

This paper investigates working processes in a liquid nozzle system powered by a gas-hydraulic accumulator used for aircraft takeoff. The study is aimed at finding regularities in the operation of a hydraulic system, which includes a gas-hydraulic accumulator and nozzles with a variable cross-sectional shape that operate at variable pressure. These regularities determine the kinematic parameters of an aircraft that is propelled by a liquid nozzle system.

Numerical modeling of the working processes in nozzles of a special shape showed an increase in vortex formation and a more dramatic increase in the velocity in the flow core at the end section of the nozzle. It was established that energy losses for nozzles with a variable cross-sectional shape are 4% greater than for conical nozzles.

The established patterns of the gas-hydraulic accumulator charging and discharging processes have made it possible to determine the optimal ratio between the mass of the liquid and the filled accumulator, equal to 0.23.

It is shown that the maximum amount of energy and liquid is obtained when the nozzles operate at a variable pressure that falls below the initial charging pressure. Based on the nozzle thrust, dependences of the takeoff height, speed, and acceleration of the aircraft on its mass were determined. It was found that at a ratio of aircraft mass to the mass of the gas-hydraulic accumulator of 2.0, the nozzle system provides only horizontal acceleration to the breakaway speed, and when the ratio is less than 0.2, vertical lift and horizontal acceleration to the breakaway speed are achieved.

The results could be used to assess the maximum capabilities of a takeoff system when applying water as the working fluid

Keywords: aircraft, gas-hydraulic accumulator, liquid jet nozzle, vertical takeoff, computational fluid dynamics, energy characteristics

DEFINING THE PATTERNS OF A JET TAKEOFF SYSTEM OPERATION IN AN AERIAL VEHICLE WITH NOZZLES OF A SPECIAL SHAPE, POWERED BY A GAS-HYDRAULIC ACCUMULATOR

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1. Introduction

Given the rapid evolution of unmanned systems, aircraft-type aerial vehicles that do not require a runway for launch have become widespread. Vehicles can be equipped with vertically placed propellers used only for takeoff or rotary engines.

Aerial vehicles can also be launched using a catapult [1]. With this takeoff technique, there is no need to use vertically placed propellers. Due to better aerodynamics, the absence of additional engines and batteries, the weight of the aircraft is reduced, and the range of use is increased. A typical solution is a pneumatic catapult, which includes a high-pressure cylinder and a guide. The need to absorb significant forces acting during launch predetermines the large mass of the installation. The catapult must be delivered and mounted at the launch site; its use involves rigid fixation on the ground.

Installation and fastening of the catapult is time-consuming, which may be unacceptable for special-purpose aerial vehicles.

Aerial vehicles equipped with solid-fuel jet engines are also used, which are employed only for takeoff. They do not require ground infrastructure and allow for quick launch of the aircraft; however, when using solid-fuel engines, there is no possibility of reuse.

Separately, technical solutions should be highlighted that involve the use of a liquid nozzle system to propel a vehicle where water is used as the working fluid [2]. The liquid nozzle system applied to launch aerial vehicles is simple, safe, and allows reuse. This solution generates significant thrust but does not use explosive and environmentally harmful components and has a low noise level. Under the condition of high-speed liquid flow, the nozzle elements are small in size. This solution provides the possibility of hidden and quick takeoff from

any terrain, which is especially important for special-purpose aerial vehicles. The use of this launch system requires additional study on the working processes in the nozzle system and energy sources that enable its functioning. Therefore, research into liquid nozzle systems used in aircraft is relevant.

2. Literature review and problem statement

The features of the process of launching an aerial vehicle using a catapult are considered in [1]. The authors conducted experimental studies of takeoff from an inclined guide and determined the breakaway speed. The results do not allow one to take into account the features of the takeoff of an aerial vehicle powered by jet engines, in particular during its vertical lift and acceleration to the required speed.

In paper [3], patterns in the working processes of jet engines are reported, in particular, the use of a displacement fuel supply system. The principle of operation of typical engines involves the supply of liquid from the tank to the combustion chamber under the action of a constant pressure drop. Therefore, features in the operation of the gas-hydraulic system, which provides the supply of liquid to the nozzle under a pressure drop that varies in a wide range, were ignored.

In [4], the results of research on the working processes of jet engines using a gaseous working fluid are reported. However, the paper does not describe thorough studies on the working processes of nozzle systems using a liquid as a working fluid as such solutions have limited application.

In the cited papers [3, 4] there are no results of research on nozzle systems of a special shape, which is caused by the peculiarity of the operation of rocket engines that require the use of jet nozzles that convert the thermal energy of the gas into kinetic energy.

In [5], the results of research on hydraulic systems used for hydro cutting are reported. The pressure in such installations exceeds 600 MPa, and the speed of fluid outflow can reach values approaching the speed of sound in the liquid. The paper does not describe results of studying the working processes of ultra-high pressure hydraulic systems taking into account the compressibility of the liquid. The paper does not contain studies of nozzles of variable cross-section, their working processes and hydraulic characteristics. The reason is that the use of hydro-cutting systems requires the use of conical nozzles of a typical design; therefore, the study of nozzles of a special shape as part of hydro-cutting systems is impractical.

In paper [6], the results of research on working processes during the outflow of the working medium through Laval nozzles with different degrees of expansion are reported. The work studied axisymmetric channels, but nozzles with a variable cross-sectional shape were left out of consideration due to their limited application.

In [7], the hydraulic characteristics were studied, and a comparison was made of nozzles of different shapes, in particular cylindrical and elliptical. The studies were carried out for channels with a variable cross-sectional shape, including a conical part. The work did not study the working processes of nozzles, the cross-sectional shape of which varies from circular to rectangular.

In [8], the results of the study of a gas-hydraulic accumulator as part of a hydraulic system are reported; its energy characteristics are determined. The considered operating mode, which involves discharging the accumulator at a constant pressure in the hydraulic system, is characterized by sig-

nificant energy losses. A more energy-efficient mode, which involves supplying fluid to the hydraulic system at a variable pressure, is not considered in the paper as hydraulic energy consumers in typical hydraulic systems operate at a stable pressure drop. In [8], a comparison of the energy characteristics of a gas-hydraulic accumulator and other energy sources, in particular an electric capacitor, is performed. However, when studying the operating modes, thermal energy losses that occur during rapid energy accumulation and battery discharge are not taken into account.

Our review of the literature [1, 3–8] gives grounds to argue that it is advisable to conduct a study aimed at finding regularities in the operation of a hydraulic system, which includes a gas-hydraulic accumulator and nozzle elements with a variable cross-sectional shape that operate at variable pressure, which determine the kinematic parameters of an aerial vehicle that is set in motion by means of a liquid nozzle take-off system.

3. The aim and objectives of the study

The purpose of our study is to determine patterns that characterize the working processes in a variable pressure hydraulic system that uses a gas-hydraulic accumulator to power nozzles with a variable cross-sectional shape at variable pressure, designed to generate traction. These patterns make it possible to define the kinematic parameters of an aerial vehicle that is driven by a liquid nozzle system during vertical takeoff and acceleration to breakaway speed.

To achieve the goal, it is necessary to solve the following tasks:

- to conduct numerical modeling of the process of liquid leakage from nozzles with a variable cross-sectional shape and conical nozzles at a variable pressure drop, compare their characteristics;
- to define the hydraulic parameters of the takeoff nozzle system operating at variable pressure based on the results of research into the process of charging and discharging a gas-hydraulic accumulator;
- to determine the takeoff height, speed, and acceleration of the aerial vehicle depending on the ratio of its mass to the mass of the gas-hydraulic accumulator.

4. Materials and methods

4.1. The object and hypothesis of the study

The object of our study is the working processes in a liquid nozzle system powered by a gas-hydraulic accumulator used for takeoff of an aerial vehicle.

The principal hypothesis assumes a decisive influence of the characteristics of a hydraulic system built on the basis of a gas-hydraulic accumulator and nozzles of a special shape on the kinematics of an aerial vehicle during vertical lift and acceleration to the required speed. It is also assumed that the working processes in nozzle elements of variable cross-section have significant differences compared to conical nozzles and require additional study to establish their hydraulic characteristics.

Results are necessary to determine the integral parameters of the nozzle system used for takeoff. It is assumed that the practical implementation of a liquid nozzle system for takeoff of an aerial vehicle requires taking into account the limitations on power, stored energy, and mass imposed on the power source and the entire system.

A promising solution for the takeoff system requires the use of a gas-hydraulic accumulator as an energy source. However, the use of such a power source involves a thorough study of its working processes during energy accumulation and discharge in order to optimize the energy intensity, power, and volume of the accumulated liquid. The defined characteristics of the take-off system, which includes the battery and the nozzle system, provide an opportunity to study the kinematics of an aerial vehicle during vertical lift and acceleration to the required speed.

The results make it possible to devise a technical solution for the take-off system that has prospects for practical application. When conducting the research, it was assumed that the liquid does not contain solid particles, as well as inclusions of steam or gas that may occur in areas of reduced pressure. The assumption was accepted that deformations of the battery housing, pipelines, and nozzle elements are insignificant and do not affect working processes in the hydraulic system.

4. 2. Structure and methods for investigating the liquid nozzle system for an aerial vehicle take-off

A typical structure of an aerial vehicle equipped with a vertical take-off and landing system includes a pulling or pushing propeller, the axis of which is located horizontally and four propellers, the axes of which are located vertically. There are more complex solutions that contain rotary engines. Such aerial vehicle can provide flight under a multicopter mode and under a fixed-wing mode. The algorithm of operation of the aerial vehicle take-off system, which includes four propellers, the axes of which are located vertically, was studied in detail. More complex are the modes of operation of the aerial vehicle during the transition from vertical lift to horizontal flight, in particular when using rotary engines [9].

