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Flow in a shortened Laval nozzle with a bell-shaped tip

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ABSTRACT :
Shortened nozzles are convenient to use with a dense layout of the rocket engine. Specially profiled nozzle maximizes space filling of engine chamber and reduces overall weight. In this regard, it is important to know the effect of reducing the nozzle total length on the flow pattern in it. A numerical simulation of the flow in two similar nozzles with different total lengths has been carried out. It is shown that a decrease in the length of the nozzle with an equal length of the conical part of the nozzle does not significantly affect the thrust characteristics. The flow in a nozzle with a tip was calculated at various inlet pressures (50–300 bar). It is shown that with a pressure increase of the inlet flow, the size of the Mach disk and the size (longitudinal and transverse dimensions) of the "barrel" increase in proportion to the pressure change. A transformation of the developed external flow in a nozzle into a closed separated flow with a small-scale toroid vortex is also observed. With a large under-expansion of the flow from the nozzle, the thrust coefficient becomes constant at different values of the inlet pressure. The influence of the pressure of the ambience on the flow pattern in the tip has been studied. There are no vortex structures from the ambience at a pressure of 0.1 bar into the separation zone behind the corner (critical) point of the nozzle, observed at pressure at sea level. While at the nozzle tip exit, separation shock of the boundary layer from the tip wall is observed, and the internal gas flow is adjacent to the tip wall, the shock intensity at the nozzle edge at the outlet slightly decreases with increasing inlet pressure. Experimental studies of the models showed satisfactory agreement with the calculation results.

KEYWORDS: *nozzle, bell tip, flow, thrust, pressure, vortex.*

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I. INTRODUCTION

In modern rocket propulsion systems, different types of nozzles are used: Laval nozzle, bell-shaped, double bell-shaped, annular, etc. The main characteristics of the Laval nozzle are well studied, different variations of its design have been proposed [1-2]. However, there are operating conditions for nozzles that cause over-expansion or under-expansion of the flow, which reduces its efficiency. Therefore, researchers are engaged in various modifications of the standard nozzle. Based on the "classic" Laval nozzle, studies are being carried out to create shortened nozzles. In [3], a minimum length nozzle was designed by the method of characteristics. This method has been very popular for designing the contour of a nozzle. Thus, the authors of [4] designed a supersonic nozzle by the method of characteristics under conditions of a two-dimensional, stationary, inviscid, isentropic flow.

For new tasks, the researchers turned to shortened nozzles with a smaller length and mass. As a base, the authors used classic conical nozzles or profiled by the method of characteristics, and then shortened them [5]. This caused slight shocks in the nozzle and somewhat increased wave loss of nozzle thrust. The shape of the nozzle also changed. Recently, a bell-shaped nozzle has been considered in rocket engines, which has a larger angle of entry into the supersonic part of the nozzle compared to the Laval nozzle [6]. This type of nozzle in solving certain problems of rocket technology has advantages over the Laval nozzle in terms of size and efficiency, reduces the complexity of production and use compared, for example, with annular nozzles having a central body [7]. The processes occurring in the bell-shaped nozzle are similar to those in the Laval nozzle. In [8], various types of nozzle exit configurations are considered: conical and profiled. Tapered is often used due to ease of production. However, it is preferable to use a shaped exit, since it increases the nozzle efficiency while reducing its mass. Until now, the authors used the method of characteristics to calculate the flow in a supersonic nozzle. This did not allow studying the complex features of the flow in a bell-shaped nozzle. The used circuit is quite complex. The bell-shaped design can have a large expansion angle just past the neck. It is then reduced to provide a small angle at the nozzle exit. Expansion waves appear immediately behind the critical section. Farther downstream, shock waves of compression occur in the bell-shaped nozzle due to the large gradient of the change in the inclination of the wall. As a rule, complex vortexes arise. Nozzles with a double bell are currently being considered [9]. The double bell nozzle has better overall altitude change efficiency than the single bell nozzle. Atmospheric pressure limits the expansion of the exhaust gases at low altitudes, so the efficiency at low altitudes is much higher. It can also expand the engine exhaust to a larger effective nozzle area at high altitudes. In [9], four different types of Bell nozzles and a Double Bell nozzle were selected and studied. It is shown that the correct choice of contour geometry makes it possible to increase the efficiency of using the structure at various heights. The Double Bell nozzle is height-adaptable and has two modes of operation. The study [10] revealed the influence of the nozzle geometry on the behavior of the flow and, as a result, on the efficiency of the nozzle. The studies were carried out using computational fluid dynamics (CFD) [9, 11], which made it possible to discover new regularities in the behavior of the nozzle flow.

