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EVALUATION OF THE RESULTS OF THE FLIGHT TESTS OF THE SMALL RESEARCH ROCKET K80 METEO 7000 ON THE WAY TO THE CREATION OF THE UKRAINIAN FAMILY OF SUBORBITAL LAUNCH VECHICLES

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Abstract

The object of this research is the process of choice the strategy for the development of the Ukrainian segment of suborbital launch vehicles (SOLVs). Problems arising in this process are analyzed and a search of ways of overcoming them was carried out. The strategy of development of a family of SOLVs is based on the previous experience of developing SOLVs in other countries. A family of SOLVs is proposed which includes five rockets with the apogee from 2 to 150 kilometers. The problem of the exclusion zones which can be reserved for falling of discarded parts of vehicles during the launch was considered. Experience of other countries in overcoming this problem was analyzed. It was decided to begin the process of formulation of a concept of a simplified SOLVs control system that would ensure keeping the rocket over the area of the launch. Within this task, a choice of components of the onboard electronic equipment (OBEE) was made. For testing the OBEE in the conditions of a real flight, a K80 Meteo 7000 rocket, a member of the proposed SOLV family, was chosen. In flight tests, most of the chosen OBEE components confirmed their operability, though some showed shortcomings in their operation. Main flight parameters of the K80 Meteo 7000 rocket were demonstrated. The reach of the apogee of 6,375 m and the velocity of Mach 1.733 was confirmed.

This research sets preconditions for practical implementation of launches of SOLVs with substantial altitudes of the apogee, while limiting the areas reserved for falling parts of the rockets. Availability of such SOLVs will enable solution of a wide range of problems in many fields of scientific research and the use of SOLVs as platforms for working out new technical solutions for other branches of rocketry.

Keywords: suborbital launch vehicles, family of sounding rockets, flight tests, onboard electronic equipment.

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1. Introduction

Suborbital launch vehicles (SOLVs), unlike orbital launch vehicles and spacecraft of different purpose, are traditionally on a side of the general direction of development of rocketry. However, they play an important role in this. These flying machines serve as supplementary means necessary for implementation of certain tasks in development and operation of complex space rocket systems. They are involved in refining of advanced technologies and solutions that can be implemented in the development of other flying vehicles and their payload. The SOLVs are a source of information about the actual environmental parameters at given altitudes. They are widely used for launching payloads containing devices and entire installations for carrying out unique experiments in various branches of scientific studies.

The range of problems that can be solved with SOLVs is virtually boundless [1]. Among the directions particularly actively developed in the past several decades there are:

1. Research in atmospheric processes.
2. Study of natural phenomena in the microgravity conditions.
3. Fundamental research in physics.
4. Working-out of promising technologies for implementation in rocketry and space technology.
5. Solving problems for military applications [2].

Systematic use of SOLVs for studying atmospheric processes began in the middle of the 20^{th} century. Since then, sounding rockets remain the only sounding devices capable of reaching altitudes from 40 to 200 km. SOLVs are involved in studying processes in the magnetosphere, ionosphere and thermosphere [3, 4]; they supplement data from weather monitoring satellites [5]. A separate case is launches of satellites in near-polar latitudes [6].

Experiments in the microgravity conditions on board of SOLVs [7, 8] are an optimal solution when the experiments last no more than 15 minutes, which is a limitation for the modern vehicles of this class. The duration of the microgravity condition that SOLVs can provide is sufficient for studying such phenomena as registering changes in living cells [7, 9] and motion and collision of particles of substances [10]. In the field of material studies, research includes accurate measurement of thermophysical properties of liquid metals, studying of growth of dendrites in the process of solidification of molten metals and refining of the grain [11].

A growth of the market of small commercial spacecraft opens more applications for the SOLVs. Considering the lack of substantial experience of commercial developers in launching and operating such vehicles in real conditions of the outer space, the use of SOLVs as a platform for testing and working out of such vehicles is promising. There are examples of successful implementation of this solution [12].

Ukraine is a country that has a considerable experience in creating rockets and spacecrafts. At the same time, the branch of SOLVs was practically ignored in the times of the USSR and has been in the times of its independence. As a result, there is almost complete lack of involvement of the Ukrainian science in the international research and lack of national projects of this kind.

