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GAS FLOW IN A TRUNCATED LAVAL NOZZLE WITH A BELL-SHAPED TIP

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Досліджується потік у вкороченому надзвуковому соплі Лаваля з дзвоноподібним насадком («дзвоном»). Така конфігурація сопла може використовуватися при створенні щільних компоновок багатоступінчастих ракет малої довжини з підвищеними енергомасовими характеристиками. Подібні види сопел розроблені в Інституті технічної механіки НАН та НКА України (ІТМ) у 90-х роках минулого сторіччя. З використанням наближених методів було проведено розрахункові дослідження параметрів різних видів укорочених сопел, виготовлені моделі таких сопел. Проведено продування холодним повітрям деяких моделей з вимірюванням їх характеристик. Отримано тіньові картини течії газу за соплом, сажемасляні картини ліній струму на стінці сопла. Ці результати були використані під час постановки цієї роботи.

У представленій роботі проводиться чисельне дослідження з використанням пакета «ANSYS» течії газу в укороченому соплі Лаваля зі сферичним насадком. Для цієї конфігурації сопла було проведено продування моделі холодним повітрям. Результати розрахунків верифіковані шляхом порівняння розподілу швидкостей в газовому потоці за його зрізом з експериментальними тіньовими картинами. Додатковим підтвердженням коректності отриманих результатів було порівняння течії за профільованим лінією струму соплом Лаваля з докладно дослідженою структурою течії недорозширеного потоку за зрізом сопла в першій «бочці» (до диска Маха). При постановці завдання в обох випадках вибиралися однакові вихідні дані та початкові умови, що дають найкращі (в сенсі верифікування) результати.

Дослідження течії в укороченому надзвуковому соплі показали наступне. За кутовою вихідною точкою укороченої ділянки сопла Лаваля з переходом потоку газу у «дзвін» спостерігається відрив потоку. Відрив зберігається при збільшенні тиску перед соплом аж до деякої критичної (для даного типу насадка) величини ступеня нерозрахунковості, після якого з подальшим збільшенням ступеня нерозрахунковості потік приєднується до стінки насадка, залишаючись приєднаним з подальшим збільшенням тиску перед соплом. Імпульсна характеристика укороченого сопла з дзвоновим насадком нижче значення для сопла Лаваля, спрофільованого по лінії струму того ж геометричного ступеня розширення.

Ключові слова: *Сопло Лаваля, вкорочене сопло, дзвоноподібний насадок, структура потоку*.

Flow in a truncated supersonic Laval nozzle with a bell-shaped tip ("bell") is investigated. This nozzle configuration can be used in tight layouts of multistage rockets of short length with improved energy-mass characteristics. Similar types of nozzles were developed at the Institute of Technical Mechanics of the National Academy of Sciences and the State Space Agency of Ukraine in the 1990s. Using approximate methods, the parameters of variously configured truncated nozzles were calculated, and their models were made. Some of the models were blown with cold air, and their characteristics were measured. Shadow patterns of gas flow downstream of the nozzle and soot-oil patterns of streamlines on the nozzle wall were obtained. These results were used in the formulation of this work.

In this work, a numerical study with the ANSYS package was carried out for gas flow in a truncated Laval nozzle with a spherical tip. For this nozzle configuration, its model was blown with cold air. The calculated results were verified by comparing the velocity distribution in the gas flow downstream of the nozzle exit with the experimental shadow patterns. An additional confirmation of the correctness of the calculated results was a comparison of the flow downstream of a streamline-profiled Laval nozzle with the underexpanded flow pattern downstream of the nozzle exit in the first "cask" (up to the Mach disk) studied in detail. The same initial data and initial conditions that give the best results in terms of verifiability were chosen in both cases.

The study of flow in a truncated supersonic nozzle showed the following results. Downstream of the corner exit point of the truncated section of a Laval nozzle, flow separation is observed where the gas flow enters the "bell". The separation is retained as the pressure upstream of the nozzle increases up to a certain critical (for a given tip type) value of the underexpansion ratio, after which (with a further increase in the underexpansion ratio) the flow attaches to the nozzle wall and remains attached with a further increase in the pressure upstream of the nozzle. The impulse response of a truncated nozzle with a bell-shaped tip is lower than that of a streamline-profiled Laval nozzle of the same geometric expansion ratio.

