability; a – angular speed of precession; d – diameter of the two-rotor impeller; l – blade length; V_0 – speed of air flow; $\delta_{\max}$ is the maximum value of the nutation angle.

The aerodynamic quality of the profile represents the ratio of the lift force coefficient to the drag coefficient at a given blade installation angle (φ_b):

$$K = \frac{C_y}{C_x}. \quad (9)$$

As the blade installation angle increases, the quality of the profile first increases due to the predominant growth in C_y, reaches the maximum value $K_{\max}$, and then decreases due to the predominant growth in C_x (Fig. 9). At large supercritical blade installation angles, K approaches zero.

The resistance coefficient C_x, on which the drag resistance R_x depends, increases almost linearly up to a certain value $C_{x\max}$ depending on the angle of installation of blades φ_b, after which the further increase in φ_b is accompanied by a decrease in C_x (Fig. 10).

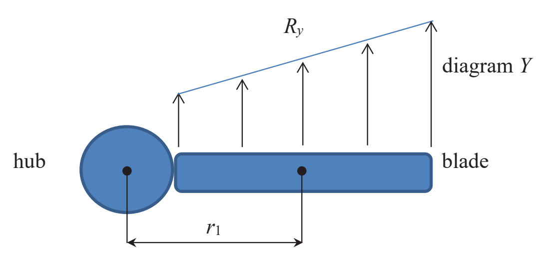

Fig. 8. Resultant rotational resistance force

A sharp drop in the value of C_x and the force R_x itself after reaching the critical angle $\varphi_{b\,cr}$ is explained by a violation of the smoothness of the flow around the blade element when strong vortices are created on its surface with a separation of the air jet. Our calculations showed that $\varphi_{b\,eff}$ for the proposed design of the blade is 15°.

The drag coefficient C_y depends mainly on the blade installation angle, the condition of the blade surface, and the speed of its rotation on the rotor axis.

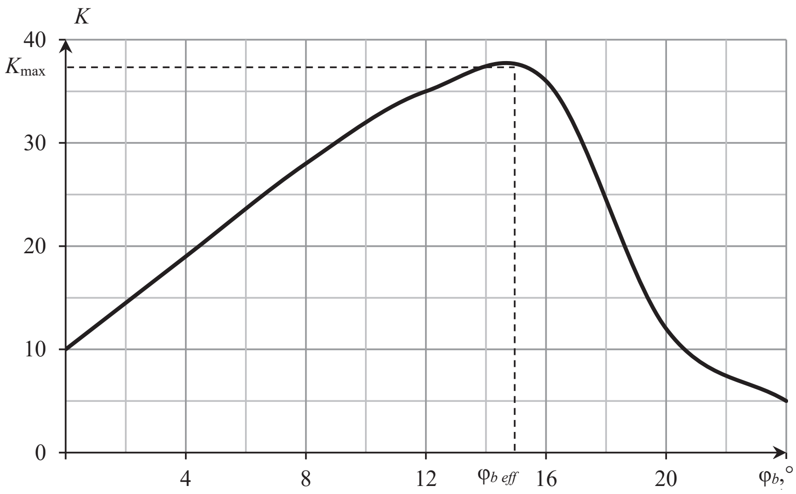

Fig. 9. Dependence of aerodynamic quality on the angle of installation of the blade

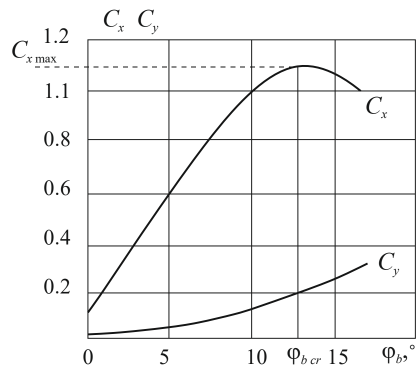

Fig. 10. Dependence of aerodynamic coefficients on the angle of blade installation

The grilles of the impeller rotate in different directions: the first (lower) – counterclockwise with an angular velocity ω_1, the second (upper) – clockwise with an angular velocity ω_2.