Important aspects of launching any rockets with the apology altitude exceeding several kilometers is the necessity of closing the aerial space over the area of the launch and provision off substantial restricted areas for ensuring safety of people and facilities. In source [13], an estimation of the size of the required exclusion zone around the point of launch of a SOLV from a military range is provided. This calculation gives an understanding that for a chosen range the altitude of the apogee of a SOLV cannot exceed the maximum altitude of aerostats and air balloons. In source [2] a problem of the limited permissible altitude of flight of a Polish suborbital rocket ILR-33 Amber is described. Considering densely populated territories and, as a consequence, small dimensions of the acting military ranges, this problem is essential for Ukraine and many other countries.

Special requirements to the SOLV's include presence of onboard electronic devices for controlling the parameters of the flight. For instance, while experimenting in the conditions of microgravity, existing angular velocities of the rocket create corresponding G-forces and distort the results of such experiments. Control of G-forces requires inclusion of accelerometers into the onboard electronic equipment of an SOLV. Source [14] shows that the on board electronic equipment of a sounding rocket for taking samples from the mesosphere must include sensors that measure velocity and altitude of the vehicle.

In source [15], it is shown that for a SOLV used for studying the upper layers of the atmosphere the key measurements are those of temperature and pressure of the environment. Respectively, the onboard electronic equipment must include sensors of temperature and absolute pressure. At the same time, it is possible to use the sensor of absolute pressure as an altimeter.

The described problems and research permit to state that there is a demand for creation of SOLVs both on the global scale and in the interests of the science and economy of Ukraine. At that, such rockets must be equipped with the control system that can solve the problem of limited exclusion zones around the areas of their launch and also satisfy the specific requirements set by the purpose of the SOLVs. The experience shows that the transition from the theory to the practical implementation is the most critical stage in development of any objects of rocket and space technology, including SOLVs. Only after having passed the stages of laboratory works, creation of the facilities for testing units, components, structures and systems and also flight tests as a summary of this activity, it is possible to fully estimate the accepted solutions and obtained results.

A substantial number of research works devoted to rocket tests is known. In [16], an analysis of data on experimental flights of the SOLV Heros 3. In that research, the use of components of OBEE is proposed, which are much more expensive and are difficult to obtain in our conditions. There, as well as in our research, the problem of the COCOM Limits for GPS units was not solved. At the same time, from the diagram [16] showing variations of such parameters as altitude and velocity, it can be seen that, in that research, a GPS receiver is used that exceeds the one used by our team in the ability to operate in the conditions of strong g-forces. In [17], complete data on flight tests of the SOLV Heros 3 are provided. An advantage of our research is presence of a differential pressure sensor, which makes it possible to base velocity measurement basing on two sensors simultaneously (alongside with the accelerometers).

The aim of this study is formation of prerequisites for creation a segment of SOLVs in Ukraine and a search for solutions of problems that emerge in development and testing of the SOLVs, in particular, the problem of the limited exclusion zones available in Ukraine and absence of available onboard electronic equipment. This will give a possibility to create prerequisites of effective development of the SOLV segment in Ukraine and other countries where such problems are substantial.

For achieving this aim, solution of the following problems is planned:

– to formulate the main strategy of development of the SOLV segment in Ukraine;

– to determine the minimum required composition of the onboard electronic equipment and facilities for its testing at the early stage of implementation of the SOLVs' capabilities;

– to carry out flight tests of the rocket and to analyze operation of the chosen onboard electronic equipment;

– to analyze correspondence of the computed and experimental parameters of the flight of K80 Meteo 7000 rocket that was studied.

2. Materials and methods

2. 1. The proposed development strategy of the segment of suborbital launch vehicles

Since the range of the problems that can be solved with the use of SOLVs is very wide, it is necessary to find solutions that enable achievement of the goals at minimum costs. The ability of a particular SOLV to accomplish one or another task is determined by its energy capability, which is most frequently determined by the dependence between the mass of the payload and the altitude of the apogee. Development of a family of SOLVs provides an advantage of unification of certain parts, units, systems, subsystems, propulsion units, components of the payload, etc. This substantially reduces the overall costs of development of SOLVs both because of reduction the amount of testing and substantial reduction of development time.