The proposed aerial vehicle take-off system contains a source of hydraulic energy 1, the main nozzle elements 2, and flow regulators 3 (Fig. 1, a). A gas-hydraulic accumulator or pump can be used as an energy source. The system can be integrated into the body or attached to it. The take-off system, which is made as a separate device, can be disconnected from the aerial vehicle and dumped after take-off. Four main nozzle elements are used for lifting. An additional nozzle element 4 is installed in the rear of the aerial vehicle, which is used to increase horizontal speed during take-off. In the case of using a gas-hydraulic accumulator, its filling with liquid is carried out before starting the aerial vehicle using an additional hydraulic system, which includes a pump and a tank with liquid. The additional hydraulic system is disconnected from the aerial vehicle after refueling.

The control system allows for independent control over all flow regulators 3, which change the volume of fluid directed to nozzle elements 2 and 4. To track the angles of pitch, roll, and yaw, sensor 5 is used, which determines the angular position of the aerial vehicle in space. The control system provides the ability to maintain a stable angular position of the aerial vehicle during takeoff or change it according to a given law.

The system allows the aerial vehicle to take off from a horizontal surface. Before takeoff, the main engine of the aerial vehicle is started, and after lifting and gaining sufficient speed, the system is supposed to be reset.

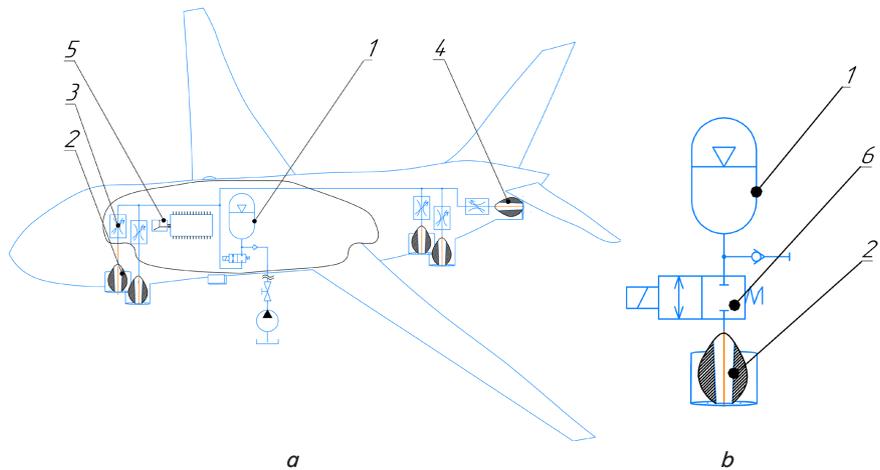


Fig. 1. Jet system for aerial vehicle takeoff: a – complex diagram; b – simplified diagram of the hydraulic system; 1 – source of hydraulic energy; 2, 4 – nozzle elements; 3 – flow regulators; 5 – angular position sensor; 6 – distributor

It is possible to use the takeoff system when placing the aerial vehicle on a special guide at an angle to the horizontal surface. The guide provides the ability to launch exclusively using an additional nozzle element 4, which is located in the rear of the aerial vehicle. The additional nozzle element provides altitude gain and acceleration to the required speed. This method of taking off the aerial vehicle involves the use of a simplified control system, which includes a distributor that provides fluid supply to the nozzle element without regulation. When the aerial vehicle is placed vertically at start-up, during start-up, a transition from vertical to horizontal flight occurs using control elements.

A simplified hydraulic diagram of the aerial vehicle take-off system is shown in Fig. 1, b. The optimal technical solution involves the use of hydraulic accumulators 1 to power nozzle elements 2, and their number corresponds to the number of nozzles. When charging, long pipelines are used to supply liquid to the accumulators. To prevent the reverse movement of liquid from the accumulators to the pump after its disconnection, check valves are used. A simplified scheme involves controlling the supply of liquid to the nozzle element using distributor 6. The use of this scheme assumes that the section of the pipeline between the accumulator and the nozzle element is short. The use of a short pipeline and a distributor with low hydraulic resistance minimizes energy losses during the operation of the take-off system.

In the take-off system of an aerial vehicle, in addition to conical nozzles with a circular cross-section (Fig. 2, a, b), it is advisable to use nozzles of a special shape, the cross-section of which changes from circular at the inlet to rectangular at the outlet (Fig. 2, c, d). A nozzle of a special shape is distinguished by a simpler production technology. A cylindrical tube is used to manufacture the nozzle, which is processed by means of plastic deformation. The use of resource-saving technologies of mass production in the manufacture of nozzles from tubular blanks significantly reduces the cost and simplifies the technical solution.

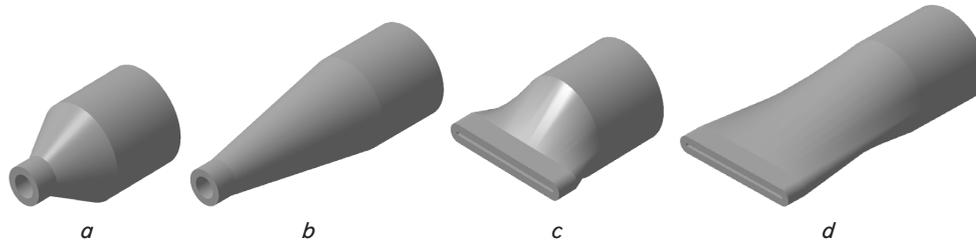


Fig. 2. Diagrams of nozzle elements: *a* – conical nozzle with a taper angle of 30°; *b* – conical nozzle with a taper angle of 10°; *c* – short nozzle of special shape; *d* – long nozzle of special shape

The research into the liquid nozzle system involved the primary modeling of the working processes of nozzle elements of various shapes and a gas-hydraulic accumulator. The next step was the study of the hydraulic system, which includes the nozzle and the source of hydraulic energy. Based on the results, the kinematics of the aerial vehicle during launch were studied.

The SolidWorks environment (Dassault Systèmes, France) was used to simulate the operation of the nozzles. The simulation involved the use of the finite volume method, which provides automatic generation of a mesh that adapts to the complex geometry of the channel. Algorithms were used to effectively model turbulent fluid flows.

The simulation involved the use of the Navier-Stokes equations averaged by Favre. This approach makes it possible to take into account the time-averaged effects of turbulence and large-scale non-stationary phenomena. Under such conditions, Reynolds stresses appear, which require additional information for solution. To close the system of equations, the algorithm uses the $k-\epsilon$ model, using the transport equation for turbulent kinetic energy and its dissipation rate. The software uses a single system of equations for both laminar and turbulent flows, which makes it possible to model the transitions between these states.

Due to the variable shape of the channel cross-section, a non-uniform basic computational grid was used, which has smaller elements in the nozzle constriction region. Additional crushing of finite volumes was used in the nozzle outlet section and in places of contact of the liquid with the walls. The boundary conditions were set in the form of pressures at the inlet and outlet of the nozzle, provided that the liquid flows into the atmosphere at a barometric pressure of 101325 Pa, and the initial temperature of the liquid was 20°C. Water was used as the working medium, and the pressure drop across the nozzle varied from 2 to 50 MPa. When modeling work processes, the nozzle taper angle was varied in the range of 10...30 degrees, and for nozzles of special shape, their length was changed.

The gas-hydraulic accumulator was simulated with an initial gas overpressure of 32 MPa. The hydraulic system was studied taking into account the change in initial pressure caused by the ambient temperature variation within $\pm 20^\circ\text{C}$.

5. Results of investigating the jet system of a take-off of an aerial vehicle powered by a gas-hydraulic accumulator

5.1. Results of numerical modeling of the process of liquid discharge from nozzles at a variable pressure drop

When liquid discharges from a high-pressure tank into an environment with atmospheric pressure through an opening,

if the hydraulic resistance of the flow part is neglected, all the potential energy of the liquid will be converted into kinetic energy. The rate of liquid discharge is determined from the following dependence [10]

$$V(p) = \sqrt{\frac{2}{\rho} \cdot \Delta p}, \quad (1)$$

where Δp is the pressure difference in the tank and the environment; ρ is the density of the liquid.

The resulting plot (Fig. 3) shows the dependence of the theoretical value of the velocity on pressure in the tank, which can be achieved without taking into account losses in the nozzle and the pipeline supplying the liquid.

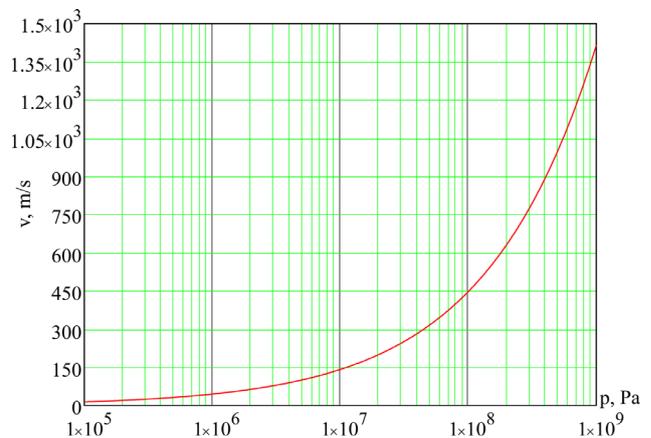


Fig. 3. Dependence of fluid flow rate on tank pressure

Analysis of the dependence reveals that when the pressure exceeds 44 MPa, a speed of 300 m/s is achieved. The use of high velocities of fluid outflow from the nozzle in the take-off system of the aerial vehicle, as well as the high density of the working fluid, makes it possible to design a compact system that provides high thrust. One of the limiting factors is the speed of sound in the environment, which for water exceeds 1400 m/s.

The complexity and large mass of ultra-high pressure hydraulic systems [5] limits their use in aerial vehicles. In addition, such hydraulic systems require a high-power energy source, which makes their use as part of the take-off system impractical. The use of pressure in the hydraulic system, which is lower than 2 MPa, is characterized by inefficient use of the fluid placed on board the aerial vehicle. At the same fluid flow rate, the nozzle system will generate a small force, which may be insufficient for lifting or achieving the break-away speed of the aerial vehicle. That is why it is most expedient to operate the aerial vehicle takeoff hydraulic system in the pressure range of 2...50 MPa.

In existing liquid nozzle systems, due to the hydraulic resistance of the nozzle and the supply pipeline, the average liquid outflow velocity and flow rate will be less than the theoretical values calculated from formula (1).