During the movement of the two-rotor impeller, the air density and the weight of the descending device change, therefore the number of revolutions of the impeller will change.

Components of drag force ΔR_x and the forces of resistance to the rotation of the rotor ΔR_y create an elementary uniform force ΔR in the center of pressure (Fig. 6). If its projection on the area of rotation is directed rotation-wise (as in the above case), then its horizontal component generates an additional lift force and accelerates the twisting aerodynamic moment M_τ (6).

The slope of the equivalent vector ΔR mainly depends on the blade installation angle φ_b.

Thus, the use of a two-rotor impeller contributes to the generation of additional lift force ΔR_y, which makes it possible to significantly reduce the speed of descending the illumination element; the calculations showed, by 10–15 %. The proposed design increases the possible duration of flare at the same height of its burning, as well as the weight of the payload of the descent device by 20–30 %.

To calculate the parameters of blades for a two-rotor impeller, calculations were performed by direct integration of the Navier-Stokes equation (10) [26] using the SST model of turbulence.

Modeling using the SST turbulence model involves solving the following equations:

– kinematic turbulent viscosity:

$$\nu_T = \frac{\alpha_1 k}{\max(\alpha_1, \omega, S, F_2)};$$

– turbulent kinetic energy:

$$\frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial x_j} =$$

$$= P_k - \beta^* k\omega + \frac{\partial}{\partial x_j}\left[(\nu + \sigma_k \nu_T)\frac{\partial k}{\partial x_j}\right]; \qquad (10)$$

– dissipation index:

$$\frac{\partial \omega}{\partial t} + U_j \frac{\partial \omega}{\partial x_j} =$$

$$= \alpha_2 S_2 - \beta^* \omega^2 + \frac{\partial}{\partial x_j}\left[(\nu + \sigma_\omega \nu_T)\frac{\partial \omega}{\partial x_j}\right] +$$

$$+ 2(1 - F_1)\sigma_{\omega 2}\frac{1}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j}.$$

Coefficients and constants:

$$F_2 = \tan\left[\left[\max\left(\frac{2\sqrt{k}}{\beta^* \omega y}, \frac{500\nu}{y^2 \omega}\right)\right]^2\right];$$

$$P_k = \min\left(\tau_{ij}\frac{\partial U_i}{\partial x_j}, 10\beta^* k\omega\right);$$

$$F_1 = \tan\left\{\left\{\min\left[\max\left(\frac{\sqrt{k}}{\beta^* \omega y}, \frac{500\nu}{y^2\omega}, \frac{4\sigma_{\omega 2} k}{CD_{k\omega} y^2}\right)\right]\right\}^4\right\};$$

$$CD_{k\omega} = \max\left(2\rho\sigma_{\omega 2}\frac{1}{\omega}\frac{\partial k}{\partial x_i}\frac{\partial \omega}{\partial x_i}, 10^{-10}\right);$$

$\alpha_1 = 5/9$; $\alpha_2 = 0.44$; $\beta^* = 0.09$;

$\sigma_{k1} = 0.85$; $\sigma_{k2} = 1$; $\sigma_k = 0.5$;

$\sigma_\omega = 0.5$; $\sigma_{\omega 2} = 0.856$;

where k is turbulent kinetic energy; ω – specific rate of dissipation; S – rapid deformation; ν – kinematic viscosity; τ_{ij} – component of the shear stress tensor; α_i, β_i – model coefficients; a_{ij} – components of the Reynolds stress anisotropy tensor; C_i, c_i – model coefficients; Re is the Reynolds number; Re_t is the turbulent Reynolds number; S_2 – component of the strain rate tensor; y is the distance from the wall; U_i, U_j are velocity components.

The results of our numerical simulation of the working process of a two-rotor impeller showed that the drag force of the blade of the first grid is 2.6471 N, the speed of lowering the illumination element is 6–7 m/s. So, one blade holds a weight of 0.27 kg, and ten blades of the first grille hold 2.7 kg, respectively. Taking into account the use of the second row of blades placed at an angle to the first grille, the drag force will be 3.3 N. Thus, the two-rotor impeller holds a weight of about 6.7 kg [17, 21, 22].