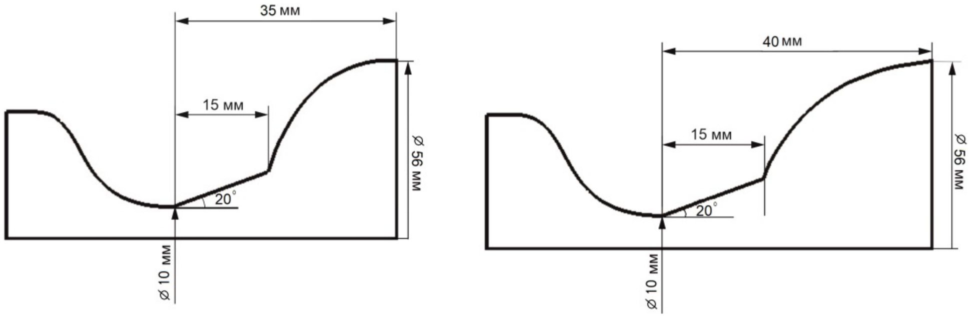
In [12], the authors pointed out the need to take into account the adaptation of its shape to the problem being solved when studying the characteristics of a nozzle of an unconventional shape. A variant of the nozzle was proposed, combining a classic conical nozzle and a bell-shaped nozzle. This was justified by the need to create dense layouts of engine. In contrast to Double Bell, such nozzle with a shortened initial supersonic section passes at the corner point into a bell-shaped nozzle with a large wall angle gradient, in the simple case, into a sphere. At the same time, the advantages of such nozzle operation are retained with a change in flight altitude.

In the present work, an attempt was made to investigate the flow in such a nozzle with one of the possible options for combining the shortened part of the Laval nozzle with a bell-shaped tip having an angle at the exit of the circuit of 0°.

The paper aim is to study the gas flow characteristics in a shortened nozzle of a rocket engine with a bell-shaped tip with changing the pressure in front of the nozzle, the pressure of the ambience and the total length of the nozzle.

II. MATERIALS AND METHODS

The study considered two variants of nozzles differing in total length (35 mm and 40 mm) with the same length of the conical inlet section - 15 mm, tip wall radius – 28 mm and 26 mm, respectively. The design of shortened nozzle contours is shown in fig.1.The supersonic nozzle has the following features. The critical section, which diameter is 10 mm, is followed by the conical section of the Laval nozzle with an opening half-angle of 20°. The transition from the nozzle to the tips is carried out at the corner point. Nozzle exit angle is 20°. The geometric expansion degree of the nozzle with the tip was constant and equal to $\frac{F_a}{F_*} = 31.36$. Changing the total length of the supersonic part of the nozzle with a constant shortened section made it possible to change the angle of entry into the tip and its configuration (radius). It should be noted that the tip radius is of fundamental importance for designing a densely packed engine.



a) b)