In this case, the average velocity V_c and the volumetric flow rate Q will be found from the following dependences:

$$V_A = \mu \cdot \sqrt{\frac{2}{\rho} \cdot \Delta p}, \quad (2)$$

$$Q = \mu f \sqrt{\frac{2}{\rho} \Delta p}, \quad (3)$$

where μ is the flow rate; f is the cross-sectional area of the nozzle.

The decrease in flow rate compared to the theoretical value is characterized by the flow rate, which varies in the range from 0 to 1.

The simplest case is the outflow of liquid through a hole in a thin wall. A wall in which the jet interacts only with the edge of the hole is considered thin. When using low-viscosity liquids, in particular water, for a round hole in a thin wall, the average value of the flow rate is $\mu = 0.62$ [11]. It should be noted that the flow rate also depends on the Reynolds number.

When a liquid flows through a hole in a thick wall, the thickness of which is two or more times the diameter of the hole, the flow rate is approximately 0.62, but it significantly depends on the shape of the flow part.

The most favorable conditions for liquid outflow are provided when using a conical nozzle. For a conical hole, the flow rate is 0.85...0.98 [11] at a taper angle $\alpha = 2...20^\circ$.

A typical implementation of a nozzle element is a confusor channel with a constant cross-section in the form of a circle but other, more technological solutions, are possible.

Hydraulic losses in the confusor channel Δp are calculated from the formula, which gives losses in fractions of the velocity head, determined by the average velocity V_c in the selected cross-section

$$\Delta p = \xi \rho \frac{V_c^2}{2}, \quad (4)$$

where ξ is the local loss coefficient.

The local loss coefficient ξ characterizes the fraction of the kinetic energy of the fluid flow that is lost when overcoming hydraulic resistance and is related to the flow rate μ .

The dependence of the local loss coefficient for a conical confusor channel with a cross-sectional area in the form of a circle on its parameters is studied in detail and described in the literature [10].

The cross-section of the supply pipeline connecting the source of hydraulic energy and the consumer is selected according to the permissible velocity value. In the general case, the fluid velocity is selected so that the hydraulic flow does not exceed 5...6% of the nominal working pressure [10]. In the case of using high-pressure systems, the velocities in the supply pipeline can reach 10–30 m/s.

In the aerial vehicle take-off system, it is advisable to use conical nozzles or nozzles of variable cross-section with a diameter ratio of 3.5, which makes it possible to provide a ratio of areas at the inlet and outlet of 12.25. This value makes it possible to implement a corresponding increase in speed using the nozzle element, which is sufficient to reduce hydraulic losses in the supply pipeline to an acceptable level.

If a significant increase in speed is required in the confusor nozzle, it is possible to use larger values of the diameter ratio, which can reach 6. In ultra-high pressure systems, which make it possible to achieve a speed of 1000 m/s at the nozzle outlet, this ratio makes it possible to increase the speed using the nozzle by 36 times.

The use of a long confusor in the nozzle take-off system is not advisable, since simultaneously with a decrease in the taper angle and a decrease in the local loss coefficient, the losses along the length will increase by a corresponding amount. In this case, the confusor can be replaced with some approximation by several sections of pipelines of constant diameter, which will have the corresponding hydraulic resistance.

Since the nozzle system can operate at a high pressure drop, the conical section of the nozzle has a cylindrical or flat hole of constant cross-section at the end, the length of which is equal to the diameter. In the absence of this component, the outlet part of the hole will wear out quickly under the influence of a fast-flowing liquid flow and abrasive particles [12]. Similar solutions are widely used in hydro-cutting systems.

In order to correctly compare the results of the research for all the above calculation schemes, the modeling was carried out for the same ratio of areas at the inlet and outlet. The cross-sectional areas of the nozzles at the inlet and outlet are the same for all scheme solutions. Conical nozzles differ in the angle of taper $\alpha / 2$, which varies from 30 degrees (Fig. 2, a) to 10 degrees (Fig. 2, b). Specially shaped nozzles (Fig. 2, c, d) have lengths of sections where the cross-sectional area varies according to the lengths of the conical sections of the nozzles. The same dimensions and a small difference in the average velocity of the fluid at the inlet and outlet allow for a correct comparative analysis of special-shaped nozzles and conical nozzles.

The modeling performed makes it possible to establish the maximum and average velocity of the fluid in the outlet section of the nozzle, the volumetric and mass flow rates, and calculate the hydraulic resistance of the nozzle elements. The pressure distribution on the walls of the special-shaped nozzles was also obtained. When using hydraulic systems with pressures up to 50 MPa, the forces acting on the walls of the nozzle elements can be significant. These values must be taken into account when calculating the strength of nozzles in order to avoid deformation or destruction of the hydraulic system elements during its operation.

Based on the simulation results, the distribution of fluid velocities along the longitudinal section of nozzles of different configurations was obtained (Fig. 4). For nozzles of a special shape, the velocity distribution is significantly different in the outlet section of the flow part, while in the inlet section the velocity distribution is practically the same for all calculation schemes.

As a result of our simulation, the pressure distribution on the wall for nozzles of a special shape was obtained, where curve 1 corresponds to a pressure drop across the nozzle equal to 50 MPa, curve 2 – 32 MPa, curve 3 – 21 MPa, curve 4 – 10 MPa, curve 5 – 2 MPa (Fig. 5). Considering the absence of axial symmetry of the nozzles, the pressure distribution dependences on the wall in two mutually perpendicular planes OXZ and OYZ passing through the nozzle axis Z were obtained. The results show some difference in pressures in the outlet section of the nozzle in mutually perpendicular planes, which does not exceed 11% of the maximum pressure. The most significant difference in pressures is observed in the transition zone to the rectangular channel. Analysis of the results reveals that the pressure distribution along the lateral surface of the channel is insignificantly different for conical

nozzles and nozzles of a special shape of the corresponding length. Accordingly, in the strength calculations, values cor-

responding to a typical design of a conical nozzle with a constant cross-section in the form of a circle can be used.

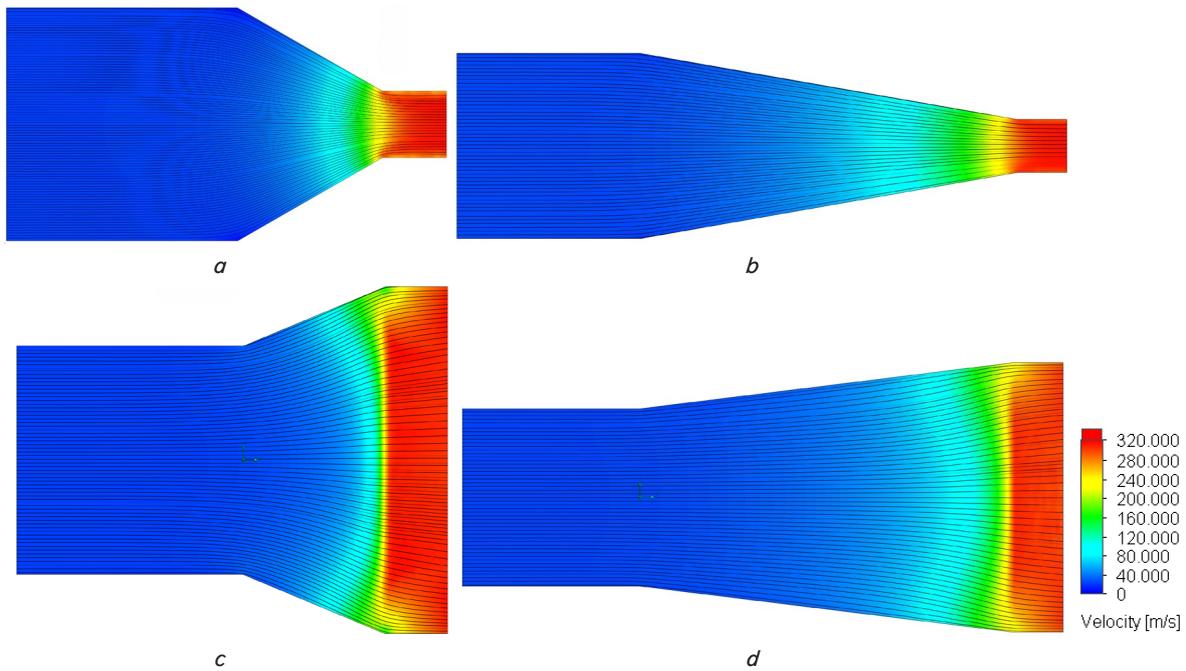


Fig. 4. Velocity distribution across the nozzle cross section:

a – for a conical nozzle with a taper angle of 30°; *b* – for a conical nozzle with a taper angle of 10°; *c* – for a short nozzle of a special shape in the OYZ plane; *d* – for a long nozzle of a special shape in the OYZ plane