To reduce the weight of the descending apparatus as much as possible, the blades of the two-rotor impeller are proposed to be made of ABS plastic. Based on the declared dimensions of the blades, the approximate weight of one blade will be 20 g, which means that the total weight of all blades is 400 g. Taking into account the weight of the hub (about 1 kg), the weight of the payload will be about 5.5–5.6 kg, most of which (about 5 kg) will fall on the illumination composition of the torch.

5. 2. Results of improving the illumination composition of the torch with the highest radiation intensity

The requirements for the development of non-parachute illumination elements are discussed below.

The illumination of an object in the direction of a given angle from the light source is determined by the following formula [2]:

$$E_\alpha = \frac{I\cos^3\alpha}{D^2}, \tag{11}$$

where I is the light intensity of the source, candela; D is the distance from the light source to the point of the illuminated surface at angle α.

Once in formula (11) D is replaced by h (h is the perpendicular distance from the light source to the surface of the object), then at $D=h/\cos\alpha$, it will take the following form:

$$E_\alpha = \frac{I\cos^5\alpha}{h^2}, \tag{12}$$

The illumination radius r will be equal to the value h tan α, that is, with a given power of the light source, the radius of the illuminated area depends on the height at which the torch is located and the angle of incidence of the light beam.

Visibility of local objects is determined by such factors as the radius of illumination; opening height; illumination contrast between the object and the background on which it is projected; illumination of the object; illumination duration.

In the case of the use of illumination equipment in the composition of aerial vehicles, it is necessary to limit the sensitivity of the composition to impact.

These circumstances made it impossible to use chlorate compositions in the specified illumination aerial vehicles, which led to the need to use less sensitive compositions based on barium nitrate. Its mass content in illumination compositions may reach 50–80 %. In addition, barium oxide, which is formed during the decomposition of barium nitrate, gives a continuous spectrum with a predominance of the yellow-green part, to which the human eye is most sensitive. Sodium salts, disintegrating during combustion with the release of sodium atoms emitting in the yellow range of the visible spectrum, increase the light strength of illumination compositions containing barium nitrate.

In order to obtain the highest intensity of radiation during the burning of illumination compositions, several conditions must be met. First, the presence of components, during combustion of which refractory substances are formed, which are in a solid (or non-volatile liquid) state at the temperature of combustion; and, secondly, the high combustion temperature of the composition. These requirements are met by compositions using aluminum, magnesium, and their alloys as fuel. When burning, metals form oxides that are at the burning temperature in a solid or liquid state and release a large amount of heat, due to which a high burning temperature is achieved.

Iditol, Bakelite, a solution of rosin in oil, SF-0112A resin, and sulfur are used as cementing agents that provide illumination compositions with the necessary mechanical strength of the pressed product [2]. Cementing agents reduce the brightness of the flame and slow down combustion, so their content in the composition is limited to 5–8 % (up to 10). If the rate of burning is still high when the cement content is up to 6 %, then part of the fuel is introduced in the form of coarse-grained metal powder, which also delays the burning.

The pressing pressure of illumination compositions is chosen depending on the properties of the composition and the required burning rate. Usually, pyrotechnic devices are pressed into the shell under a pressure of 50–100 MPa, and illumination sprockets – under a pressure of 200–300 MPa. The products are most often given the shape of a cylinder, and an incendiary composition with a fuse thread is added from one end during pressing, which is used for ignition [2].

As a result of our research, a pyrotechnic composition has been proposed, the main components of which are listed in Table 1.

