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INFLUENCE OF TIP GEOMETRY OF A SHORTENED SUPERSONIC NOZZLE ON ITS CHARACTERISTICS

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Укорочені сопла використовуються для щільного компонування двигуна ракети. Такі сопла мають профільований насадок, який дозволяє максимально заповнювати простір та зменшувати загальну вагу. У даній роботі досліджується вплив геометрії насадка вкороченого надзвукового сопла на його характеристики. Розглянуто особливості потоку газу при різних початкових тисках та різних умовах зовнішнього середовища в надзвуковій області сопла з дзвоноподібним насадком різної довжини. Проводилося моделювання течії всередині сопла з подальшим витіканням струменя в навколишній простір. Моделювання течії розглянутих насадків на рівні моря показало подібну структуру ізоліній чисел Маха, відмінність полягала лише в інтенсивності вихрової структури настінної області насадка. Зі збільшенням тиску на вході в сопло пропорційно збільшується довжина першої «бочки» та зменшується вихрова структура у пристінковій ділянці насадка. При моделюванні течії в умовах роботи у верхніх шарах атмосфери картина течії змінюється. Надзвуковий потік у соплі безвідривний і тому вихрові структури із зовнішнього середовища відсутні. Потік за зрізом відхиляється від осі на кут, який визначається течією Прандтля–Майєра на кутовій точці зрізу насадка, а форма першої «бочки» спотворена впливом висячого стрибка. Аналіз отриманих результатів показує, що тиск довкілля за зрізом сопла значно впливає на структуру течії в соплі. Встановлено, що коефіцієнт тяги розглянутих контурів при роботі на рівні моря зменшується зі збільшенням тиску на вході в сопло, що пояснюється зменшенням впливу зовнішнього тиску на стінку насадку. При роботі у верхніх шарах атмосфери течія примикає до стінки насадка і коефіцієнт тяги для розглянутих насадків різної довжини має однакове постійне значення при різних вхідних тисках. Показано, що зменшення довжини насадка при інших рівних геометричних розмірах сопла істотно не впливає на імпульсні характеристики.

Ключові слова: *укорочене сопло, надзвуковий потік, дзвоноподібний насадок, імпульсні характеристики, вихрова течія.*

Truncated nozzles are used for tight packing of the rocket engine. Such nozzles have a profiled tip to maximize the filling of space and reduce the overall weight. This paper is concerned with the study the effect of the tip geometry of a truncated supersonic nozzle on its characteristics. The features of the gas flow at different initial pressures and different environmental conditions in the supersonic area of a nozzle with a bell-shaped tip of different lengths are considered. The flow inside the nozzle followed by the jet outflow into the surrounding space was simulated. The flow simulation for tips at sea level showed a similar structure of the Mach number isolines, and the only difference was in the intensity of the vortex structure near the tip wall. As the pressure at the nozzle inlet increases, the length of the first "barrel" increases proportionally, and the vortex structure near the tip walls decreases. For the upper atmosphere, the flow pattern is different. The supersonic flow in the nozzle does not undergo separation, and therefore there are no vortex structures from the external environment. The flow downstream of the tip exit deflects from the axis through the angle determined by the Prandtl–Meier flow at the corner point of the tip exit, and the shape of the first "barrel" is distorted by a hanging shock. An analysis of the obtained results shows that the ambient pressure downstream the nozzle exit significantly affects the flow pattern in the nozzle. It is established that the thrust coefficient of both circuits at sea level decreases with increasing pressure at the nozzle inlet, which is explained by a decrease in the effect of the ambient pressure on the tip wall. In the upper atmosphere, the flow is adjacent to the tip wall, and the thrust coefficient for nozzles of different lengths has almost the same constant value at different inlet pressures. It is shown that a decrease in the length of the nozzle, all other geometrical dimensions of the nozzle being equal, does not significantly affect the impulse characteristics.