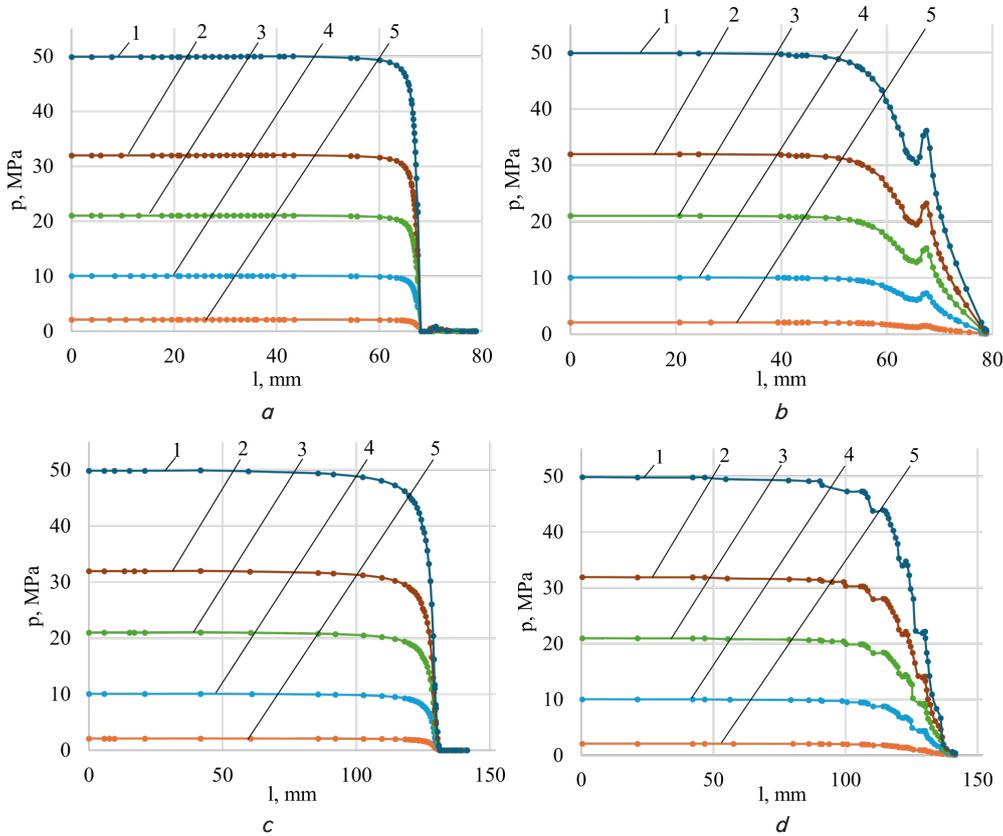


Fig. 5. Pressure distribution on the surface of nozzles of special shape:

a – for a short nozzle in the OXZ plane; *b* – for a short nozzle in the OYZ plane; *c* – for a long nozzle in the OXZ plane; *d* – for a long nozzle in the OYZ plane; 1 – for a pressure drop across the nozzle of 50 MPa; 2 – for a pressure drop across the nozzle of 32 MPa; 3 – for a pressure drop across the nozzle of 21 MPa; 4 – for a pressure drop across the nozzle of 10 MPa; 5 – for a pressure drop across the nozzle of 2 MPa

According to the simulation results, the velocity distribution along the nozzle axis was determined (Fig. 6). The plots illustrate the change in the maximum velocity in the flow core where curve 1 corresponds to a pressure drop across the nozzle equal to 50 MPa, curve 2–32 MPa, curve 3–21 MPa, curve 4–10 MPa, curve 5–2 MPa. The flow parameters at the nozzle outlet correspond to dependence (1). The simulation results for long nozzles corresponding to the schemes shown in Fig. 2, *b, d* are generally characterized by a less intense increase in velocity along the axis compared to short nozzles. For conical nozzles of constant cross-section, the velocity increases more smoothly, and the transition areas from the conical to the cylindrical part are practically not visible on the plot. For nozzles of variable cross-section, a characteristic area is observed in the transition area to a rectangular section. In this zone, at certain simulation parameters, there are noticeable velocity fluctuations, which is most likely caused by significant velocity redistribution in the flow and intense vortex formation. The velocity fluctuations caused by vortex formation are more pronounced for short nozzles.

As a result of our simulation, dependences of the mass flow rate and volume flow rate on the pressure drop across the nozzle were derived. The mass flow rate is the same at the inlet and outlet of the nozzle and takes into account the change in the volume of the liquid at high pressure values. The volume flow rate at the inlet of the nozzle will decrease at high pressures due to some compression of the liquid and will differ from the flow rate at the outlet of the nozzle. Fig. 7 shows the dependence of the mass flow rate at the inlet on the pressure drop across the nozzle. The data correspond to power dependence (3).

As a result of the simulation, dependence of the liquid density on pressure was obtained, which corresponds to the theoretical data [5] and shows a decrease in the liquid volume within 3.5% during the operation of the hydraulic system at the maximum pressure value.

The decrease in the volume of the liquid at high pressure affects the volume flow rate and slightly changes the functional dependence between the pressure drop across the nozzle, the flow rate coefficient and the flow rate at the outlet of the nozzle. Therefore, the flow rate coefficient μ was determined from the mass flow rate using the following dependence

$$\mu = \frac{Q_m / \rho^*}{f \cdot \sqrt{\frac{2}{\rho} \cdot \Delta p}}, \tag{5}$$

where Q_m is the mass flow rate of the liquid; ρ^* is the density of water under normal conditions.

Dependence (5) made it possible to take into account the compressibility of the liquid and obtain the same values of coefficient μ at different pressure values.

As a result of the modeling, it was found that for a conical nozzle with a cross-section in the shape of a circle with a taper angle of 10 degrees, the flow rate coefficient $\mu = 0.96$. For a conical nozzle with a cross-section in the shape of a circle with a taper angle of 30 degrees, $\mu = 0.86$. For a long conical nozzle with a cross-section of variable shape (Fig. 2, *d*) $\mu = 0.92$. For a short conical nozzle with a cross-section of variable shape (Fig. 2, *c*) $\mu = 0.82$. When changing the taper angle or length of nozzles of a specialized shape, the flow rate coefficient will change within the specified limits.

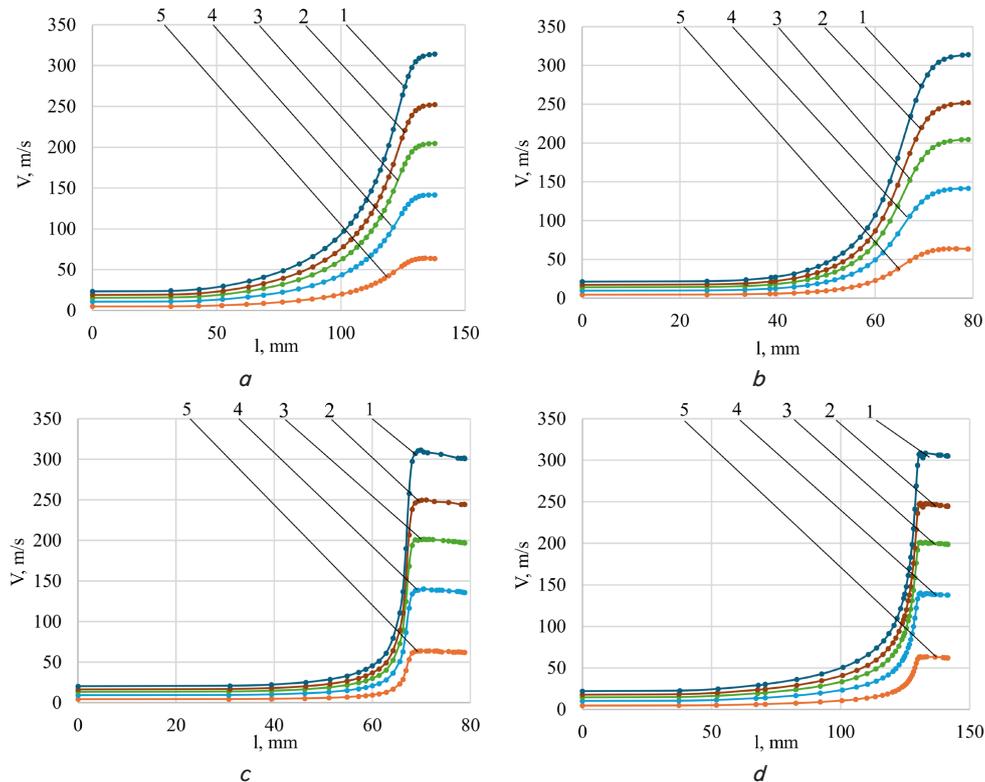


Fig. 6. Velocity distribution along the nozzle axis:

a – for a conical nozzle with a taper angle of 30°; *b* – for a conical nozzle with a taper angle of 10°; *c* – for a short nozzle of a special shape; *d* – for a long nozzle of a special shape; 1 – for a pressure drop across the nozzle of 50 MPa; 2 – for a pressure drop across the nozzle of 32 MPa; 3 – for a pressure drop across the nozzle of 21 MPa; 4 – for a pressure drop across the nozzle of 10 MPa; 5 – for a pressure drop across the nozzle of 2 MPa

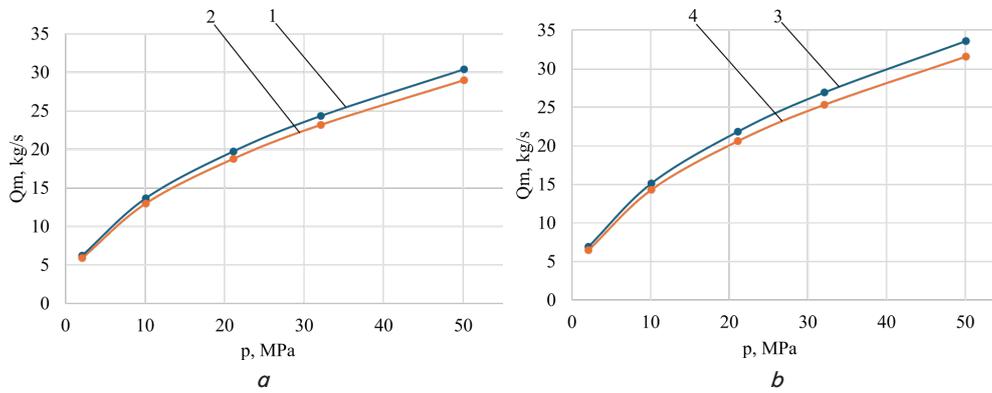


Fig. 7. Dependence of mass flow rate on pressure drop across the nozzle:
a – for short nozzles; *b* – for long nozzles; 1 – for a conical nozzle with a taper angle of 30°; 2 – for a short nozzle of a special shape; 3 – for a conical nozzle with a taper angle of 10°; 4 – for a long nozzle of a special shape

Our studies confirm that larger values of coefficient μ correspond to smaller lengths of the conical nozzle, and the maximum value of the coefficient corresponds to theoretical data [10]. The use of nozzles with a variable cross-section reduces the flow rate by 4%, which is caused by additional energy losses for the redistribution of velocities in the fluid flow when the shape of the cross-section changes and vortex formation. These processes are illustrated by the dependences of velocity on the coordinate measured along the channel axis (Fig. 6, *c*, *d*).