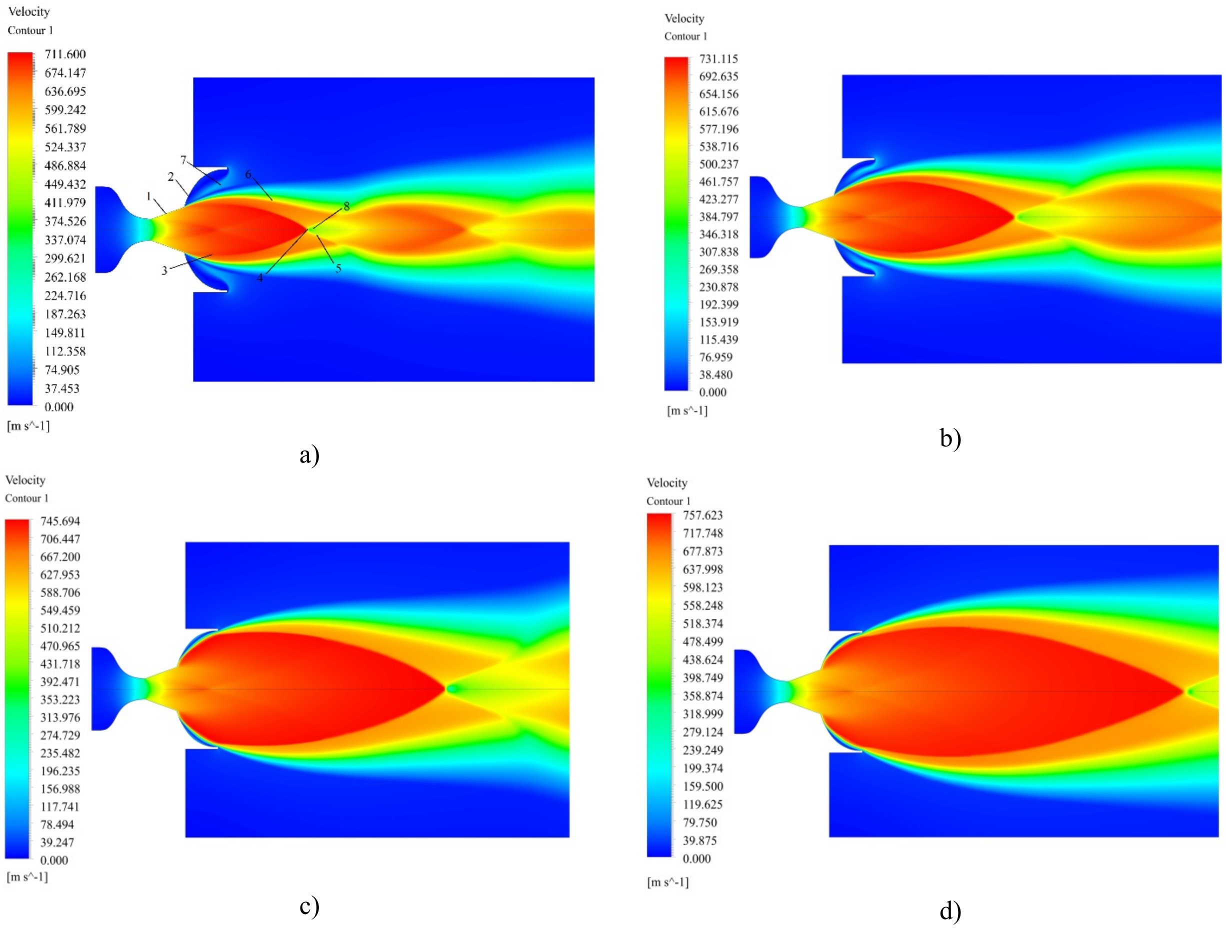
Fig.1. Shortened supersonic nozzles with a bell-shaped tip

The choice of initial conditions (in particular, the physical properties of the gas, etc.) was justified in [13] by verifying the results of the authors' calculations (using the ANSYS Fluent package) with the gas flow in the well-known Laval nozzle. Only one-half of the nozzle is simulated due to symmetry reasons, and symmetry boundary conditions are used at the corresponding planes. The result analysis of using various turbulence models for a disturbed flow [14] showed that the TR-SST model, a combination of the k-ε and k-ω models, is the most adequately describing the disturbed flow in a rocket engine nozzle. The temperature effects are not taken into account this study; the flow is purely cold flow (300 K).