Keywords: *truncated nozzle, supersonic flow, bell-shaped tip, impulse response, vortex flow.*

Introduction. In modern rocket propulsion systems, various types of nozzles are used: Laval nozzle, annular nozzle, bell-shaped nozzle, double bell nozzle, etc. The characteristics of the Laval nozzle are well studied by many authors and its different variations are considered [1, 2]. Recently, interest has been shown in shortened nozzles with various tips. Shortened nozzles are used for tight packing of the rocket engine. Such nozzles have a profiled nozzle, which allows you to fill the space as much as possible and reduce the total weight, which in turn is an urgent task. In the 90s of the 20th century, the authors [3, 4] considered shortened nozzles with various types of tips. The studies were carried out mainly using approximate methods of calculation and experiments on models. Currently, such studies are carried out using numerical methods for calculating the characteristics of the flow in the nozzle using ready-made software packages.

In previous works of the authors [5, 6], the characteristics of the gas flow in shortened nozzles with bell-shaped tips were considered under changing pressure at the nozzle inlet and under conditions at sea level or in the upper atmosphere. The influence of the external space on the combustion processes in a rocket engine and, accordingly, on the flow characteristics in a supersonic nozzle are considered in [7, 8]. At the same time, variants of a shortened nozzle with a different total length and a different conical inlet section were studied in [5] for different values of the degree of non-design flow and it was shown that, in this case, the flow patterns (velocity fields) change with a change in the length of the conical part. In [6], the wave structure of gas flow in a supersonic shortened nozzle (5 mm) with a bell-shaped tip (30 mm) of a compressed, elliptical shape and large length (compared to the conical section at the nozzle inlet) is studied. Studies show [2] that the compression of the bell-shaped tip affects the wave structure of the gas flow in the nozzle.

In this regard, it is important to understand what effect a decrease in the tip length has on the flow pattern, wave structure, and impulse characteristics of the nozzle.

The purpose of this work is determination the influence of the tip geometry of a shortened Laval nozzle on the structure of the supersonic flow in the nozzle.

Geometric model and computational technique. The paper considers the features of gas flow at different initial pressures P_0 and different environmental conditions behind the supersonic part of a nozzle with a bell-shaped tip of different lengths. The simulation of the flow inside the nozzle with the subsequent outflow of the jet into the surrounding space is carried out using the ANSYS software package.

In this work, we study bell-shaped tips (Fig. 1). The conical nozzle at the tip inlet, in both cases, has a half-angle of 20^0. The contour of nozzle № 1 is given in [4], where the results of experimental studies of this nozzle are also given. The length of the conical part along the axis was 20 mm for both nozzles, the difference between the considered nozzles was in the length of the tip: for nozzle № 1 – 15 mm, and for nozzle № 2 – 25 mm. The total length of the supersonic part of the nozzle is 35 mm (nozzle № 1) and 45 mm (nozzle № 2), respectively. The radius of the exit section of the tip is 28 mm. The diameter of the critical section of the nozzle is 10 mm. The angle of the contour wall relative to the nozzle axis is 0^0.