One more advantage achieved owing to development of a family of SOLVs is that it gives an opportunity to organize development as an evolutionary process. Each next product inherits a considerable part of technical solutions of the previous variant, which enables incremental increase of the manufacturing and testing facilities and improve approaches to designing due to the experience obtained through operation of real products.

Creation of a family of SOLVs it typical practically for all national programs in this field. The most popular solution within the framework of families of solid-propellant SOLVs is combining solid-propellant engines, which can be very clearly seen in the NASA Sounding Rockets program [4].

2. 2. Activities of the «Rocketry agency» student project as a prerequisite for research

In 2018, on the basis of Oles Honchar Dnipro National University and Space Lab Noosphere Engineering School (Ukraine) a non-profit educational project «Students' Rocket» was established, which was later renamed as «Rocketry agency». The operation of the project began with development and launch of a small K80 CanSat rocket. Further, it was decided to develop a family of SOLVs and, in the development of which, to gradually increase the altitude of the apogee of the rockets and their general technical level, with parallel development of the technological capabilities and testing facilities. **Fig. 1** shows the first variant of this family of SOLVs.

Fig. 1. A family of rockets of the «Rocketry agency» project

Within this family, development of five rockets is planned:

1) K80 CanSAT – a single-stage solid-propellant rocket intended for launching an educational project for launching model satellites of the popular in many countries CanSAT type at the altitude of around 2 km [18]. It passed all stages of testing as of 2019;

2) K80 Meteo 7000 – a single-stage solid-propellant rocket that can serve as a supersonic aerodynamic laboratory of short-term action. Prospectively, it can be used as a domestically produced anti-hail rocket;

3) K80 Meteo 20000 – a two-stage solid-propellant rocket capable of achieving altitudes comparable with those of K80 Meteo 7000 and perform similar tasks. The second stage repeats many features of K80 Meteo 7000, and the first stage of a larger diameter is a foundation for more powerful SOLVs;

4) K80 Meteo 40000 – a two-stage solid-propellant rocket. It is the first rocket in the family capable of reaching the altitude of 40+ km, that is, the boundary beyond the reach of aerostats. With this rocket, data on the state of the atmosphere can be achieved in altitudes up to 50 km; that is, it can be used as a meteorological rocket;

5) K300 GEO – the first liquid-propellant rocket in the family, capable to reach beyond the conventional boundary of the atmosphere. Its prospective use is a geophysical rocket and as a platform for experiments in the microgravity conditions. Transition to the liquid propellant components in this rocked is stipulated by the high cost and limited availability of components required for the solid propellant.

The obtained and expected parameters of the rockets of this family were presented in [19, 20].

As a platform for testing onboard electronics, the K80 Meteo 7000 rocket was chosen (**Fig. 2**). This rocket is supersonic, and during the operation of its solid-propellant engine, substantial G-forces emerge (>8 g), which provides a short period for testing of the onboard electronic components in rather extreme conditions.

In the previous stages of development of this rocket, the following problems were solved:

– a composition of the mixed solid propellant based on ammonium perchlorate with improves ecological parameters was developed and worked out [20]. In parallel, more environmentally friendly alternatives to ammonium perchlorate are looked for [21, 22];

– the design of the solid-propellant engine of the diameter of 80 mm was worked out. An automated non-destructive inspection in manufacturing the casings of solid-propellant engines was developed and implemented [23];

– the design of the payload bay (the head) of the K80 Meteo 7000 rocket was developed;

– a set of ground equipment for launching the K80 Meteo 7000 rocket was developed, including telemetry receivers and means of monitoring the flight trajectory. In its development, ground equipment used for testing K80 CanSat rocket was upgraded.