The results of studying the working processes in nozzles with a variable cross-section and their integral indicators correspond to the results of studies on similar nozzle systems [7, 10]. With the same cross-sectional area at the inlet and outlet, the hydraulic characteristics of conical nozzles for long nozzles with a variable cross-section do not differ significantly. Short nozzles with a variable cross-section are characterized by significant vortex formation, which leads to a significant increase in energy losses.

The reduction in the μ coefficient and the corresponding additional energy losses for long nozzles of special shape are acceptable, which allows their use instead of conical ones. Nozzles of variable cross-section have a lower mass and simpler manufacturing technology, which provides advantages when used in the take-off system of an aerial vehicle.

5. 2. Determining hydraulic parameters of the take-off nozzle system based on the results of the gas-hydraulic accumulator study

The use of a nozzle system for vertical controlled lifting of an aerial vehicle weighing more than 50 kg and acceleration to the breakaway speed will require large power consumption. According to preliminary estimates, for lifting an aerial vehicle of the given mass, the total cross-sectional area of the nozzle elements should be 113 mm², which corresponds to one nozzle with an outlet diameter of 12 mm. The practical implementation of the technical solution may involve the use of several nozzle elements with the corresponding cross-sectional area, fluid flow rate, and thrust.

The dependence of water flow rate on the pressure drop for a nozzle element with a cross-sectional area $f = 113 \text{ mm}^2$ and a flow rate coefficient $\mu = 0.86$ is shown in Fig. 8. With these parameters, at a pressure drop of 10 MPa, the flow rate will be 16 l/s, and at 50 MPa the figure will increase to 36 l/s.

In this case, the power consumption N will vary according to the following dependence

$$N = \Delta p \cdot Q = \Delta p^2 \cdot \mu \cdot f \cdot \sqrt{\frac{2}{\rho}} \tag{6}$$

The dependence of consumed power on pressure when using a nozzle element with $f = 113 \text{ mm}^2$ and $\mu = 0.86$ is shown in Fig. 9. At a pressure drop of 10 MPa, the power will be 155 kW, and when reaching 50 MPa, the indicator will increase to 2000 kW.

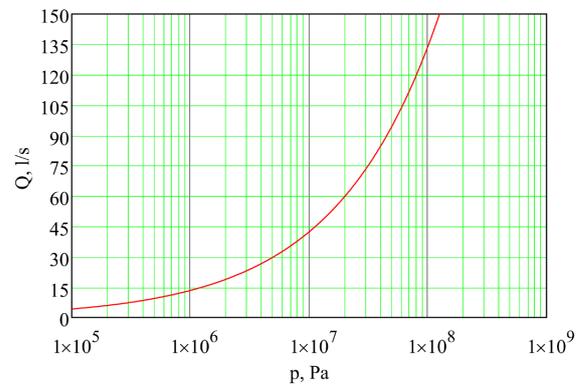


Fig. 8. Dependence of flow rate on pressure drop for a nozzle with $f = 113 \text{ mm}^2$

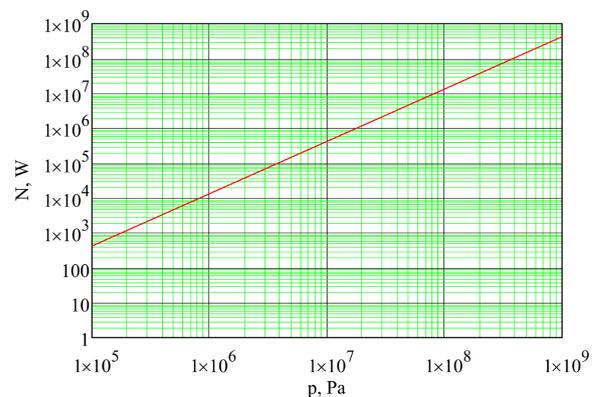


Fig. 9. Power dependence on pressure drop for a nozzle with $f = 113 \text{ mm}^2$

The take-off system operates for a short period of time, not exceeding a few seconds. Given the small energy costs for the operation of the nozzle system and the need for short-term generation of high power, the use of pumps is impractical. The reason is that the pumps are driven by electric motors, which usually receive energy from electrochemical power sources installed on board the aerial vehicle. Electric motors and power sources of significant power have a fairly large mass.

It is promising to use a gas-hydraulic accumulator in the take-off system, which uses the energy of compressed gas for short-term supply of fluid to the nozzle elements. The gas-hydraulic accumulator has a higher energy density than a spring accumulator, and its main advantage is a high specific power [8]. The design of the gas-hydraulic accumulator includes a massive metal housing in which the liquid and gas are separated by a rubber membrane. Nitrogen is used as the working fluid, and the main factor determining its energy density is the maximum charging pressure.

A typical solution is a balloon gas-hydraulic accumulator of the AS20 type from Epol [13], which has a nominal volume of 20 liters, a maximum pressure of 36 MPa, and a mass of 48 kg. The ability to provide high flows allows the use of such devices in the take-off system of an aerial vehicle. Under the most optimal operating mode, the accumulator makes it possible to fill about 15 liters of liquid. If water is used as the working fluid, the ratio between the mass of the liquid and the mass of the filled accumulator is 0.23. This ratio is typical for high-pressure gas-hydraulic accumulators and does not significantly depend on the size and other parameters.

The initial charging pressure of the accumulator P_p , which is equal to the pressure of the gas placed in the gas cavity, determines the usable volume of the accumulator V_p , i.e., the volume of liquid that can be filled into the accumulator and its energy intensity. For an isothermal process, a change in the volume of gas in the accumulator is described by the following dependence [11]

$$V_2 = V_1 \cdot \frac{P_1}{P_2}, \tag{7}$$

where $P_1 = P_p$ – initial gas pressure, equal to initial charging pressure; $V_1 = V_k$ – initial gas volume, equal to the structural volume of the accumulator; V_2 and P_2 – current volume and gas pressure in the accumulator.

The usable volume of the accumulator V_p is found as the difference between the structural volume and volume V_2 corresponding to the maximum charging pressure

$$V_p = V_k - V_2. \tag{8}$$

The isothermal process is characteristic of slow battery discharge and makes it possible to estimate its maximum energy capacity E using the following dependence [11]

$$E = P_p \cdot V_p \cdot \ln\left(\frac{P_2}{P_p}\right). \tag{9}$$

At a given maximum pressure value of 32 MPa and a structural volume of 20 liters, we obtain the following dependences of the usable volume and energy capacity of the accumulator on the initial pressure (Fig. 10).

According to our results, the optimal value of the usable volume and energy capacity is achieved at a ratio of the maximum and initial pressure of 4...5. At a ratio equal to 4, the initial pressure will be 8 MPa, the usable volume will be 15 liters (75% of the structural volume), and the maximum energy capacity will be 166 kJ. It is impractical to use lower values of the minimum pressure, despite the increase in the volume of the fluid that the accumulator will contain, since this significantly reduces the energy capacity. Under optimal operating conditions, the specific energy density of a gas-hydraulic accumulator in a charged state will be 2.6 kJ/kg or 0.7 Wh/kg,

which is a typical value for high-pressure hydraulic accumulators. The specific energy density of the device is significantly lower than that of electric energy storage devices [8], but the hydraulic accumulator provides a high specific power required for the operation of the nozzle system.

When the accumulator is rapidly charged, the gas temperature will increase significantly. Under normal conditions, the temperature increase will be determined from the following dependence [10]

$$t_2 = (t_1 + 273) \cdot \left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 273, \tag{10}$$

where t_1 and t_2 are the initial and final temperatures in °C; n is the polytropic index, which for an adiabatic process is equal to 1.4.

With the optimal ratio of pressures P_1 and P_2 , the temperature can increase by 186 degrees during charging. Since the temperature increase is significant, after the gas in the battery cools to ambient temperature, the pressure will decrease, which will lead to the loss of a significant portion of the stored energy. To obtain the maximum energy capacity of the battery, which is intended to power the takeoff nozzle system of the aerial vehicle, its charging should occur slowly. Under this condition, at the end of the charging process, the temperature will be close to the ambient temperature, which minimizes energy losses.

With rapid discharge of the battery, which corresponds to the operating conditions of the takeoff nozzle system of the aerial vehicle, the working processes have characteristic features. Fig. 11 shows the dependence of pressure on the fluid flow rate during battery discharge. Curve 1 corresponds to an isothermal process, and curve 2 to an adiabatic process, which is typical for the nozzle system of an aerial vehicle takeoff. In the latter case, due to the decrease in gas temperature when the pressure drops to the initial value (8 MPa), the flow rate will be only 55% of the usable volume V_p ; respectively, part of the energy will not be used. To obtain maximum energy, the battery discharge should be continued to the pressure value at which the flow rate reaches the maximum value. In this case, the maximum volume of liquid and energy will be obtained from the battery. According to the simulation results, 23% less energy will be obtained in the adiabatic process than in the isothermal process.