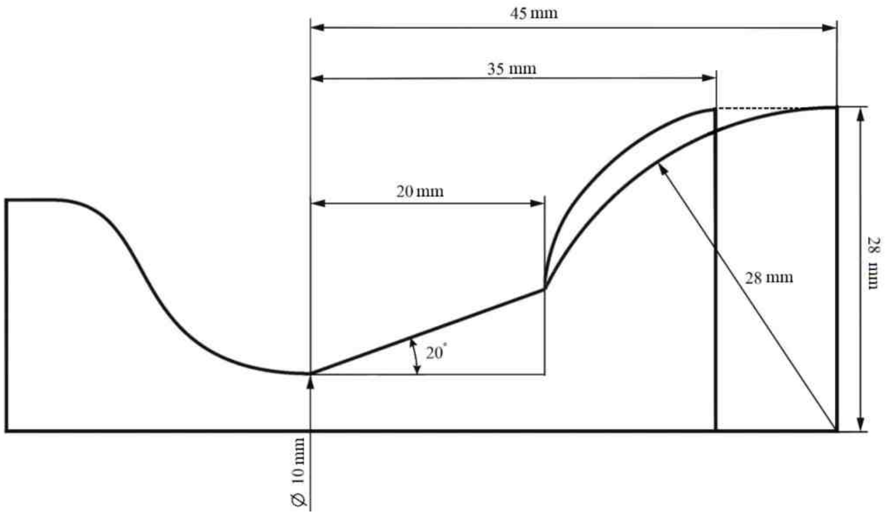


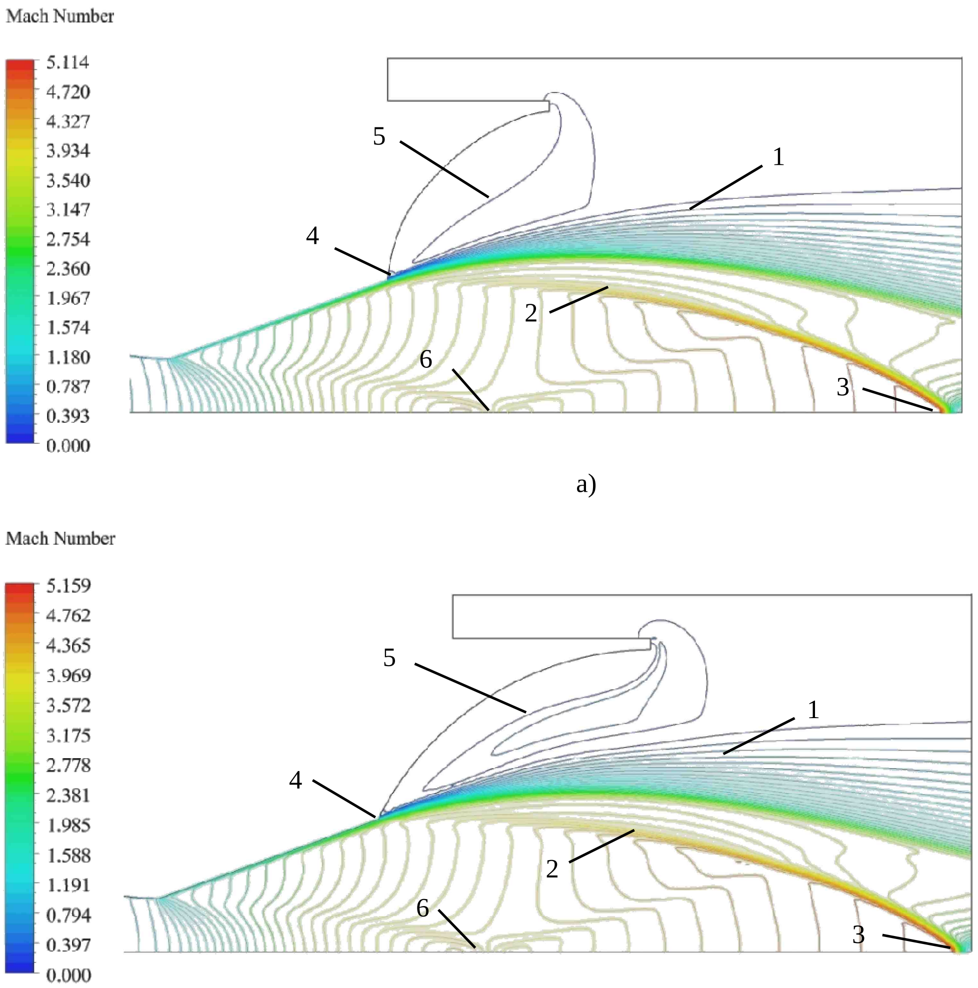
Fig. 1 – Circuit of shortened nozzles with a bell-shaped nozzle with a total length of L = 35 mm (nozzle № 1) and L = 45 mm (nozzle № 2)

The calculations were carried out on a plot of size $5L \times 5L$, where L — nozzle length.