III. RESULTS AND DISCUSSIONS

3.1 Influence of inlet pressure on the flow pattern

The calculations were carried out at pressure at the nozzle inlet p_0=50, 100, 200 and 300 bar. The ambient pressure was assumed to be p_H=1 bar, which corresponded to the position on the earth surface, and p_H=0.1 bar for flights in the upper atmosphere. The calculation was carried out using the ANSYS Fluent software package with the initial flow characteristics: ideal gas, isentropic index γ=1.4, flow temperature T_0=300 K, turbulence model kω-SST. Figure 2 shows the results of calculating the flow in a shortened Laval nozzle with a bell-shaped nozzle 35 mm long (Fig. 1a) at an external pressure p_0 = 1 bar and various inlet pressures: p_0 = 50, 100, 200, and 300 bar. Designations in fig. 1a) are applied to all Fig.1



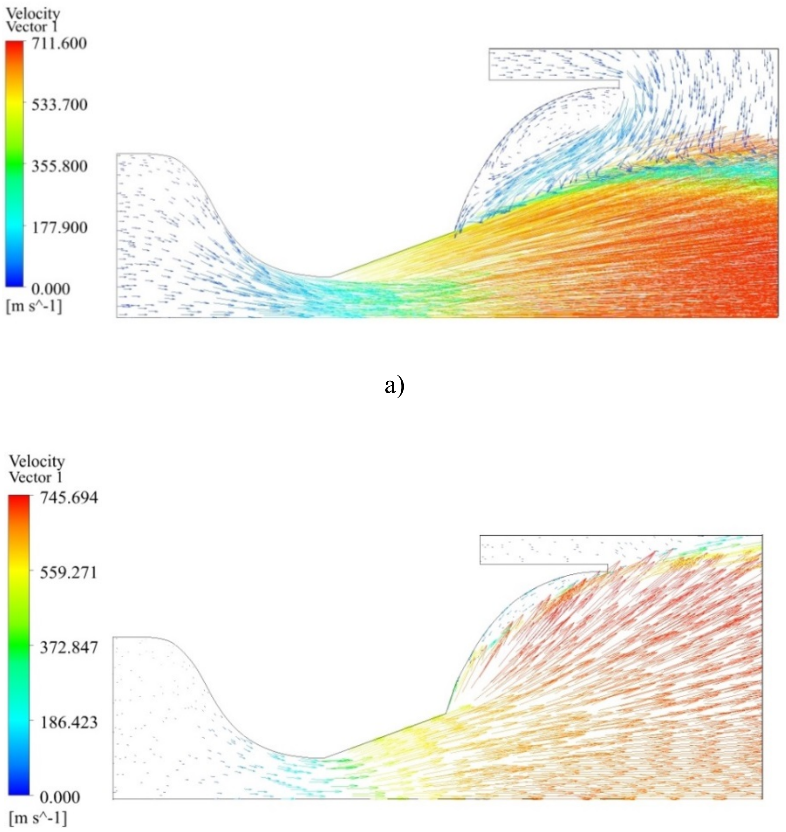
a) b) c) d)

1 –shortened Laval nozzle; 2 – bell-shaped nozzle; 3 – hanging shock; 4 – Mach disk;5 – reflected shock;6 – secondary hanging shock; 7 – separation zone; 8 – zone of low speeds behind the Mach disk

Fig. 2.Flow in a shortened nozzle with a length of 35 mm at an external pressure of p_H=1 bar and various pressures at the nozzle inletp_0=50 bar (a), p_0=100 bar (b), p_0=200 bar (c),p_0=300 bar (d)

As it is seen from fig. 2, the size of the Mach disk and the size (longitudinal and transverse dimensions) of the "barrel" change with the inlet pressure. With increasing pressure, they increase in proportion to the change in pressure. At pressures of 50 and 100 bar, a developed flow from the external medium into the separation zone behind the corner point of the nozzle is observed. Figure 3 a) shows the field of vectors in a nozzle 35 mm long (Fig. 1a) at p_0=50 bar, which details the vortex flow pattern in the tip. A powerful toroid vortex is formed near the tip wall, which propagates almost the entire length of the tip. At the tip of the nozzle, at the free boundary of the jet flowing from the shortened nozzle, the formation of a hanging shock is observed due to the inflow of an external flow onto the jet boundary.