Table 1

Pyrotechnic compositions of illuminating action

Component composition	Content, %						
Barium nitrate	70	62	50	66	68	75	80
Magnesium powder	12	–	–	30	–	4	–
Aluminum powder	2	–	–	–	–	–	–
Aluminum powder	12	–	36	–	28	18	15
Aluminum-magnesium alloy powder	–	27	4	–	–	–	–
Sodium silicofluoride	2	–	–	–	–	–	–
Drying oil	2	–	–	–	–	3	6
SF-0112A resin	–	11	–	–	–	–	–
Sulfur	–	–	9	–	–	–	–
Industrial oil	–	–	1	–	–	–	–
Iditol or shellac	–	–	–	4	4	–	–
Pulp powder	–	–	–	–	–	–	5

As the calculations showed, for the light intensity of the source I=2.0–2.5 million candelas, which is provided by the composition of the mixture given in Table 1, and its ejection height of about 2,000 m, creates an illumination zone with a diameter of 2,000–2,500 m. At the declared descending speed of the descent device of 6–7 m/s, sufficient illumination of the object is provided for 5 minutes.

5. 3. Results of building a mathematical model of body movement to the point of launching the illumination elements

Taking into account the above and works [5, 27, 28], the system of differential equations of motion of a body of variable mass to the point of opening of the illumination elements will take the form:

$$\begin{cases} \dot{x} = V\cos\theta\cos\psi/\left(1-2Y/R_E\right); \\ \dot{y} = V\sin\theta; \\ \dot{z} = V\cos\theta\sin\psi; \\ \dot{V} = a_t - a_x\cos\gamma - g_0\sin\theta\left(1-2Y/R_E\right); \\ \dot{\theta} = -\dfrac{\cos\theta g_0}{V} - \dfrac{a_x\cos\gamma W_x\sin\theta}{VV_r} + \dfrac{V\cos\theta}{R_E+Y} - \Omega_E\cos B\sin\left(a_r-\psi\right); \\ \dot{\psi} = -\dfrac{a_x\cos\gamma W_z}{\cos\theta VV_r} + 2\Omega_E\left(\sin B - \cos B\cos\left(a_r-\psi\right)\tan\theta\right); \\ \dot{\pi}(y) = -\dfrac{\pi(y)\dot{y}}{R\left[\tau_y+\Delta\tau\right]}, \end{cases} \tag{13}$$

where for active-reactive aircraft [29]:

$$a_x = 0.474\frac{id^2}{q_0+\Delta q}\pi(y)V_{r\tau}^2 C_x(V_{r\tau}),$$

$$\cos\gamma = \frac{V - W_x\cos\theta}{V_r};$$

for winged aircraft [29]:

$$a_x = 0.474\frac{i_a d^2}{q_A}10^3\pi(y)\frac{F_{58}(V_{r\tau})}{(1-\mu_y)}, \pi(y) = \frac{e^{\pi_0}}{\dfrac{y}{e^{R\cdot\tau_y}}},$$

$$V_r = V\sqrt{1-\frac{2(W_{ax}\cos\theta\cos\psi + W_{az}\sin\psi\cos\theta)}{V}+\frac{W_a^2}{V^2}},$$

$$\cos\gamma = \frac{V - W_{ax}\cos\theta}{V_r},$$

$$W_a^2 = W_{ax}^2 + W_{az}^2, V_{r\tau} = V_r\sqrt{\frac{\tau_{ON}}{\tau_y}}, \Delta T_{tab} = T_{tab} - 15\,^\circ\mathrm{C},$$

$$a_t = \frac{\omega_0(I_{1N} + K_1\Delta T_{tab})}{m_0[\tau_{aN} - K_2\Delta T_{tab}](1-\mu_y)},$$

$$\mu_y = \frac{\omega_0(t - t_H)}{g_0 m_0(\tau_{aN} - K_2\Delta T_{tab})}, m_0 = \frac{q_0}{g_0}.$$