The calculations were carried out in a non-stationary axisymmetric formulation based on the Reynolds-averaged Navier–Stokes equations, using the kω SST turbulence model with near-wall functions and correction for compressibility. This turbulence model was chosen taking into account the analysis carried out in [3]. Air with adiabatic index $\gamma = 1.4$ is used as a working medium. The calculations were carried out at the nozzle inlet pressure P_0 = 50, 100 bar. The ambient pressure was assumed to be P_n = 1 bar, which corresponded to the operation on the earth's surface, and P_n = 0.1 bar for flights in the upper atmosphere.

Main part. The paper investigates supersonic flows in shortened nozzles with a total length of the supersonic part of 35 mm (nozzle № 1) and 45 mm (nozzle № 2). These nozzles differ in the length of the bell-shaped tip (15 mm and 25 mm, respectively) and the degree of distortion of the spherical contour of the nozzle.

Figure 2, a), b) shows the distribution of Mach numbers at a pressure at the nozzle inlet P_0 = 50 bar and an external pressure P_n = 1 bar for nozzle № 1 and nozzle № 2. From the analysis of the Mach number distribution pattern, it can be seen that in the inlet conical part of the nozzle, a preliminary expansion of the gas flow occurs, and behind its cut (end), an outflow of a flow underexpanded in the nozzle is observed.



a)

b)

Fig. 2 – Isolines of the Mach numbers of the gas flow in nozzle № 1 (a) and № 2 (b) at inlet pressure P_0 = 50 bar and at sea level (P_n = 1 bar)

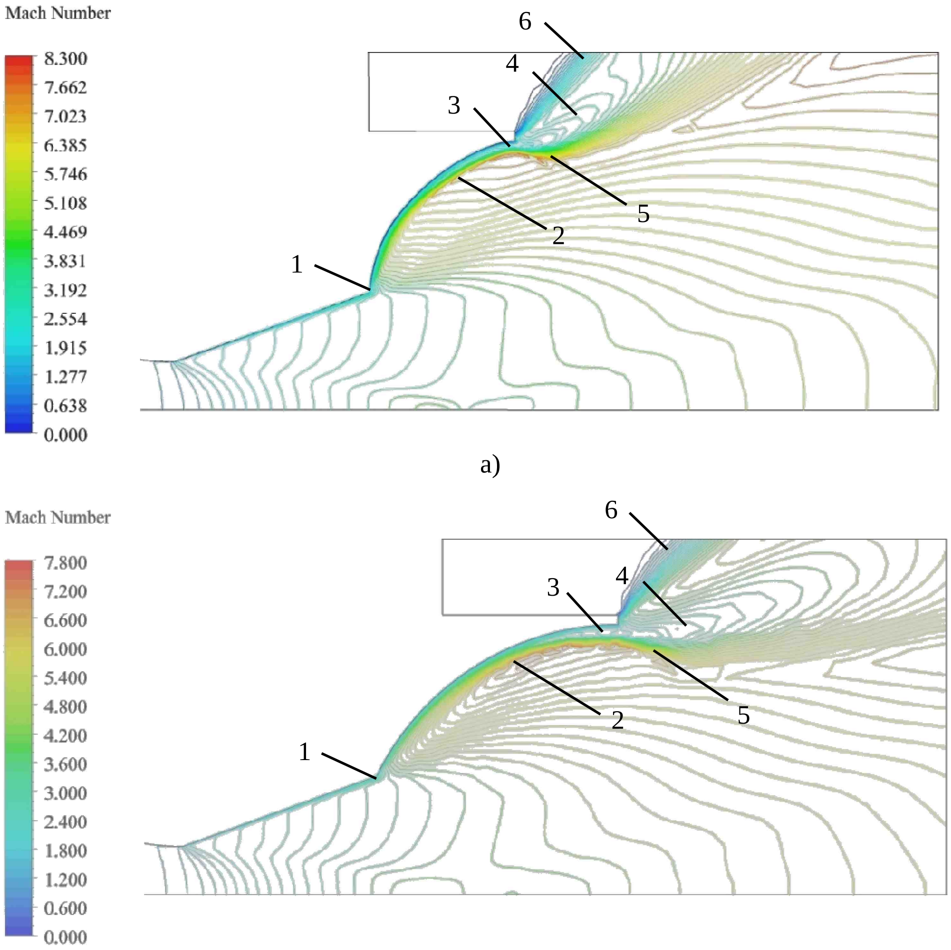
Supersonic flows (Fig. 2) in nozzles № 1 and № 2 have not only similarities, but also slight differences. In front of the free boundary of the jet 1, a hanging shock 2 is formed from the nozzle due to the supersonic compression of the characteristics reflected from the free boundary of the jet near the exit edge of the nozzle. This jump ends with a Mach disc 3.