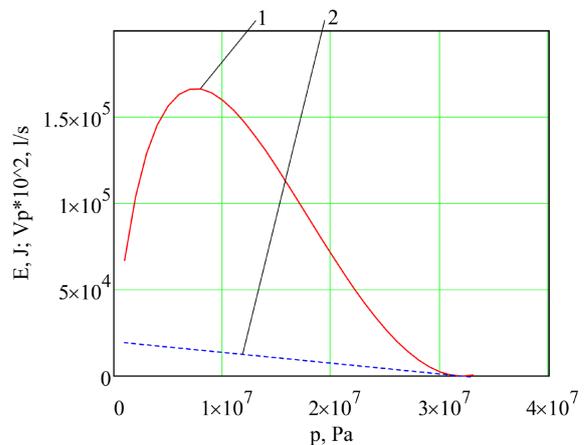


Fig. 10. Dependence of accumulator parameters on initial pressure: 1 – dependence of energy capacity on initial pressure; 2 – dependence of usable volume on initial pressure

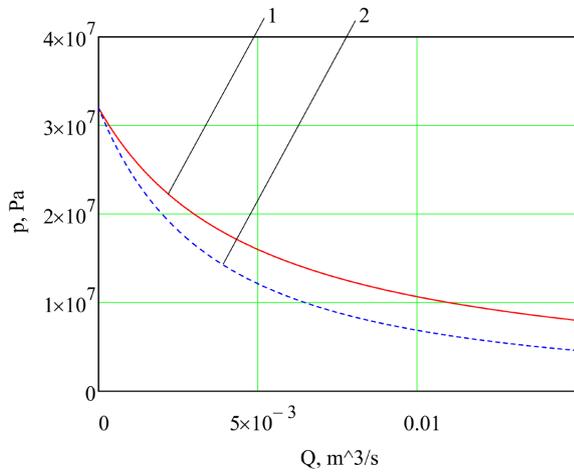


Fig. 11. Comparison of the battery discharge process: 1 – adiabatic; 2 – isothermal

To obtain maximum energy from the accumulator, it is necessary to enable the operation of the hydraulic system at variable pressure. Accordingly, the nozzle system must function and provide the necessary parameters in a wide range of pressures. The hydraulic system of the aerial vehicle includes an accumulator, a valve that regulates the fluid supply, a pipeline, and a conical nozzle (Fig. 1, b) and does not contain a reducing valve since, in this case, a significant part of the energy will be lost. The elements of the hydraulic system have a sufficiently high hydraulic resistance, respectively, their working processes will determine the rate of discharge of the accumulator. Given that the hydraulic resistance of the valve and pipeline is significantly less than the resistance of the nozzle, let's consider a simplified scheme that includes a nozzle element that works in conjunction with a gas-hydraulic accumulator. In this case, the hydraulic resistance of other devices is taken into account in the nozzle flow rate.

When the pressure in the hydraulic system drops from the maximum to the minimum value, it is necessary to establish the dependence of all parameters on time. If a nozzle with a flow rate of μ is used, the integral flow rate of the liquid Q_I (the total volume of liquid supplied by the battery since the start of the discharge process) will be given by

$$Q_I(t) = \int_0^t \mu \cdot f \sqrt{\frac{2}{\rho} \cdot P(t)} \cdot dt, \tag{11}$$

where $P(t)$ is the current value of the pressure at the nozzle inlet.

In an isothermal process, pressure $P(t)$ will be determined by the current value of the integral flow rate. If an approximate relationship is used, this value will be found from the following formula

$$P(t) = \frac{P_{max} \cdot V_{min}}{V_{min} + Q_I(t)}, \tag{12}$$

where P_{max} is the maximum battery charging pressure; V_{min} is the minimum gas volume in the battery.

Considering that in the nozzle system of the aerial vehicle takeoff the battery discharge occurs quickly, this process can be considered adiabatic with a polytropic index, which for nitrogen is equal to $n = k = 1.4$. Accordingly,

the pressure change will be described by the following dependence

$$P(t) = \frac{P_{max}}{\left(\frac{V_{min}}{V_{min} + Q_I(t)} \right)^{1/n}}. \tag{13}$$

The simulation of the operation of the variable pressure system consisting of a gas-hydraulic accumulator and a nozzle element was performed in the Simulink environment of the MATLAB software package. Fig. 12 illustrates the relationship between the excess gas pressure in the accumulator, the volumetric flow rate, and the integral flow rate of the liquid. The simulation involved solving a system of differential equations by numerical methods. The simulation begins with the initial value of the excess gas pressure in the accumulator P_{max} , which is equal to 32 MPa. The simulation includes a model of the nozzle element, which allows the current pressure value $P(t)$ to be used to calculate the volumetric flow rate $Q(t)$ using dependence (3). The model includes an integrating element that at each step of the simulation calculates the integral flow rate of the liquid $Q_I(t)$ according to dependence (11). The model of the gas-hydraulic accumulator allows pressure $P(t)$ to be calculated using the integral flow rate using dependence (13). In the next step of the simulation, the initial pressure value is fed to the model input. The simulation continues until the integrated flow rate reaches a maximum value of 15 liters.

The temperature change is taken into account using a random component equal to the corresponding change in gas pressure in the accumulator, the maximum value of which is calculated according to dependence (10). The random value is added to the initial pressure in the first step of the simulation.

Since the flow rate is calculated at the nozzle outlet, where the pressure is close to atmospheric, the change in liquid density is not taken into account. It should be noted that the compressibility of the liquid will slightly affect the working processes of the accumulator, which can accommodate a slightly larger mass of liquid at high pressure values.

As a result of our simulation, the dependence of flow rate on time $Q(t)$ (Fig. 13), the integral flow rate on time $Q_I(t)$ (Fig. 14), and pressure on time $P(t)$ (Fig. 15) was obtained.

Analysis of the simulation results make it possible to establish that the duration of the accumulator emptying under the given initial conditions is 1.06 s and does not significantly depend on the random value caused by the change in ambient temperature. During emptying, the flow rate changes from 24 to 10 l/s, and the pressure drops from 32 to 4.6 MPa. The data presented indicate the rapidity of the working processes in the nozzle system operating in conjunction with the gas-hydraulic accumulator.

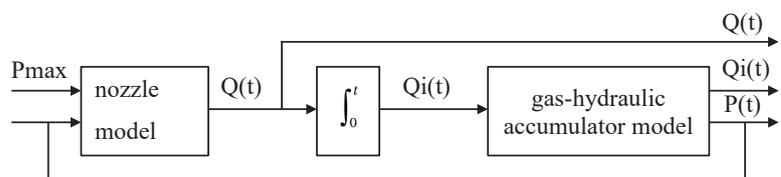


Fig. 12. Visualization of the relationship between excess gas pressure in the accumulator, volumetric flow rate, and integral fluid flow rate

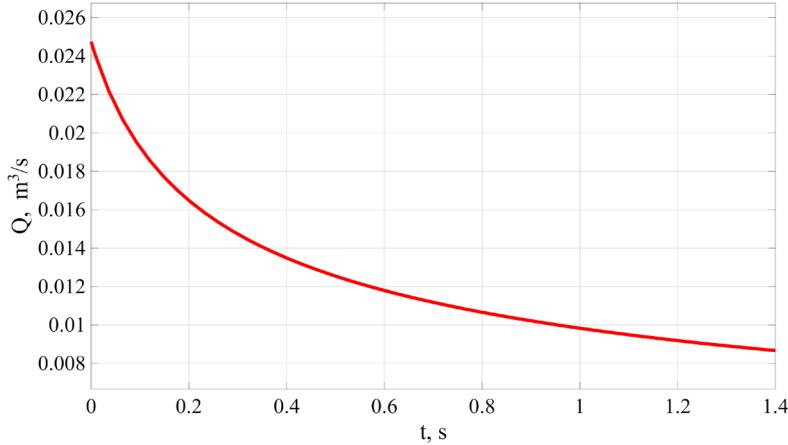


Fig. 13. Dependence of flow rate on time

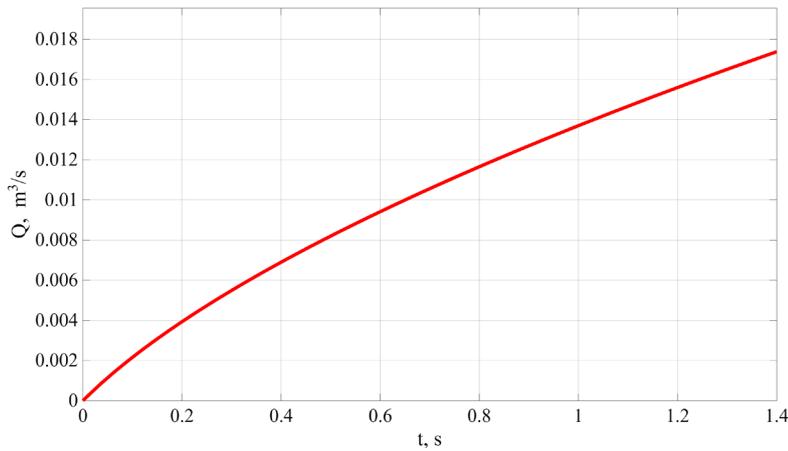


Fig. 14. Dependence of integral flow rate on time

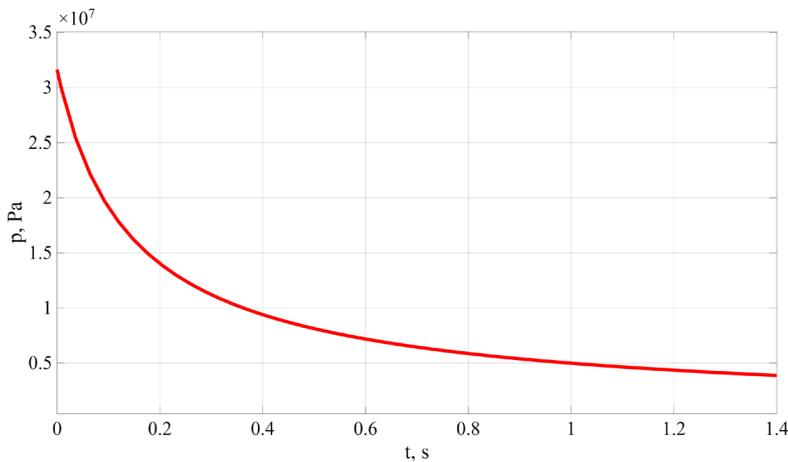


Fig. 15. Pressure dependence on time

Our results justify the practical application of a hydraulic system that uses all the liquid accumulated in the accumulator during rapid discharge. The established energy characteristics of the system, the dependence of the flow rate, pressure, and generated force on time correspond to the results reported in [8, 10], as well as allow us to compare the parameters of hydraulic systems operating at constant and variable pressure.

5.3. Determining the lift height, speed, and acceleration of an aerial vehicle

The derived dependences of pressure and flow on time make it possible to calculate the thrust generated by the nozzle

element during the emptying of the gas-hydraulic accumulator. To find thrust $F(t)$, the following dependence is used

$$F(t) = Q(t) \cdot \rho \cdot V_A(t) = \frac{Q^2(t) \cdot \rho}{f}, \quad (14)$$

where $V_A(t)$ is the dependence of the average liquid velocity at the nozzle outlet on time.