Distribution of air temperature with altitude:

$$\tau_y = \begin{cases} \tau_y = 288.9 - 6.328Y\cdot 10^{-3} + \Delta\tau, \text{ if } Y \le 9.300; \\ \tau_y = 230 - 6.328\cdot 10^{-3}(Y - 9{,}300) + \\ +1.172\cdot 10^{-6}(Y - 9.300)^2 + \Delta\tau, \\ \text{if } 9.300 < Y \le 12.000; \\ \tau_y = 221^\circ + \Delta\tau, \text{ if } Y > 12.000; \end{cases}$$

in the passive section of the trajectory [29]:

$$a_x = \frac{i_P d^2}{q_P}10^3\pi(y)F_{58}(V_{r\tau}), i_P = i_a/0.85,$$

$$q_P = q_A - \omega_0, \cos\gamma = \frac{V - W_{Px}\cos\theta}{V_r},$$

$$V_r = V\sqrt{1-\frac{2(W_{Px}\cos\theta\cos\psi + W_{Pz}\sin\psi\cos\theta)}{V}+\frac{W_P^2}{V^2}},$$

$$W_P^2 = W_{Px}^2 + W_{Pz}^2,$$

$$V_{r\tau} = V_r\sqrt{\frac{\tau_{ON}}{\tau_y}},$$

where a_t is reactive acceleration; a_x is the acceleration of the drag force; θ_0 is the initial pitch angle; ψ is the yaw angle; g_0 is the acceleration of free fall near the Earth's surface; $\pi(y)$ is a function of atmospheric pressure distribution by height; F_{58} ($V_{r\tau}$) is the resistance reference function; R is the gas constant per 1 kg of dry air; τ_y is the law of air temperature distribution by height; $\Delta\tau$ is the increase in air temperature; I_1 is the unit thrust impulse of the engine; ω_0 is the weight of the reactive charge; μ_y is the relative consumption of the mass of the aircraft during time t in relation to the initial mass of the aircraft m_0; K_1, K_2 is the dimensional coefficients that take into account the effect of the temperature of the jet engine T_{tab} on the unit thrust impulse of the engine I_1 and the engine operation time τ_a, respectively; I_{1N}, τ_{1N} is the unit thrust impulse of the engine and its operation time at tabular temperature T_{tab}=15 °C; q_0 is the initial weight of the aircraft; q_A is the weight of the aircraft on the active part of the trajectory; q_P is the weight of the aircraft on the passive part of the trajectory; i_a, i_P are the shape factor of the aircraft on the active and the passive part of the trajectory, respectively; d is the caliber of the aircraft; W_{ax}, W_{az} is the longitudinal and lateral components of the ballistic wind on the active part of the trajectory; W_a is the wind speed on the active part of the trajectory; V_r is the relative speed of the aircraft; $V_{r\tau}$ is the relative speed of the aircraft taking into account the virtual air temperature; Ω_E is the angular velocity of the Earth's daily rotation; R_E is the radius of the Earth; a_r is the geodetic launch azimuth; Y is the height of the trajectory.

The system of differential equations (13) was solved using fourth-order numerical integration applying the Runge-Kutta method.

Computer simulation of aircraft movement along the trajectory to the point of ejection of illumination elements was carried out on the basis of a mathematical model of the movement of a body of variable mass.

Ejection of the illumination element is carried out with the help of a knockout charge, which is triggered by a pyrotechnic device – a remote tube or another way (for example, a remote detonator with a clock mechanism). The operation of the device begins with the launch of the aerial vehicle (shot) and ends with the initiation of the knockout charge of the aerial vehicle at the end of a predetermined time.

Our mathematical model of the movement of a body of variable mass to the point of ejection of an illuminating element makes it possible to determine with high accuracy the installation for firing illuminating ammunition and the time of ejection of illuminating elements.

The accuracy of determining the settings by the proposed method increases by 30–40 %. The time to calculate settings is significantly reduced, from 4–5 minutes to 1–2 minutes.

6. Discussion of results of designing an aerodynamic brake for descending the illumination element

To solve the task to design a reliable aerodynamic brake for descending the illumination element, let's pay attention to the aerodynamics of the profiled blades. As a working body, a blade grille is considered, the working process of which is based on the principles of aerodynamic turbines. Under the influence of the air flow created when the illumination element is lowered, the impeller begins to rotate. To increase the time the illumination element stays at the desired height range, it is necessary to generate an aerodynamic force that counteracts the force of gravity. That is why the idea arose to combine the aerodynamic characteristics of turbine blades and aerial vehicle blades aimed at generating a lift force [6, 8, 9].