In nozzle № 1, the length of the tip was reduced by compression, and, as a result, the radius of the nozzle at its cut was changed, in contrast to the tip in nozzle № 2. This affected the flow in the near-wall region of the tip. For both nozzles, a large-scale vortex structure 5 is observed near their walls behind the corner point 4. Moreover, for a short nozzle (nozzle № 1), this vortex has a lower intensity.

The structure of Mach number isolines for both nozzles has a similar character. A characteristic hanging "saddle" shock 6 of low intensity is observed in the core of the gas flow behind the cut of the inlet conical part of the nozzle. The length of the first "barrel" practically does not change with increasing nozzle length.

For rocket engines operating in the upper layers of the atmosphere, it is important to know the characteristics of the flow in the nozzles at low external pressure of the atmosphere. For this purpose, the patterns of gas flow in the nozzles described above at an external pressure P_n = 0.1 bar are considered.

Figure 3 shows isolines of the Mach numbers in the gas flow at an inlet pressure P_0 = 50 bar and an ambient pressure during operation in the upper atmosphere P_n = 0.1 bar in № 1 (a) and № 2 (b). According to the figures, with a change in environmental conditions, the gas flow in the nozzles changes. The supersonic flow in the nozzle fills the entire space of the tip and does not allow external flow to get inside. There are no vortex structures (Fig. 2) from the external medium to the separation zone behind the tip corner point observed at sea level (P_0 = 1 bar).



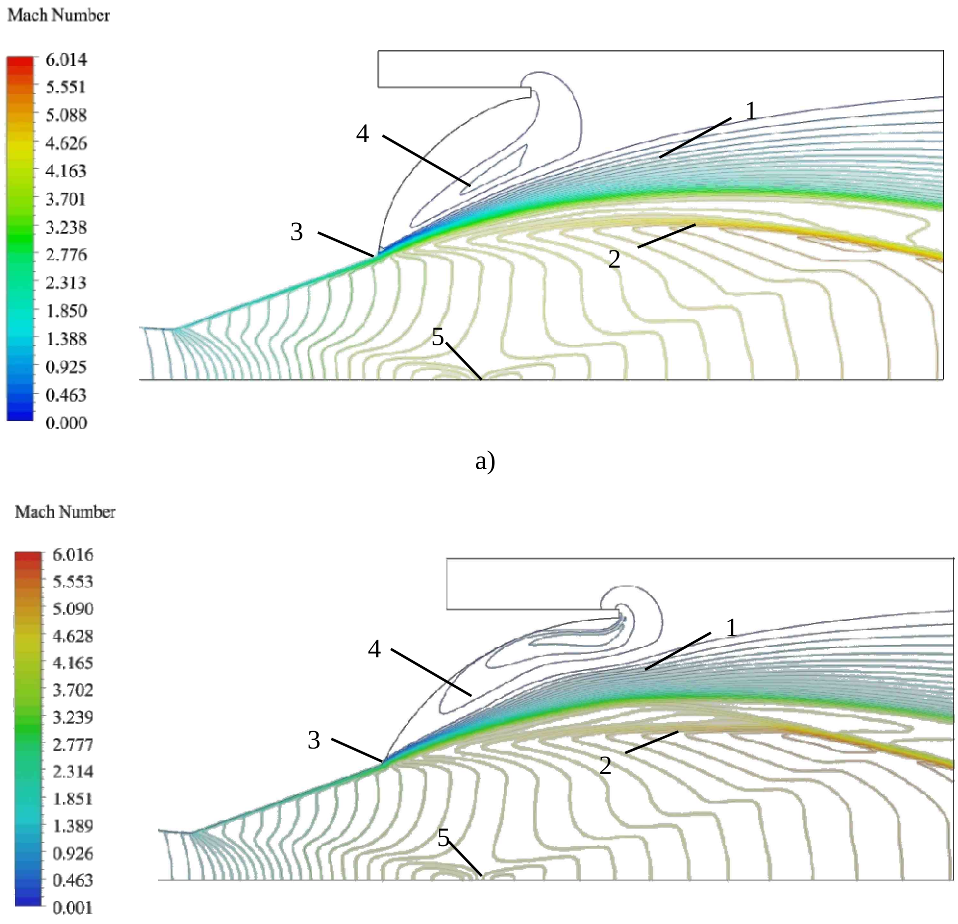
a)