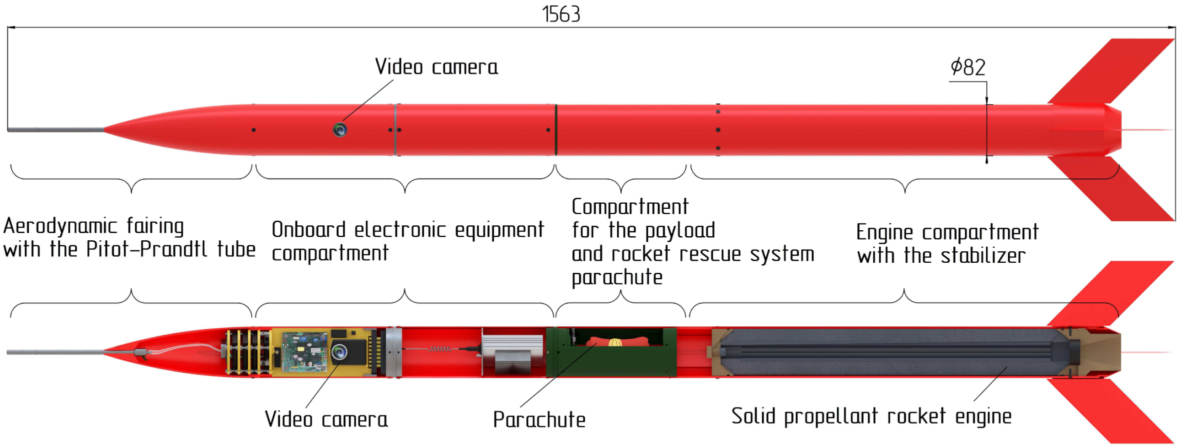

Fig. 2. Exterior appearance and design layout scheme of the K80 Meteo 7000 rocket

Performance characteristics of the suborbital complex with the K80 Meteo 7000 rocket are presented in **Table 1**.

Table 1
Performance characteristics of the suborbital complex with the K80 Meteo 7000 rocket

Number of stages	1
Length, mm	1563
Diameter, mm	82
Starting weight, kg	7.6
Engine – with load-carrying casing	SPRE SI 5000
Solid propellant type	Mixed
Charge	Bonded filler
Average engine thrust, N	1200
Specific impulse of thrust, s	195
Total impulse, H×c	5560
Payload weight, kg	0.5
Flight control system	Available
Maximum g-force	25
Control system	N/A
Stabilization system	Passive aerodynamic
Rescue system	Two-stage combined
Flight altitude, m	Up to 8000 m
Launch complex	Mobile

2. 3. The main scheduled stages of flight testing of the K80 Meteo 7000 rocket

1. Operation of the onboard electronic equipment at the prelaunch preparation.

2. Firing and operation of the solid-propellant engine (in the boost path). At the end of the boost path, the rocket moves at a supersonic speed.

3. Stable flight along the trajectory close to a vertical line up to the apogee at the altitude of 6 to 7 km.

4. Separation of the rocket after passing the apogee with the use of a solid-propellant gas generator into:

– the head part, that is, the bay containing the onboard electronics, payload, sensors and telemetry transmitter;

– the rocket part, which is the hull of the exhausted solid propellant engine and the empennage of aerodynamic stabilizers.

The head part and the rocket part are fastened to each other with the use of a Kevlar cord to ensure landing of all components of the rocket in the point, coordinates of which are determined by the GPS/GLONASS receivers, substantially simplifies search of the rocket. Besides, separation of the rocket into two parts at the altitude close to the apogee enables the «flat spin» that substantially reduces velocity on the descending segment of the trajectory due to the increase of the head atmospheric drag and the area facing the incidental air flow.

5. Flight in the descending segment of the trajectory before deployment of the parachute;

6. Deployment of the parachute at the predetermined altitude of 500 m.

7. Descent with the parachute. At this segment, the rocket must be decelerated to the speed not more than 10 m/s.

8. Landing of the rocket with the permissible speed that ensures potential reuse of all parts of the design, except the solid-propellant engine.

2. 4. Computed parameters of K80 Метео 7000 rocket

For evaluation of the main flight parameters of the rocket, the following software was used:

– for evaluation of the aerodynamic characteristics (in particular, coefficients of aerodynamic drag) – Aerolab software system [24] (**Fig. 3**);

– for computation of the main flight parameters – Altimmex-SP2 software system [25] (**Table 2**).