The combination of characteristics implies the fact that in order to induce a lift force, the blades move due to the geometric similarity to the blades of steam turbines [19] and, at the same time, generate a lift force directed against the force of gravity.

The geometric difference is that the blades of steam turbines are designed under the condition of maximum loss of kinetic energy flow when passing through the blade grid and generation of high torque on the turbine shaft. This factor predetermines the geometry of the channel between blades, which changes the flow direction from 60° to 90° [8, 11, 12].

In the case of an aerodynamic brake, the angle of change in the direction of the air flow is 45°. The interblade channel is made with a diffuser to reduce the flow rate in it and redistribute energy in the direction of increasing pressure on the back side of the blade. Given this, a lift force is generated and the condition of reducing the speed for descending an illumination element is fulfilled.

From the point of view of the design layout, the novelty of the aerodynamic brake under consideration (Fig. 10) is in the use of two blade grills rotating in different directions. This design is used in aviation on helicopters and airplanes, as well as in wind turbines [10–13]. But, as an aerodynamic brake, it is used for the first time.

The shape and dimensions of the impeller blades are set based on the design and weight of the payload; for this study, they take the form shown in Fig. 3.

The advantage of this design is the possibility of creating such kinematic flow characteristics at the exit from the first grid, which will significantly increase the efficiency of the next row of blades. Therefore, the efficiency of the counter-rotor design increases by at least 2.5 times [14, 15], which makes it possible to reduce the speed of lowering the illumination element by 10–15 % and increase the weight of the payload by 20–30 %.

To reduce the weight of the descending apparatus as much as possible, the blades of the two-rotor impeller are proposed to be made of ABS plastic. Based on the declared dimensions of the blades, the approximate weight of one blade will be 20 g, which means that the total weight of all blades is 400 g. Taking into account the weight of the hub (about 1 kg), the weight of the payload will be about 5.5–5.6 kg, most of which (about 5 kg) will fall on the illumination composition of the torch.

Numerical modeling was carried out in the ANSYS CFX software package, which makes it possible to predict the aerodynamic characteristics of the aerodynamic brake with high accuracy [21, 22]. Taking into account the works on the determination of the vortex wake behind the counter-rotor wheel of the thrust propeller [23], the optimal geometric characteristics of the blade profile were determined by mathematical modeling. The resulting parameters satisfy the condition of the required speed of descent of the illumination element at the given weight of the lowering device and reliability.

From the point of view of mathematical modeling of the work process, a complex analysis of the distribution of pressure fields, flow velocity vectors and, as a result, aerodynamic forces arising in the interblade channel of a counter-rotor aerodynamic turbine was carried out. The latter acts as an aerodynamic brake for lowering the illumination element in the air stream.

In contrast to the parachute technique for braking illumination elements, the proposed technique enables the retention of the descent device, weighing about 6.7 kg, by a two-rotor impeller. At the same time, the weight of the payload and the time spent in the air increase significantly. In addition, the problem of significant wear of the torch by side wind is eliminated.

The disadvantage of the proposed layout of the descending apparatus is that the lateral wear of the descending apparatus is not completely extinguished by the wind. This does not lead to drastic changes in illumination parameters but is an impetus for further research.

To improve the illumination composition of the torch with the highest intensity of radiation, it is necessary to meet a number of conditions, the main ones of which are the presence of the necessary components and a high combustion temperature of the composition.

The components of the illumination torch must form refractory substances that are in a solid or non-volatile liquid state at the burning temperature. These requirements are met by compositions based on aluminum, magnesium, and their alloys. When burning, metals form oxides that are at the burning temperature in a solid or liquid state and release a large amount of heat, due to which a high burning temperature is achieved.

Iditol, Bakelite, a solution of rosin in oil, SF-0112A resin, and sulfur are used as cementing agents that provide illumination compositions with the necessary mechanical strength of the pressed product [2]. Cementing agents reduce the brightness of the flame and slow down combustion, so their content in the composition is limited to 5–8 % (up to 10). If the rate of burning is still high when the cement content is up to 6 %, then part of the fuel is introduced in the form of coarse-grained metal powder, which also delays the burning.