At a pressure of more than 200 bar, this developed separated flow transforms into a closed vortex zone, starting behind the corner point of the transition from the shortened Laval nozzle to the nozzle. On the nozzle end, the specified vortex zone closes at the corner point of the tip end. Figure 3b) shows the field of vectors in the same nozzle at an inlet pressure p_0=200 bar, where the transformation of the developed external flow (Fig. 3a) into a closed separated flow in the nozzle is clearly visible, propagating from the corner point of the transition of the shortened nozzle into the nozzle to the nozzle shear, with a small-scale toroid vortex.



a)

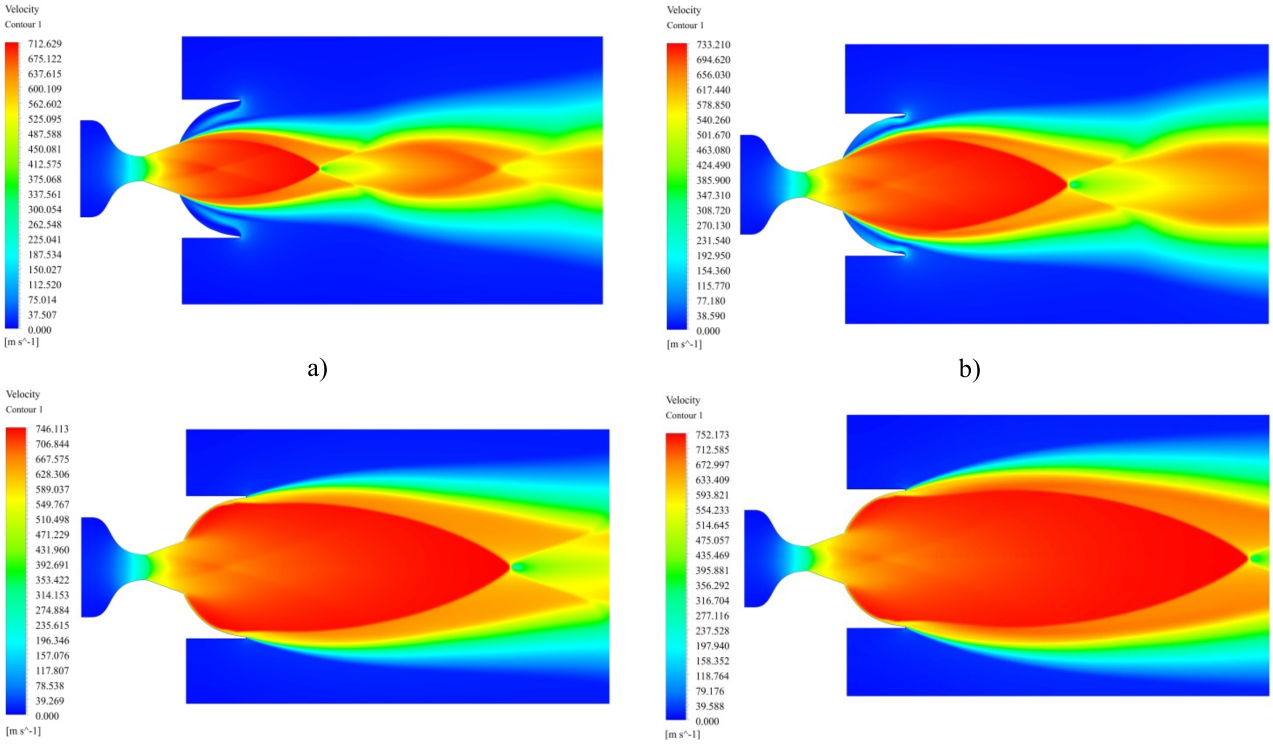
b)