Keywords: *Laval nozzle, truncated nozzle, bell-shaped tip, flow pattern.*

Introduction. For designing new rockets used to conditions of severe dimensional restrictions (dense layouts of aircraft), nozzles with a compressed (bell-shaped) contour of the supersonic part are of special interest. In particular, it can be a shortened Laval nozzle with a bell-shaped tip, similar in configuration to the structural elements of the next rocket stage, or a nozzle with a forced reversal (cen-

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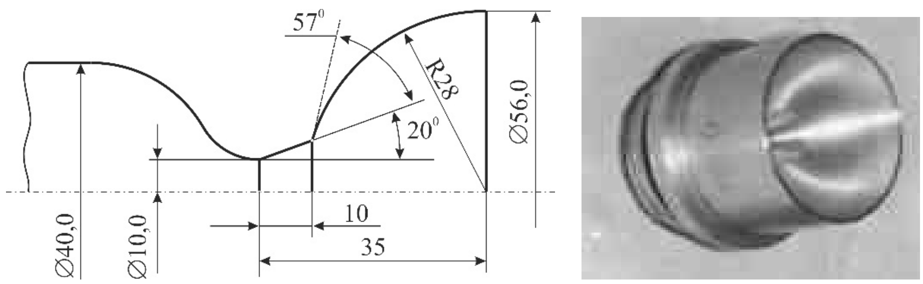
tral plate-type body) of the flow in the critical section, also having a short profile. Thus, Aerojet Strategic Propulsion developed a project [1, 2] for a dense layout of a solid-fuel two-stage ballistic missile, in which the contour of the nozzle of the first rocket stage was close to the configuration of the front bottom of the second stage. It made possible to reduce the overall rocket length and increase its energy-mass characteristics. Similar projects were developed in some organizations of the former USSR. At the Institute of Technical Mechanics of the National Academy of Sciences and State Space Agency of Ukraine (ITM) short nozzles of various configurations were studied. The main results of these studies are given in [3, 4]. The studies were carried out mainly using approximate calculation methods and experiments on models.

Currently, such studies are carried out using numerical methods for calculating the flow characteristics in the nozzle using ready-made software packages, for example, ANSYS. At the same time, new features of the gas flow in the nozzle are revealed, which were not found in previous works, but which has not only scientific but practical interest. Numerical studies of the flow in the Laval nozzle [5] and the annular nozzle [6] can serve as an example of such works.

An essential role in such studies is played by the verification of the results obtained, which are largely determined by the choice of initial conditions for the solving problem.

The purpose of this work is a numerical study of the flow in a shortened supersonic nozzle with a bell shaped tip. In this case, the configuration of the nozzle studied in [3].

Main part. Figure 1a) shows a sketch of the investigated nozzle. Such a nozzle was fabricated and tested in cold air at ITM [4]. A photograph of the studied model of a shortened nozzle with a tip is shown in Figure 1b).

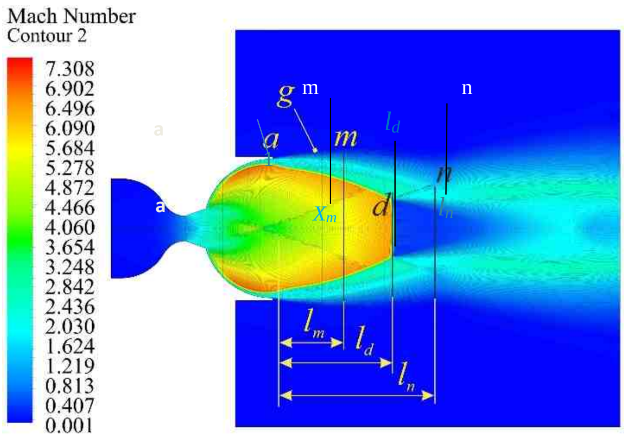


a) b)