Based on our simulation results, the dependence of the traction force generated by the nozzle element on time was constructed (Fig. 16).

Analysis of the results with the given parameters reveals a significant drop in the traction force during battery discharge, with the maximum value reaching 5600 N and the minimum 760 N. During the operation of the nozzle system, a drop in the traction force acting on the aerial vehicle is observed, by 7 times. Thus, when using the system for vertical lift, a significant acceleration will act on the aerial vehicle, which limits the scope of the system.

Thrust makes it possible to calculate the acceleration of an aerial vehicle from a known mass. When using a takeoff system to lift an aerial vehicle vertically while the engine is running, the acceleration $a(t)$ will be calculated from the following dependence

$$a(t) = \frac{F(t)}{m_1 + m_a^* - Q_I(t) \cdot \rho} - g, \quad (15)$$

where m_1 is the mass of the aerial vehicle; m_a^* is the mass of the battery filled with liquid; g is the acceleration of gravity.

After the jet system has finished working, the aerial vehicle will move under the influence of gravity with an acceleration $a(t) = -g$.

The nozzle system can be used for vertical lift, climb, and also for increasing horizontal speed, working in conjunction with a pulling or pushing propeller of an aircraft-type aerial vehicle. In the latter case, the acceleration will be calculated from the following formula

$$a(t) = \frac{F(t)}{m_1 + m_a^* - Q_I(t) \cdot \rho}. \quad (16)$$

The dependence of acceleration on time also makes it possible to calculate the dependence of speed and height on time by integration.

In this case, it is possible to determine the maximum speed and height of lift during vertical takeoff of the aerial vehicle.

The design of the takeoff system assumes that the parameters of the nozzle system are calculated based on the known mass of the aerial vehicle, after which the gas-hydraulic accumulator is selected, and the total mass is found. In order to optimize the characteristics, we shall apply an approach that assumes that the optimal mass of the aerial vehicle is determined based on the known parameters of the jet takeoff system, in particular, the dependence of the traction force and fluid flow on time and the mass of the gas-hydraulic accumulator. With a known volume of fluid in the accumulator and

the accumulated energy, the maximum speed of the aerial vehicle and the height of lift during vertical takeoff will not significantly depend on the cross-sectional area of the nozzle elements. This indicator can vary in a fairly narrow range and determines the operating time of the system. The maximum value of the nozzle cross-sectional area will be limited by the permissible acceleration, and the minimum by the need to generate a thrust force sufficient to lift the aerial vehicle.

To determine the optimal parameters of the take-off system, we express the mass of aerial vehicle m_l in fractions of the mass of the empty gas-hydraulic accumulator m_a . The dependences of acceleration, speed, and height of ascent during vertical take-off on time for aerial vehicle of different masses are illustrated in Fig. 18. The most favorable operating conditions of the take-off system correspond to the ratio of the mass of the aerial vehicle to the mass of accumulator m_l / m_a ,

which is in the range of 0.1...0.2. In this case, the capabilities of the system are most fully used, which make it possible to gain altitude and achieve the required horizontal breakaway speed of the aerial vehicle [1]. With the mass ratio $m_l / m_a = 0.2$ (Fig. 17, a), the maximum ascent height will be 38 m, and the maximum speed can reach 20 m/s during vertical take-off. When moving along a complex trajectory, the system provides the ability to rise to a small height and achieve the required value of the horizontal breakaway speed. It should be noted that the large ratio of the takeoff system mass to the aerial vehicle mass limits its application and will require the system to be reset after launch.

In the case when the mass ratio m_l / m_a is within 1...2, the take-off system under certain conditions will be able to enable the take-off of the aerial vehicle and the transition to horizontal flight under the action of the main engine. In this case, small accelerations act on the aerial vehicle. At $m_l = m_a$ (Fig. 17, b), the maximum height during vertical ascent will be 12.6 m, and the maximum speed will reach 9 m/s. Low values of the given parameters impose restrictions on the aerodynamic characteristics of the aerial vehicle and the main engine. When using an inclined guide to launch the aerial vehicle, the given parameters make it possible to achieve the required breakaway speed for aerial vehicle at a low value of the specified parameter.

With an aerial vehicle mass exceeding $4 m_a$, the nozzle system will not be able to enable its launch. For an aerial vehicle with a mass of $m_l = 4m_a$, the acceleration will be greater than zero for 0.27 s, which is significantly less than the operating time of the nozzle system, the maximum lift height will not exceed 0.6 m, and the maximum speed will reach 1.3 m/s. Even when using an inclined guide, the large mass of the aerial vehicle will not make it possible to the required horizontal speed to be achieved.

The dependences of maximum speed during vertical lift on m_l / m_a are shown in Fig. 18. With the ratio $m_l / m_a = 0.1...1$, the lift height lies in the range of 10...25 m. The dependence of maximum speed during horizontal launch of the aerial vehicle on m_l / m_a is shown in Fig. 19.

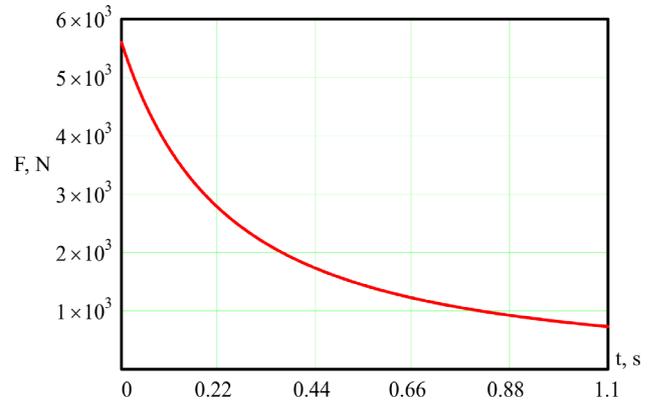


Fig. 16. Dependence of the thrust force of the nozzle element on time

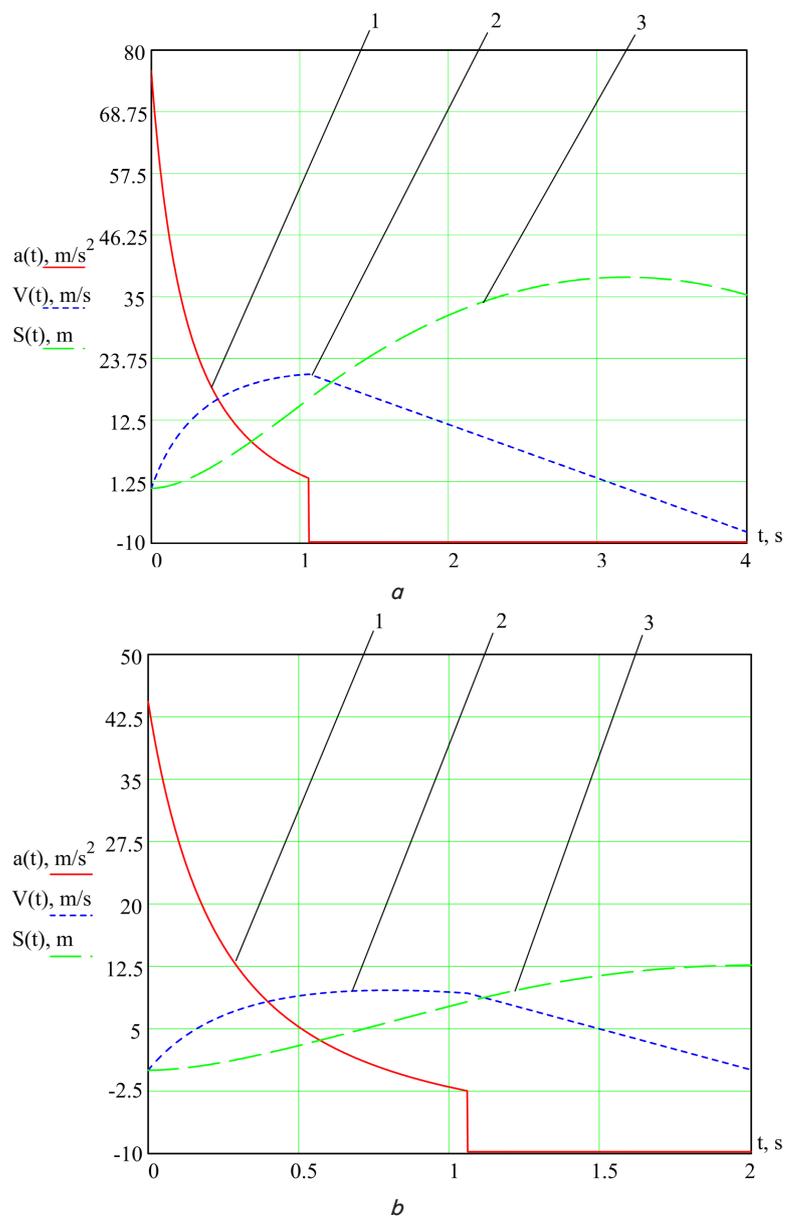


Fig. 17. Dependence of kinematic parameters of the aerial vehicle on time during vertical lift: a – for $m_l / m_a = 0.2$; b – for $m_l / m_a = 1$; 1 – dependence of acceleration on time; 2 – dependence of velocity on time; 3 – dependence of lift height on time

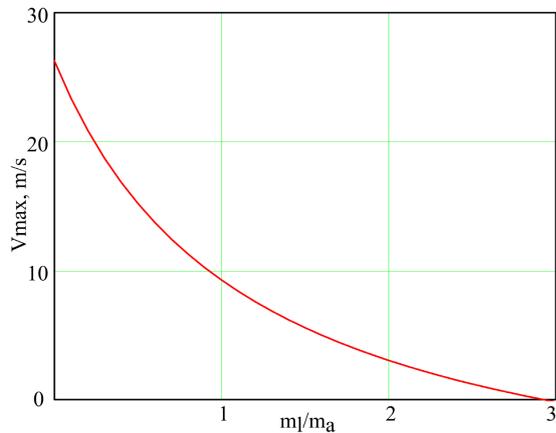


Fig. 18. Dependence of the maximum speed of an aerial vehicle on its mass during vertical takeoff