Fig. 3. Gas flow in a 35 mm long nozzle at external pressure $p_{н}$= 1 bar, inlet pressure:p_0=50 bar (a) and p_0 = 200 bar (b)

3.2. Effect of Changing the Total Nozzle Length on the Flow Pattern

Shortened nozzles are convenient to use with a dense layout of the rocket engine. Specially profiled nozzle maximizes space filling and reduces overall weight. In this regard, it is important to know the effect of reducing the total length of the nozzle with a nozzle on the flow pattern in it. Numerical simulation of the flow in two similar nozzles with different total lengths – 35 mm and 40 mm (Fig. 3-4), the geometry of which is shown in Fig. 3, was carried out. 1. The calculations were carried out at the inlet pressure p_0=50 bar and 100 bar, the pressure of the ambience behind the nozzle exit $p_{н}$=1 bar.

Studies have shown that with a change in the total length and radius of the tip wall, the vortex structure behind the corner point of the tip changes. The length of the first “barrel” practically does not change with increasing nozzle length, while for a longer nozzle with an increase in inlet pressure (p_0 more than 100 bar), the external flow adheres to the wall of the nozzle tip.



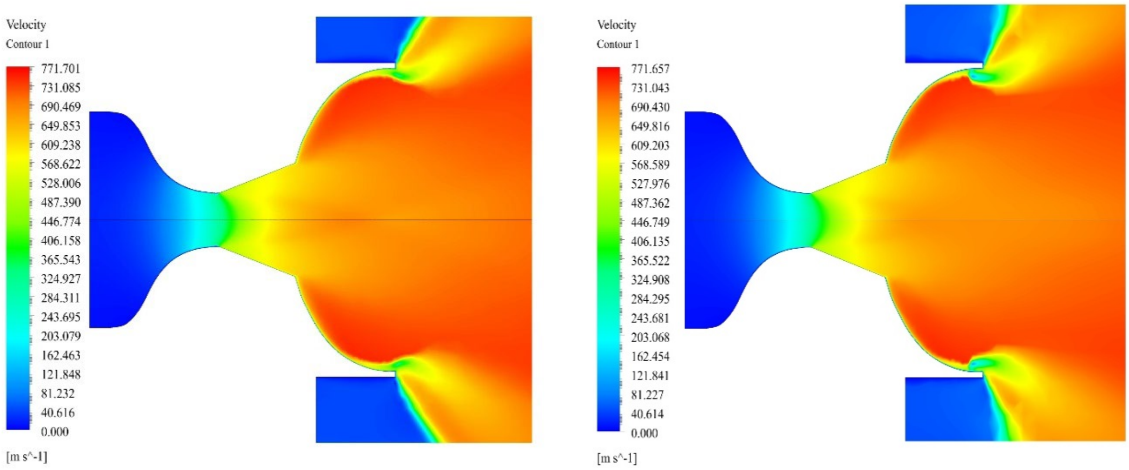
a) b)

c) d)