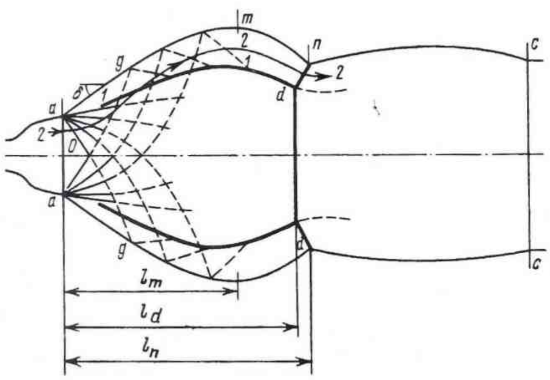
Fig. 1 – Model of a shortened Laval nozzle with a bell shaped tip [4]

The critical section (diameter $d_* = 10$ mm) is followed by the conical section of the Laval nozzle with an opening half-angle of 20°. The conical section of the nozzle passes into a bell shaped tip with an entry angle (relative to the nozzle wall) into the nozzles of 57°. The transition from the nozzle to the tip is carried out at the corner point. Exit angle from the tip is 0°. The length of the conical nozzle section is 10 mm. The length of the shortened nozzle with a tip is 35 mm. Radius of conical section end is $d_a = 17.3$ mm. Nozzle wall radius is 28 mm. The geometric expansion degree of the nozzle with the tip, determined by the relative pressure in front of the nozzle, is $\frac{F_a}{F_*} = 31.36$.

The correctness of the initial condition choice (in particular, models of turbulence, physical properties of gas, etc.) before performing calculations of a shortened nozzle with a tip was substantiated by result verification of gas flow calculations in the Laval nozzle. The comparison results of flow patterns are shown in Figs. 2, where 2 a) is the velocity distribution calculation of underexpanded flow behind the Laval nozzle exit ($d_* = 10$ mm, $d_a = 17.3$ mm, $M_a = 2.48$, $p_0 = 50$ bar) using the software package "ANSYS"; 2 b) – a picture of an underexpanded flow behind the Laval nozzle exit, taken from [7], where 1 is a hanging shock, 2 is a streamline, d-d Mach disk, d-n is a reflected shock, agmn – the boundary of the jet (of the first "cask").



a)



b)

a) the calculated picture of the jet velocity distribution from the profiled Laval nozzle; b) the flow pattern of an underexpanded gas jet from the Laval nozzle [7]

Fig. 2 – Flow in a shortened Laval nozzle profiled along the streamline

The flow structure in the Laval nozzle is not considered here. It has been studied in sufficient detail by various authors using various methods. In this paper to verify the results of ANSYS software package calculations for a bell shaped tip, the main characteristics of the first “cask” (the structure of the gas jet behind the nozzle exit, ending with a Mach disk) are compared with the underexpanded flow obtained by exact and approximate calculation. In Fig. 2 numbers and letters show the main parameters of the first "cask". In Fig. 2a) vertical lines (x_m, l_d, l_n) indicate the calculation results of the the first "cask" parameters according to the one-dimensional theory, namely the flow parameters for the distances from the nozzle exit (a-a) to the characteristic section of the first "cask".

According to the one-dimensional theory, the reduced mass flux density in the Laval nozzle is determined by the relation.

$$q(M) = M\left[\frac{2}{k+1}\left(1+\frac{k-1}{2}M^2\right)\right]^{-\frac{k+1}{2(k-1)}} = \frac{F_*}{F}$$

where M – the Mach number of the gas flow in the considered section, $k = \frac{c_p}{c_v}$ – adiabatic exponent, F – nozzle cross-sectional area (with index * – in the critical section of the nozzle, a – at the nozzle exit).