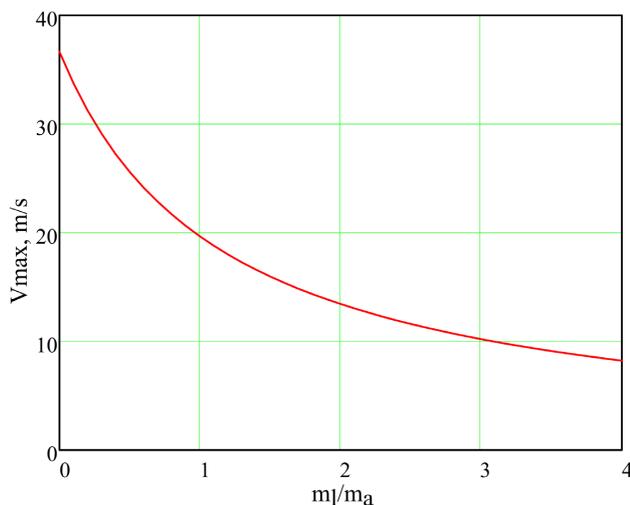


Fig. 19. Dependence of the maximum speed of an aerial vehicle on its mass during horizontal flight

The plots above (Fig. 18, 19) make it possible to establish the optimal parameters for the take-off system by the type of launch, the mass of the aerial vehicle, and its aerodynamic characteristics, in particular the breakaway speed. Based on our graphical dependences, it is possible to choose the optimal ratio between the mass of the aerial vehicle and the gas-hydraulic accumulator, which ensures the achievement of the required speed.

Studies on the take-off of an aerial vehicle and the achievement of the required speed carried out without taking into account the resistance of the environment could be applied at low flight speeds. For the case of vertical lift with a low speed, the theoretical results will not significantly differ from the experimental ones.

6. Discussion of results based on investigating the liquid jet system of an aerial vehicle takeoff

To implement the aerial vehicle takeoff system, it is proposed to use more technological nozzles of variable cross-section (Fig. 2, c, d), which can be made from a cylindrical pipe by means of plastic deformation. Our studies of nozzles of different lengths, having an optimal ratio of the areas of the inlet and outlet openings equal to 12.25, enable the achievement of

a liquid outflow velocity sufficient to ensure the functioning of the nozzle system.

Determining regularities that characterize the working processes in liquid nozzle systems of a special shape in comparison with conical nozzles in terms of hydraulic characteristics and energy losses showed the existence of more intense vortex formation in the outlet section (Fig. 5) and a sharper increase in velocity along the nozzle axis (Fig. 6). It was found that the hydraulic losses in specialized nozzles are 4% higher than for conical nozzles of constant cross-section, reported in [10] with the corresponding dimensions and ratio of the areas of the inlet and outlet openings.

The assessment of the power of the nozzle system of an aerial vehicle take-off (Fig. 9) made it possible to substantiate the advantages of using a gas-hydraulic accumulator as an energy source in comparison with a pump powered by an electric motor, which, with the corresponding specific power, has a much larger mass.

The study of dependence of the energy capacity and fluid flow of the gas-hydraulic accumulator on the initial parameters (Fig. 11) allowed us to establish optimal operating modes and showed the feasibility of its use in combination with nozzle elements at variable pressure. The optimal operating mode of the nozzle system involves a drop in pressure in the accumulator during discharge to a value that is less than the initial charging pressure, which makes it possible to use the accumulated fluid in full. In this case, the specific energy capacity of the gas-hydraulic accumulator will be 2.6 kJ/kg. This value corresponds to the data given in [8], and the difference in the results is caused by the peculiarities of the battery operating mode as part of the take-off system. The established regularities of the battery operation during rapid discharge make it possible to obtain the maximum energy capacity and total fluid flow.

The mathematical model of the system, which works in combination with the gas-hydraulic accumulator at a variable pressure drop, was built based on dependences (10), (11), (13), and made it possible to determine the key characteristics. The dependences of the flow rate, integral flow rate, and pressure on time (Fig. 13–15) were derived, as well as the dependence of thrust on time (Fig. 16); the period of operation of the take-off system was established. Analysis of the results reveals large accelerations of the aerial vehicle during launch and the short duration of the system operation, the operating time of which is 1.06 seconds. The resulting dependences are necessary for calculating the parameters of the nozzle system and the gas-hydraulic accumulator, which makes it possible to enable the take-off of a certain model of aerial vehicle.

The energy source that drives the takeoff nozzle system of the aerial vehicle has a significant mass. The resulting parameters allowed us to optimize the system depending on the ratio of the mass of the aerial vehicle to the mass of the battery m_l / m_a . The constructed dependences of acceleration, speed, and takeoff height on time for aerial vehicle of different masses (Fig. 17) make it possible to establish restrictions characterizing the operation of the system, in particular caused by the need to generate a thrust force greater than the total mass of the aerial vehicle and the need to accelerate to a speed that should exceed the takeoff speed. Analysis of the results reveals that the most favorable operating conditions for the takeoff system correspond to the ratio of the masses of the aerial vehicle and the battery $m_l / m_a = 0.2$. With a $m_l / m_a = 0.2$ ratio value not exceeding 2, the launch system provides the ability to accelerate the aerial vehicle to the takeoff speed and can be used under certain conditions. In both cases, the mass of the

launch system, which includes the gas-hydraulic accumulator, is comparable to the mass of the aerial vehicle.

The practical significance of the established regularities is in determining the limitations and optimal parameters of the system, which can enable the lifting of the aerial vehicle and acceleration to the required speed. Given the significant mass of the energy source, determining the ratio of the mass of the aerial vehicle to the mass of the battery is a prerequisite for designing an ergonomic reusable take-off system.

Our results make it possible to design a jet take-off system that allows for quick launch from any surface. These characteristics are necessary for special-purpose aerial vehicles. The optimal technical solution involves resetting the system immediately after take-off. This gives the liquid nozzle system for launching the aerial vehicle advantages compared to a pneumatic catapult, which also contains a high-pressure tank.

Our research is limited to studying the working processes in the nozzle system when generating the effort necessary for the vertical take-off of the aerial vehicle and acceleration to the required speed during horizontal movement. Given the short-term nature of the system's operation, the change in the vertical component of the absolute speed during horizontal movement is not considered. The research also did not take into account the resistance of the environment, which limits the application of the results only to the case of flight at low speeds. The shortcomings of the study include the lack of consideration of the working processes and establishing the characteristics of the take-off nozzle system when using other working fluids. The use of water enables the functioning of the system in a limited temperature range, and other fluids can be used at low temperatures.

Advancing this research implies testing the take-off system as part of the aerial vehicle and obtaining its characteristics under actual conditions. Experimental studies will make it possible to more accurately take into account the influence of aerodynamic characteristics during take-off of the aerial vehicle and while achieving the required speed.

7. Conclusions

1. Numerical modeling of the process of fluid outflow from nozzles with a variable cross-sectional shape at a variable pressure drop has made it possible to detect an increase in vortex formation and a more dramatic increase in the velocity in the flow core at the end section of the nozzle compared to conical nozzles. Analysis of the characteristics allowed us to establish that energy losses when using nozzles with a variable cross-sectional shape are 4% higher than for conical nozzles. Despite the somewhat lower energy efficiency, the use of nozzles with a variable cross-sectional shape in the takeoff system of an aerial vehicle is more expedient due to better manufacturability.

2. Our studies of the process of charging and discharging a high-pressure gas-hydraulic accumulator, in particular the dependence of the accumulated energy and usable volume on the initial parameters, made it possible to determine the optimal ratio between the mass of the liquid and the mass of the filled accumulator for the takeoff nozzle system, equal to 0.23. High flow and hydraulic power made it possible to justify the use of a gas-hydraulic accumulator in the aerial vehicle launch system in comparison with other power sources. The peculiarities of the gas-hydraulic accumulator's working processes made it possible to determine the operating parameters that make it possible to use the maximum amount of energy and working fluid necessary for the operation of the take-off

nozzle system. It was established that the maximum amount of energy can be obtained when the nozzle elements operate at variable pressure, and its minimum value during discharge will be lower than the initial charging pressure, which allows the accumulated fluid to be used in full. Determining the hydraulic parameters of the take-off nozzle system operating in conjunction with the gas-hydraulic accumulator made it possible to establish the short-term nature of the system's operation, the operating time of which does not exceed 2 seconds. Based on the dependence of pressure and flow on time, the dependence of the nozzle element's thrust on time was derived, which is a key parameter that determines the possibility of practical implementation of the take-off system.

3. The thrust of the nozzle element has made it possible to determine the dependence of the height of the lift, speed, and acceleration of an aerial vehicle on time during vertical lift and horizontal flight. The results were obtained for different ratios of the mass of the aerial vehicle to the mass of the gas-hydraulic accumulator m_l / m_a which determines the main characteristics of the take-off system. Analysis of the resulting data revealed that with a m_l / m_a ratio equal to 2.0, the energy and thrust characteristics of the system make it possible to enable horizontal acceleration of the aerial vehicle to the breakaway speed. With a ratio of the mass of the aerial vehicle to the mass of the accumulator not exceeding 0.2, the system can provide vertical lift from an unprepared surface and horizontal acceleration to the breakaway speed. Our results do not take into account the drag of an aerial vehicle and the features of its launch, in particular, start from an inclined guide or vertical lift with subsequent transition to horizontal flight. Nevertheless, they make it possible to assess the maximum capabilities of the nozzle system under typical launch techniques.

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, as well as the results reported in this paper.

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Data availability

The data will be provided upon reasonable request.

Use of artificial intelligence

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

Authors' contributions

Serhii Strutinskiy: conceptualization, methodology; **Dmytro Kostiuk**: investigation, validation; **Igor Gryshko**: validation, formal analysis; **Andrii Zilinskyi**: investigation, formal analysis.

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