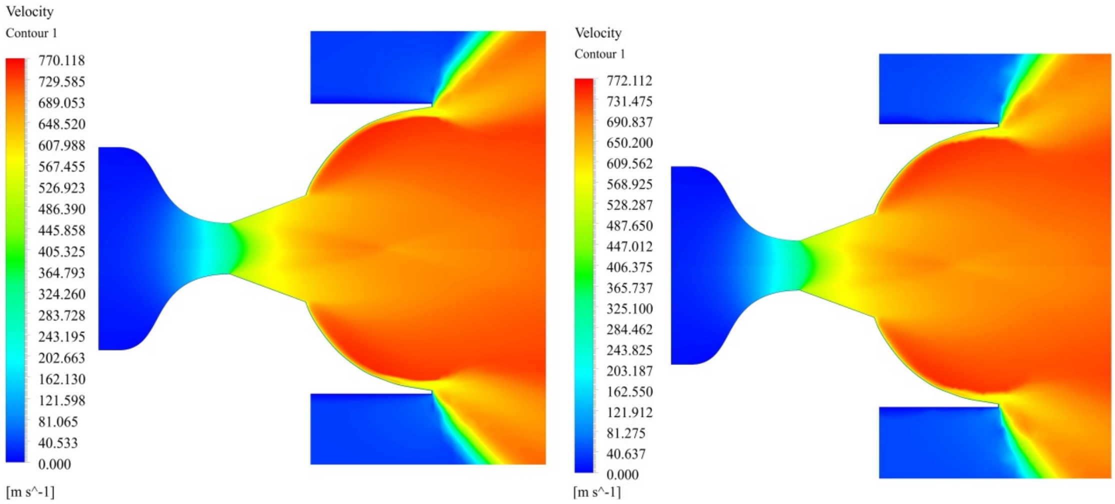
Fig. 4 Flow in a shortened nozzle with a total length of 40 mm with nozzles at different pressures at the nozzle inlet p_0=50 bar(a), p_0=100 bar(b), p_0=200 bar(c),p_0=300 bar(d)

3.3 Investigation of the flow in the nozzle at low external pressure

For rocket engines operating at high altitude, it is important to know the characteristics of the flow in the nozzles at low external pressure of the atmosphere, or even in its absence, i.e. in the void. This fact significantly affects the efficiency of the engines. For this purpose, the gas flow in the nozzles described above was studied at an external pressure $p_н$=0.1 bar. Figure 5 shows the flow structure at the initial inlet pressure p_0=50, 100 bar.



a) b)



c) d)

Fig. 5. Gas flow in a shortened nozzle with a length of 35 mm (a, b) and 40 mm (c, d) at inlet pressure p_0=50 bar(a, c) andp_0=100 bar (b, d) and pressure of the ambience behind the nozzle exit $p_н$=0.1bar

An analysis of the results showed that the pressure of the external medium behind the nozzle exit significantly affects the structure of the flow in the nozzle. The supersonic flow in the nozzle fills the entire space of the nozzle and does not allow external currents to reach its wall. There are no vortex structures (Fig. 5b) from the ambience into the separation zone behind the nozzle corner point observed at sea level (p_0 = 1 bar). At the cut of the nozzle tip, separation of the boundary layer from the wall of the nozzle is observed. The internal gas flow adjoins the wall of the tip, and the intensity of separation at the tip edge at the outlet slightly increases with increasing inlet pressure (Fig. 5b). As the nozzle radius increases (for a nozzle 40 mm long - Fig. 5 c, d), the angle of internal flow impingement on the wall at the nozzle exit decreases (compared to the flow in a nozzle 35 mm long). This leads to a decrease in the intensity of the shock moving away from the wall and a decrease in the efficiency of the separated flow in the lambda structure of the flow.

3.4 Traction characteristics of the nozzle with a tip

The results of calculating the thrust characteristics of the considered nozzles were compared with the experimental study results of similar nozzles carried out at the Institute of Technical Mechanics of the National Academy of Sciences and the State Space Agency of Ukraine [15]. To verify the calculations, the results of experimental studies of a similar shortened nozzle 40 mm (Fig. 6) and 35 mm long with a bell-shaped tip were used.