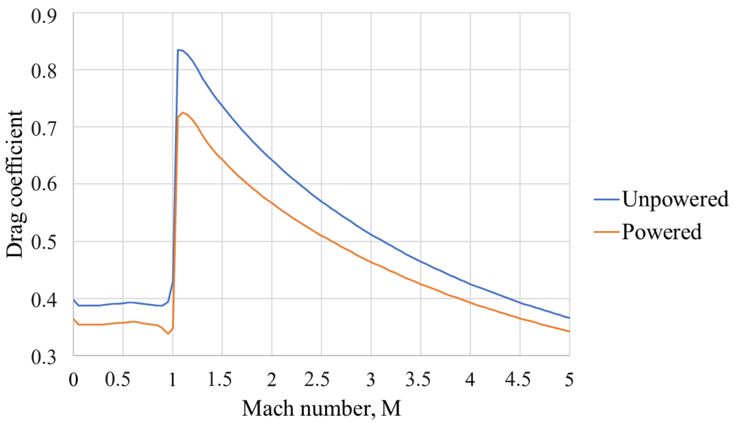

Fig. 3. Dependence of frontal drag coefficient on the Mach number with operating (Powered) and switched off (Unpowered) rocket engine, as calculated with Aerolab software [24]

Table 2
Main parameters of the flight of K80 Meteo 7000 rocket calculated with Altimmex-SP2 software [25]

Parameter	Value
Altitude of the apogee, m	6656
Maximum velocity, m/s	569
Maximum g-force, units	16
Time to the apogee, s	31.9
Altitude of the shutdown of the engine, m	2385

2. 5. Assumptions and simplifications of the study

The computational part contains the following assumptions:

1) parameters of the atmosphere are assumed to be static (according to [26]). The wind disturbances are not considered;

2) the thrust profile of the engine is assumed the one obtained on the test bench during firing tests.

The experimental part of the study contains the following assumptions and simplifications:

1) the accuracy of the obtained experimental data is limited by the accuracy of components used in the OBEE;

2) absence of information on the ability of some of the components of the OBEE to operate in the conditions of high velocities and g-forces and influence of such conditions on the accuracy of their measurements.

The research is limited to studying of behavior of OBEE components in the range of flight parameters of K80 Meteo 7000 rocket, which can be achieved according to its mass, size and power characteristics. The obtained experimental data are limited by only one experiment and require reproduction in experiments with the initial parameters as close as possible to the one provided here.

2. 6. Basic data on the equipment used in the flight tests

The onboard electronics (**Fig. 4**) included the following devices for determining flight parameters at any given moment of time:

1) absolute pressure gauge – ASDXACX015PA2A5;

2) differential pressure gauge – HSCDRRT001PD2A3;

3) temperature sensor – LM35 Temperature Sensor;

4) 3-axis accelerometer of strong accelerations (up to 100 g) – AnalogDevices ADXL78 – Single-Axis, High-g, iMEMS® Accelerometer;

5) 3-axis accelerometer of small accelerations (up to 16 g) – as part of the BOSCH BMC150 device – 12 bit 3-axis Accelerometer and 3-axis geomagnetic sensor;

6) 3-axis magnetometer – as part of the BOSCH BMC150 device – 12 bit 3-axis Accelerometer and 3-axis geomagnetic sensor;

7) GPS receiver – FGPMMOPA6C.

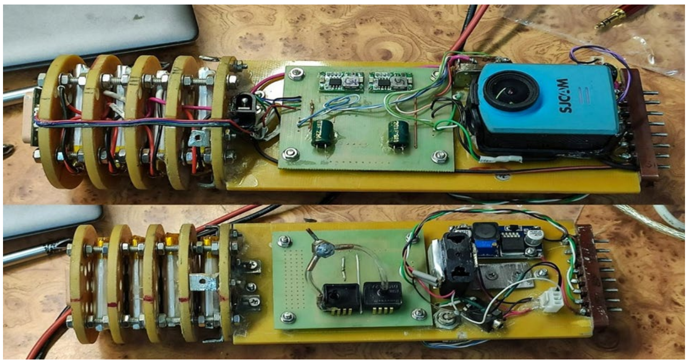

Fig. 4. Onboard electronic equipment of the K80 Meteo 7000

The data from the sensors were processed in real time by specialized controllers. Further, data were formatted into telemetry blocks and transmitted to the ground telemetry receivers. The frequency of transmission of the telemetry blocks was 4 blocks per second during the flight and one block per second in the waiting mode. This was done with a 5-watt transmitter.