b)

Fig. 3 – Isolines of the Mach numbers of flows in nozzle № 1 (a) and № 2 (b) at inlet pressure P_0 = 50 bar when operating in the upper atmosphere (P_n = 0.1 bar)

As it is seen from Fig. 3, a hanging shock 2 originates from the corner point 1 of the tip entry and propagates to the nozzle exit. Zone 3 is formed between shock 2 and the packing wall; this is a zone of low velocity and high pressure. If we compare this zone in Figs. 3, a) and 3, b), we can see that this area is practically absent in the short nozzle head (Fig. 3, a). The flow from zone 3, flowing out of the tip, forms an expanding flow 4. This flow affects the hanging shock 2 and distorts its shape and the shape of the first "barrel" 5. The free boundary 6 of the flow behind the cut deviates from the axis by an angle determined by the Prandtl–Meyer flow at the corner point of the tip cut. Comparing Fig. 2 and Fig. 3, we can conclude that the dimensions of the first (distorted) "barrel" in Fig. 3 significantly exceed the dimensions of the barrel at P_n = 1.0 bar in Fig. 2.

Figure 4 shows the distribution of Mach numbers of the flow at P_0 = 100 bar, P_n = 1 bar.



a)

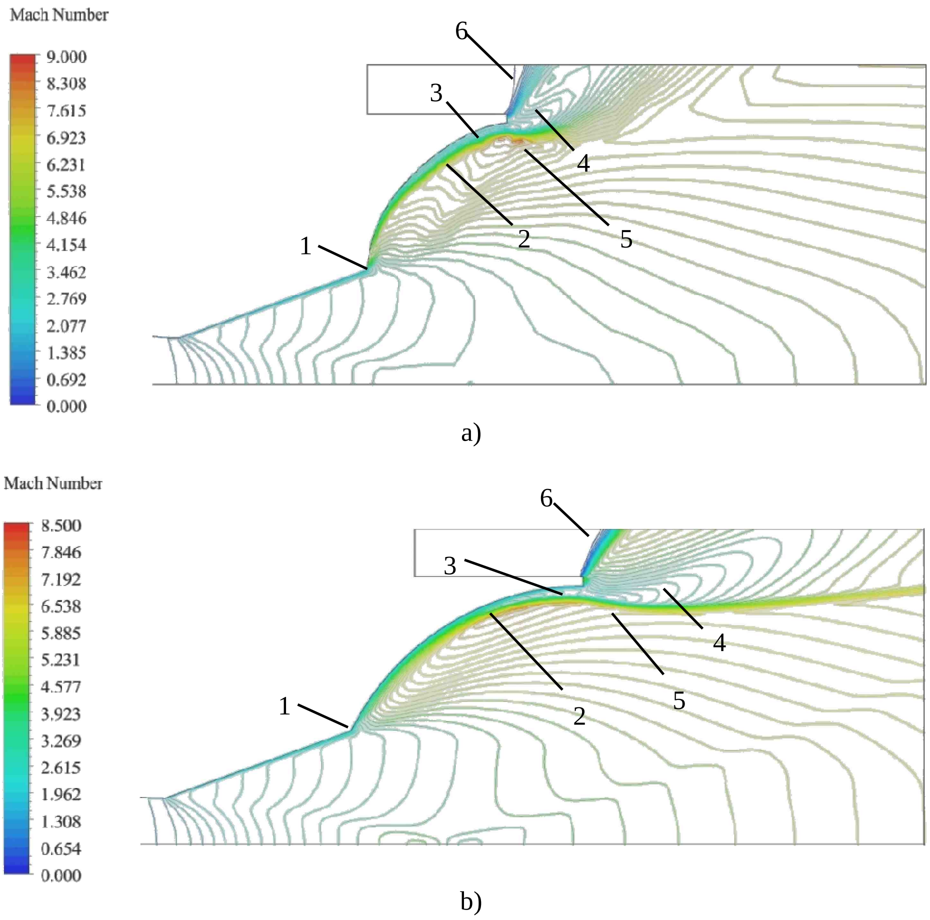
b)