It should be noted that the pressing pressure of illumination compositions must be chosen depending on the properties of the composition and the desired burning rate. The shape of the torch should be chosen depending on the shape and size of the means of delivery of illumination elements. For use in artillery-type aerial vehicle, it is natural to choose a cylindrical shape. The ignition device must reliably ignite the main composition of the torch. Its composition and shape are chosen according to a specific sample.

As our calculations showed, for the light intensity of the source $I=2.0–2.5$ million candelas, which is provided by the composition of the mixture given in Table 1, an illumination zone with a diameter of 2,000–2,500 m is created at an opening height of 2,000 m. At a speed of the descent device of 6–7 m/s, the object is illuminated for 5 minutes.

Considering the high flight speeds of aerial vehicles (projectiles) as means of delivery, it is necessary to limit the sensitivity of chemical components to impact.

In contrast to [1], the component composition proposed in this study meets all the stated modern requirements for effective illumination of the area. However, there is a wide field of possibilities for obtaining new chemical compounds, improving their composition, power, reducing weight, etc.

The task to construct a mathematical model of the movement of the body to the point of opening of the illumination elements was solved using a system of differential equations of a body of variable mass (13). The latter makes it possible to obtain the optimal time of throwing illumination elements and to determine with high accuracy the setting for firing illumination ammunition.

In contrast to traditional methods for determining firing positions, the accuracy of determining positions with the proposed method increases by 30–40 %. The time to calculate settings is significantly reduced, from 4–5 minutes to 1–2 minutes.

In the future, it is necessary to build a system of differential equations of motion of aerial vehicle that would take into account the influence of eccentricity of the traction force, center of mass, aerodynamic eccentricity, etc.

The proposed technique for descending the illumination elements of illumination projectiles was tested on combat artillery fire by military unit A1723 at the 250 State training ground of military unit B2050 in July 2021 [30].

As research tests have shown, dropping a BpAK illumination capsule from a height of 1,200 meters provides a descent speed of 6 m/s, the illumination time was about 3 minutes. This confirms the calculations reported in the current paper.

Our recommendations from the study could be used for designing new types of illumination aerial vehicles (munitions).

7. Conclusions

1. The use of a two-rotor impeller to generate a lift force makes it possible to reduce the maximum speed of the torch descent and increase the time of illumination of the area.

Numerical modeling determined the coefficients of drag and lift, as well as the parameters of the impeller when air flows around it with different Reynolds numbers based on the ANSYS CFX software package.

The proposed design makes it possible to create such kinematic flow characteristics at the exit from the first grid, which significantly increase the efficiency of the next row of blades. The counter-rotor design of the braking device makes it possible to reduce the lowering speed of the illumination element by 10–15 % and increase the weight of the payload by 20–30 %. This layout additionally makes it possible to get rid of the significant influence of the side wind.

2. The requirements for illumination parameters have been substantiated and an improved composition of the illumination torch was proposed. The necessary illumination of the area is provided by the light power of the torch of 2.0–2.5 million candelas. This power of the source creates an illumination zone with a diameter of 2,000–2,500 m at an opening height of 2,000 m, which, in combination with the declared characteristics of the descent device, ensures an illumination time of the object within 5 minutes.

3. A mathematical model of the movement of a body of variable mass to the point of opening of the illumination elements has been proposed. The model describes the movement of a body of constant and variable mass; it is a system of differential equations. It takes into account the influence of wind, rotation, and curvature of the Earth. It makes it possible to determine the parameters of movement for conventional and active-reactive aerial vehicles on both active and passive sections of the trajectory, taking into account the distribution of temperature and air pressure with height. In addition, SDE takes into account the longitudinal and lateral components of the ballistic wind separately in the active and passive sections of the trajectory. SDE was solved by using fourth-order numerical integration using the Runge-Kutta method with an integration step of 0.001 s, taking into account meteorological, ballistic, and geophysical firing conditions. That has made it possible to determine with high accuracy the point of ejection of illumination elements above the illumination object.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

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

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