The fairing of the rocket was equipped with the receptor of the atmospheric pressure – a Pitot-Prandtl tube, the feeders from which were connected to gauges of absolute and differential pressure.

Also, as supplementary means of acquisition data on the flight tests, the payload included two video cameras (for general view and nadir view), which recorded footage during the entire flight.

At the beginning of the flight of the rocket, video footage was taken also from the ground observation stations.

3. Results and discussion

3. 1. Main results of flight tests

In the course of flight tests of the K80 Meteo 7000 rocket, it fully accomplished its mission. On all stages of the flight, the onboard electronics operated properly. For processing the data, MS Excel and Mathcad 15 software systems were used [27].

During the flight tests, the temperature sensor confirmed its normal performance by providing the output of the current temperature. However, the data appeared to be of low informative value because of the substantial lagging of its measurements and fast change of the flight parameters of the rocket. At the same time, the stable stream of output from the sensor marks it as a promising option for long-term flights beyond the terrestrial atmosphere, where the conditions of the environment change less quickly.

Data from the GPS and GLONAS receivers were presented in the telemetry block – time mark, current coordinates, velocity and altitude. It can be noted that at considerable G-forces (>8 g) at the boost path of the flight, operation of receivers was unstable. Data on the velocity and altitude were close to data of other sensors only at the segments of steady-state subsonic flight. At the same time, marks of the time and current coordinates were provided accurately, but with a moderate lag. The point of landing of the rocket corresponded to the coordinates provided by both receivers.

The data from the absolute pressure gauge were generated during the entire flight of the rocket and are shown as a dependence of the absolute pressure on time (**Fig. 5**).

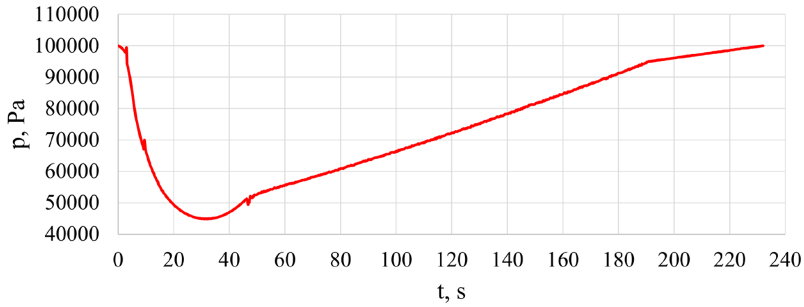

Fig. 5. Dependence of the absolute pressure on the time

On the grounds of [26], to each value of the absolute pressure, a corresponding geometric altitude was determined. The result of this processing is shown in **Fig. 6**.

Data from the absolute pressure gauge establish the following significant results:

– the altitude of the apogee is 6.375 m;

– the time of reaching the apogee is 31.7 s.

Fig. 6 shows that the descending branch of the trajectory has two linear segments with different inclination angles to the horizontal axis. This is explained as descend in the separated state and after deployment of the parachute. The point, at which the angle changes is at the altitude of 530 m, which is close to the value set in the sequence diagram.

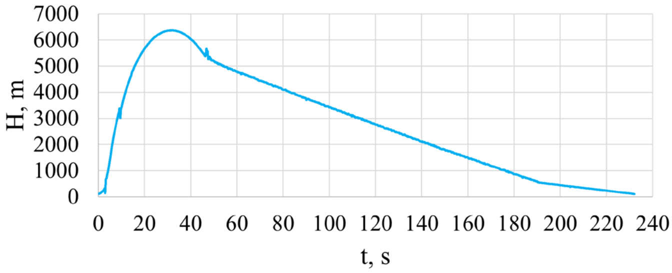

Fig. 6. Dependence of the altitude on the time

Data of the differential pressure gauge (**Fig. 7**) can be considered correct only on the ascending branch of the trajectory. This is because on the descending branch, the Pitot-Prandtl tube constantly changes its angle relative to the incidental air flow, and it operates correctly only withing a certain range of angles of incidence.