Fig. 4 – Isolines of Mach numbers of flows in nozzle № 1 (a) and № 2 (b) at inlet pressure P_0= 100 bar when operating at sea level (P_n = 1 bar)

In this case, the flow structure practically does not differ from the structure at P_0 = 50 bar, P_n = 1.0 (Fig. 2) and in front of the free boundary 1 of the jet, a hanging shock 2 is formed from the nozzle, which is caused by supersonic compression of the characteristics reflected from the free jet boundary near the exit edge of the nozzle. There is a decrease in the separation vortex zone 4 (Fig. 4) near the packing wall, formed due to the entry of the atmosphere into the tip.

The free flow boundary 1 starts from the corner point 3 into the tip, just as in the case of P_0 = 50 bar, P_n = 1 bar, the wave structures inside the first "barrel" (Fig. 4 and Fig. 2) are similar. The length of the first "barrel" in comparison with P_0 = 50 bar (Fig. 2) increases in proportion to the increase in inlet pressure. In both cases, inside the first "barrel" there is a "saddle-shaped" compression wave 5 of similar geometry.

Figure 5 shows the distribution of Mach numbers in the gas flow at P_0 = 100 bar, P_n = 0.1 bar for two tips of different lengths.



a)

b)

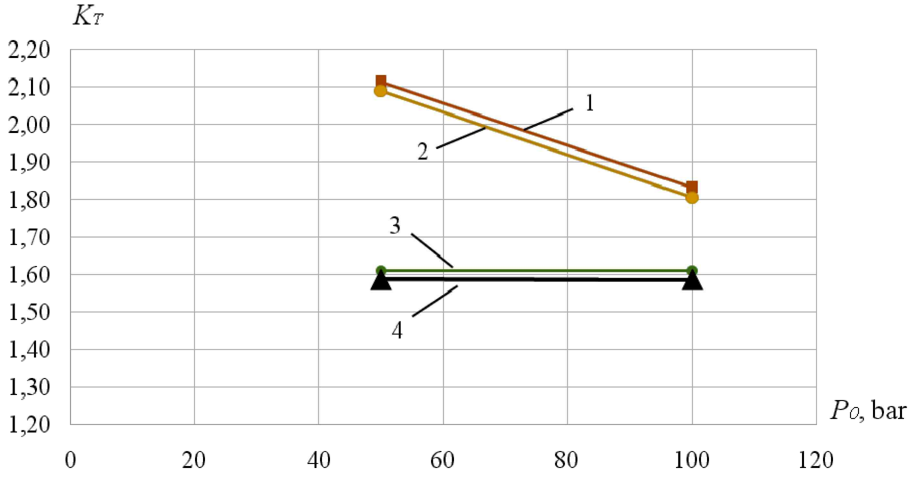
Fig. 5 – Isolines of the Mach numbers of flows in nozzle № 1 (a) and № 2 (b) at inlet pressure P_0 = 100 bar when operating in the upper atmosphere (P_n = 0.1 bar)

At the wall of the tip, the flow is just as unseparated as in the case of P_0 = 50 bar (Fig. 3), a hanging shock 2 is formed from the corner point 1 of the entrance to the tip and propagates to the tip cut of the nozzle. Between shock 2 and the wall of the tip, zone 3 of low velocity and high pressure is practically absent for nozzle № 1, and for nozzle № 2 it is more pronounced. In this case, the flow from zone 3, flowing out of the tip, forms an expanding flow 4 up to the free boundary 6 of the flow. The shape of the first “barrel” 5 is distorted by the influence of a hanging shock 2.