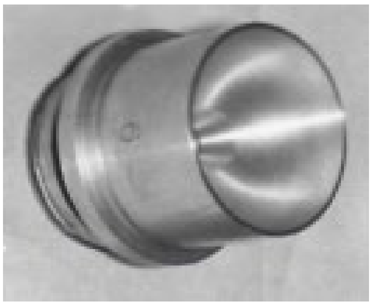
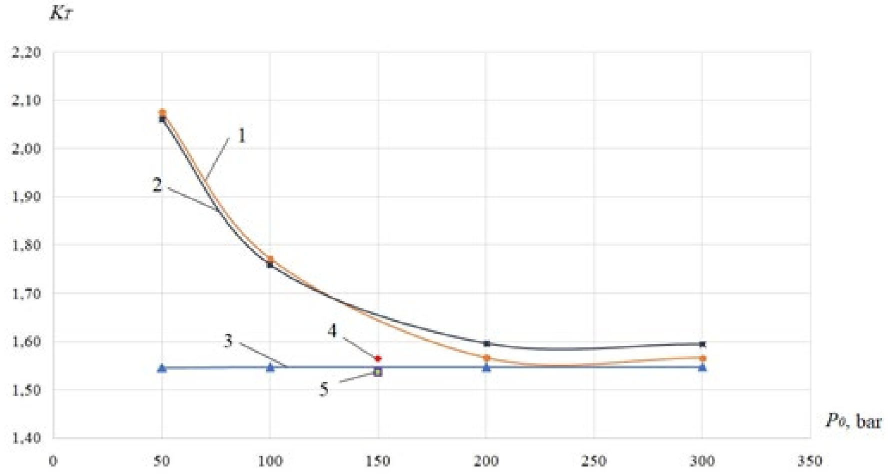


Fig. 6 Experimental model of a shortened nozzle with a total length of 40 mm

Figure 7 shows the value of the thrust coefficient (K_T) of experimental nozzles with a total length of 40 mm (4) and 35 mm (5), but with the same conical part of the nozzle, obtained by blowing in cold air at a pressure at the nozzle inlet p_0=150 bar. The value of the thrust coefficient obtained in the experiment satisfactorily agrees with the calculation results, respectively, shown by curves 1 and 2 at an inlet pressure of 1 bar and curve 3 at an inlet pressure of 0.1 bar. An analysis of the results shows that a change in the nozzle length with other equal geometric dimensions of the nozzle, does not significantly affect the thrust characteristics (see curves 1 and 2). It has been established that with an increase in the inlet pressure, the thrust characteristics (thrust coefficient) decrease and tend to a constant value of K_T obtained at a low pressure of the ambience (i.e., under flight conditions outside the atmosphere) – curve 3.



Calculations for nozzles: 1 – 40 mm long, 2 – 35 mm long
at the pressure of the ambience behind the nozzle exit $p_{н}$=1.0 bar;
3 – at the pressure of the ambience behind the nozzle exit $p_{н}$=0.1 bar;
4, 5 – experimental data for a nozzle with a length of 40 mm (4) and 35 mm (5)

Fig. 7. Thrust coefficients for shortened nozzles

IV. CONCLUSION

The study of the flow in the nozzle with a tip at various nozzle inlet pressures (p_0=50 – 300 bar) showed that with an increase in p_0, the size of the Mach disk and the size (longitudinal and transverse dimensions) of the "barrel" increase in proportion to the change in pressure. At p_0> 200 bar, the developed external flow into the tips is transformed into a closed separated flow with a toroid vortex.

At a low external pressure (0.1 bar), the flow from the shortened nozzle adjoins the tip wall, forming a detachable λ-shaped structure at the nozzle (tip) exit. This is due to the flow on the tip wall at a large angle. With an increase in pressure at the nozzle inlet, the intensity of this separation increases, and the free boundary of the jet behind the nozzle shear deviates to a larger angle.

It is shown that a decrease in the length of the nozzle with an equal length of the conical part of the nozzle does not significantly affect the thrust characteristics. The thrust coefficient K_T of a nozzle with a tip at $p_{н}$=1 bar decreases with increasing pressure p_0 at the nozzle inlet due to the effect of external pressure on the tip wall. After the flow adjoins the tip wall (at p_0> 200 bar), K_T does not change with a further increase in p_0. This is confirmed by the behavior of K_T at low $p_{н}$=0.1 bar i.e. with a large underexpansion of the flow from the nozzle, when K_T = const for different values of p_0. The calculation results for K_T are in good agreement with the experimental results.

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