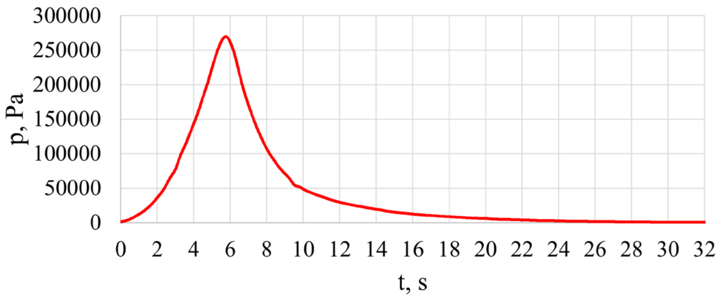

Fig. 7. Dependence of the differential pressure on the time

The experimental data were transformed by establishing correspondence of each value of the differential pressure and Mach number according to [28]. For correction of the speed of sound with respect to the altitude, data of the absolute pressure gauge were used. The outcome of this data processing is shown in **Fig. 8**.

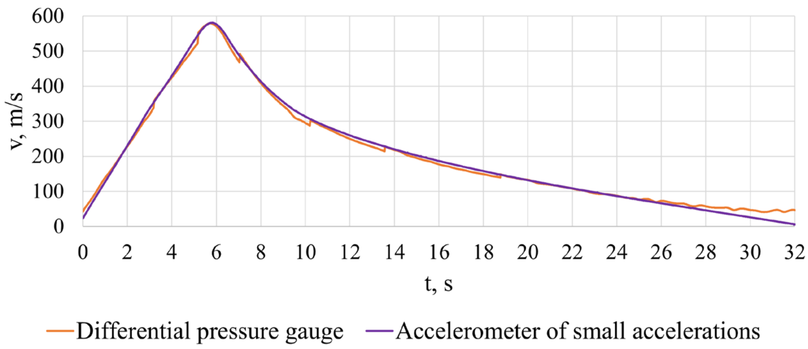

Fig. 8. Dependence of the velocity (m/s) on the time according to the differential pressure gauge and accelerometer of small accelerations

Data from the differential pressure gauge establish the following significant results:

– the maximum velocity is achieved at the end of the boost path of the trajectory and is 577 m/s (Mach 1.733);

– the time of reaching the maximum velocity is 5.87 (this corresponds to the time of the active (boosted) segment of the trajectory);

– the minimum velocity on the time interval [0 s; 32 s] is at 31.5 s from the time indicated by the liftoff sensor, which can be considered the passage of the apogee. The time of reaching the apogee estimated with the data from the absolute and differential pressure gauges match: 31.7 s and 31.5 s respectively.

Accelerometers of strong and small accelerations operated normally; their outputs were virtually the same along all axes. Since the maximum G-force for the K80 Meteo 7000 rocket achieved almost 12 g along the longitudinal axis Z and not more than 3.5 g along the transversal axes Y and Z. Data from the accelerometer of small accelerations were obtained for the entire flight segment. Since this accelerometer is more accurate, only its data are shown here (**Fig. 9**).

By integrating the data from the accelerometer of small accelerations along the X axis, let's obtain the velocity on the boost segment of the trajectory. As can be seen from **Fig. 8**, the shape of the diagram of the velocity obtained by integration is close to the data collected from the differential pressure gauge.

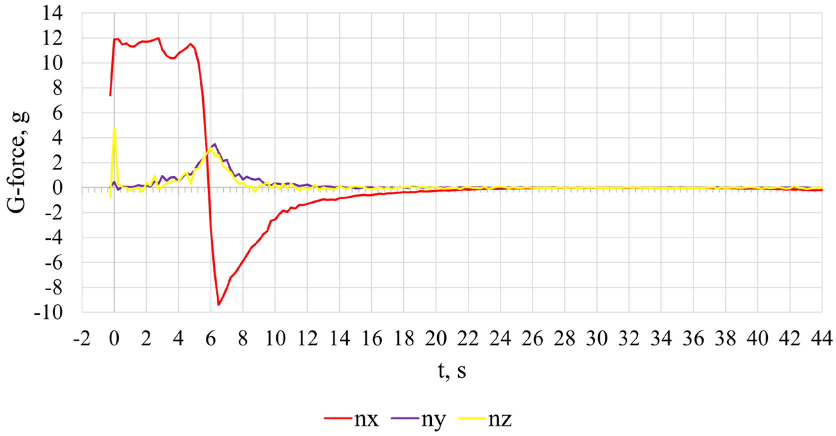

Fig. 9. Dependence of g-forces on the time, according to the data from the accelerometer of small accelerations

The three-axis magnetometer demonstrated normal operation. The data on the change of the roll channel corresponded to the pattern of the motion of the rocket, which was established with the help of the information obtained from two video cameras mounted onboard.