An analysis of the results shows that the pressure of the external space behind the nozzle exit significantly affects the structure of the flow in the nozzle. The supersonic flow in the nozzle is continuous and does not allow external flows to hit the wall. There are no vortex structures shown in Figs. 2 and 4 from the external medium to the separation zone behind the corner point of the tip, observed at sea level (P_n = 1 bar).

For the considered cases, the thrust coefficient (K_T) was also calculated. In this case, it's equal to the integral of the pressure forces (along the contour) divided by the thrust of the "spectacled" nozzle, i.e. $P_0 \cdot F_{cr}$.

Figure 6 shows the dependences of K_T on the initial pressure and nozzle length.



1 – nozzle № 1 at external pressure P_n=1 bar;
2 – nozzle № 2 at external pressure P_n=1 bar;
3 – nozzle № 2 at external pressure P_n=0.1 bar;
4 – nozzle № 1 at external pressure P_n=0.1 bar

Fig. 6 – Thrust coefficients for nozzle № 1 and nozzle № 2

It can be seen from the graph that for nozzle № 1 at external pressure for flow at sea level, K_T is greater than that for nozzle № 2 under the same conditions. But, if we consider the flow in the upper layers of the atmosphere, then K_T is greater for nozzle № 2.

The thrust coefficient K_T for nozzle № 1 and nozzle № 2 at P_n =1 bar decreases with increasing pressure P_0 at the nozzle inlet due to the effect of external pressure on the tip wall. And when operating in the upper layers of the atmosphere, the flow is adjacent to the wall of the tip and for two tips of different lengths the thrust coefficient K_T has almost the same constant value K_T = const at different values of P_0.

An analysis of the results shows that a change in the length of the tip, with other equal geometric dimensions of the nozzle, does not significantly affect (difference no more than 1%) the impulse characteristics (see in fig. 6 curves 1, 2 and 3, 4). It has been established that with an increase in the inlet pressure, the impulse characteristics (thrust coefficient) decrease and tend to a constant value of K_T obtained at a low pressure of the external environment (i.e., under conditions of flight in the upper layers of the atmosphere) – curves 3, 4. This is explained by the influence of the degree of overexpansion of the gas flow in the tip with a change in the relative (to the pressure of the external environment) pressure at the nozzle inlet, and the changing of the flow structure in the tip into a separated flow.

Conclusions. It is shown that the pressure of the external environment (behind the nozzle exit) significantly affects the flow structure in the bell-shaped tip. When operating at sea level and low inlet pressure (P_0<50 bar), considered tips have a separation zone starting from the corner entry point into the tips. For considered tips, the vortex structures in the separation zone slightly differ in intensity (velocity of the vortex flow). With an increase in pressure at the nozzle inlet, the length of the first "barrel" increases proportionally and the size of the separation zone decreases.

When operating in the upper layers of the atmosphere, the flow from the shortened nozzle adjoins the tip wall behind the corner point, and behind the tip cut it deviates to a large angle, which increases with increasing pressure at the nozzle inlet. In this case, an increase in the size of the first "barrel" of the flow from the nozzle is observed.

The thrust coefficient of both circuits of the considered nozzles decreases for sea level operation with increasing pressure at the nozzle inlet, which is explained by a decrease in the effect of external pressure on the tip wall. When operating in the upper layers of the atmosphere, the flow is adjacent to the tip wall and the thrust coefficients for tips of different lengths have almost the same constant value at different inlet pressures.

The study found approximately the same (difference no more than 1 %) impulse characteristics of the shortened nozzle with the investigated forms of bell-shaped tips of an elliptical configuration, therefore, the length of the considered tips does not significantly affect the impulse characteristics of the shortened nozzle.

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