Table 3 shows the main flight parameters obtained as a result of flight tests compared to theoretical calculations.

Table 3
Main parameters of flight of K80 Meteo 7000 rocket obtained in a flight test in comparison with the computed ones

Parameter	Computed value	Experimental value
Altitude of the apogee, m	6656	6375
Maximum velocity, m/s	569	~580
Maximum g-force, g	16	Not exceeding 12
Time to the apogee, s	31.9	31.5–31.7
Altitude of engine's shutdown, m	2385	1945

3. 2. Discussion

At the current stage, outcomes of the flight tests of the Meteo 7000 rocket demonstrated the possibility in principle to register certain flight parameters at a selected moment of time, which is a necessary condition of normal operation of the future attitude control systems of SOLVs. At the same time, some of the onboard sensors showed limited accuracy, substantial lag and inability to operate at strong G-forces (>8 g). The limitations shown by the GPS and GLONAS receivers and the temperature sensor are explained by the use of relatively cheap, commercially available devices. As limitations inherent in the research, testing of the onboard electronic equipment at the altitudes not exceeding 7 km and accelerations not exceeding 12 g can be mentioned. Besides, the collected information on the flight parameters needs testing for reproducibility, which is planned further on. Further improvement of components of the attitude control system requires a search for sensors with improved performance parameters. A potential complication here can be an increase of the costs of such devices.

The decision to separate the rocket, after its passage of the apogee, into the head and the rocket parts showed its effectiveness for reduction of the speed during the free fall. At the same time, this flight scheme represents complications for registering parameters of speed and G-force on the descending branch of the trajectory because of constant random changes of the positioning of the rocket. For this reason, data on the flight for the entire trajectory from the launch to landing was successful only for the absolute pressure gauge, which is shown in **Fig. 5, 6**. Therefore, for rockets with a higher altitude of the perigee, an option of multistage parachute rescue systems should be considered.

4. Conclusions

The main strategy of development of SOLVs in Ukraine must become their designing as «families». The «Rocketry Agency» project has proposed an initial variant of a family of SOLVs, which involves a gradual transition from small research rockets with the apogee of 2 to 7 km to rockets with the apogee above the Kármán line. Flight tests of K80 Meteo 7000 show successfulness of the practical implementation of the approach to development of the proposed family of rockets.

Having analyzed problems and tasks that emerge in connection with SOLVs, an initial variant of the onboard electronic equipment was designed, the components of which are the necessary prerequisites for operation of SOLVs according to their intended purpose. As components of the onboard electronics, absolute and differential pressure gauges, three-axis accelerometers, temperature sensor, GPS and GLONAS receivers and a three-axis magnetometer were included. The K80 Meteo 7000 rocket was chosen as a platform for testing the onboard electronics.

A program was developed for testing components of the onboard electronic equipment mounted on K80 Meteo 7000. It included operation in the pre-launch mode and registration of the flight data in the boosted and passive segments of the trajectory. In the flight tests, a considerable amount of data was obtained on the parameters of motion of the K80 Meteo 7000 small research rocket. All main stages of flight tests were accomplished. Most components of the onboard electronics and the structure of the rocket showed their operability and performed their functions according to the developed test program. The first stage of testing of the components of the orientation system, which is a part of the perspective control system of the SOLVs showed shortcomings in operation of some of the chosen sensors. These shortcomings include incorrect operation in segments with strong G-force.

Flight tests of the K80 Meteo 7000 rocket allow to assert that the calculated values of parameters correspond to the experimental data with a sufficiently high accuracy. The cause of the apogee altitude in the experiment being somewhat lower than the calculated one can be the difference of the thrust profile of the engine from the one obtained in the firing test and the assumption of static parameters of the Earth's atmosphere used in computations.

Conflict of interests

Authors declare that they do not have conflicts of interests related to this research, including such of financial or personal nature, authorship or any other nature, that could influence the research and its results presented in this paper.

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Availability of data

The data can be provided upon a grounded request.

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