For the nozzle shown in Fig. 2a), $q(M_a) = 0.39$. This value corresponds to the Mach number of the flow at the cut (exit) of the shortened section of the Laval nozzle $M_a = 2.48$. The parameters of the first “cask” calculated according to the one-dimensional theory for the nozzle overdesign degree $N = \frac{p_0}{p_n\left(1+\frac{k-1}{2}M_a^2\right)^{k/k-1}} = 3.02$ have the following values:

– distance from the nozzle exit to the maximum cask diameter

$\frac{x_m}{d_a} = 0.7M_a\sqrt{kN} = 3.57$;

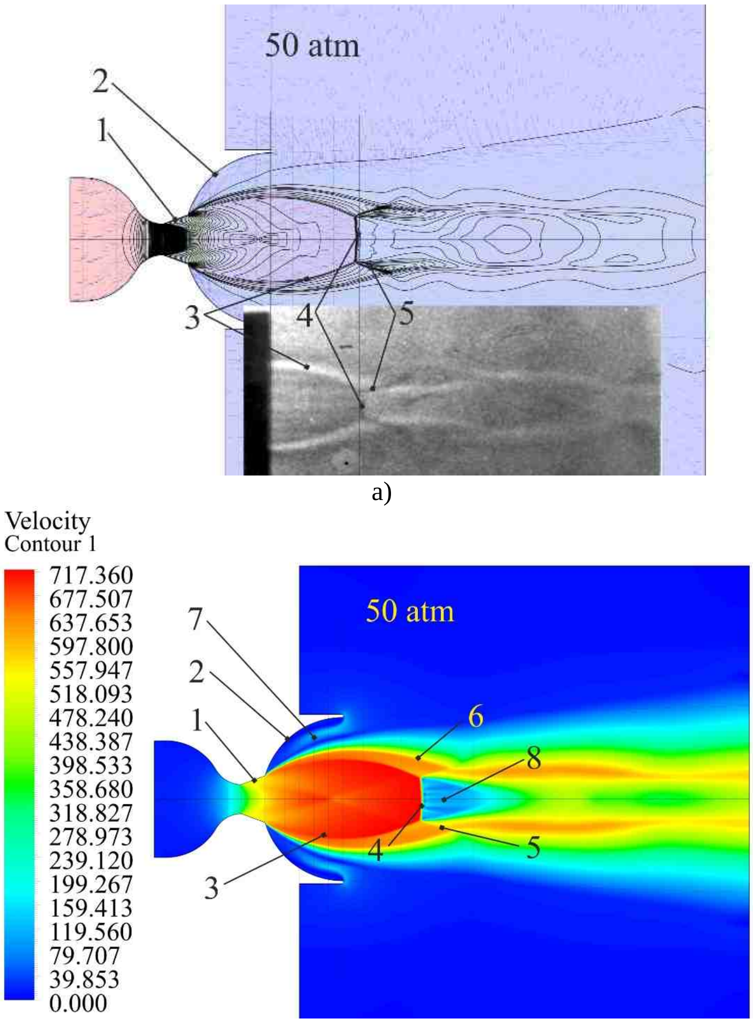
– distance from the nozzle exit to the end of the first cask $\frac{l_n}{d_a} = 1.6x_m = 5.71$,

– distance to the Mach disk $\frac{l_d}{d_a} = 0.8l_n = 4.57$.

In Fig. 2a), on the scale of the figure, the values of the indicated characteristic dimensions x_m, l_d, l_n are specified. An analysis of figures 2a) and 2b) shows their satisfactory consistency both qualitatively (in the sense of the jet wave structure) and quantitatively (in the sense of the correspondence between the package 3D calculation and the calculation according to the one-dimensional theory of the the first "cask" geometric parameters).

The flow is studied in a shortened Laval nozzle with a bell shaped tip, while the geometric parameters are taken: $d_a = 17.3$ mm, $d_{a,tip} = 17.3$ mm. The calculations are carried out at a pressure at the nozzle inlet p_0 =50 bar, 75 bar, 100 bar and ambient pressure $p_н$ =1 bar.

Figure 3, 4 and 5 shows the calculating results of the flow in a shortened Laval nozzle with a bell shaped tip where figure with letter a) show density distribution in the flow with shadow pattern of the flow; figure with letter b) show velocity (Mach number) distribution in the flow. The shadow pattern (see photo below) was obtained in experiments [4] behind the cut of a bell shaped tip with the same nozzle geometry as a whole (see Fig. 1). These three figures explain the influence of inlet flow pressure p_0 on the flow characteristics. The calculation is performed with the ANSIS software package for the initial flow characteristics: ideal gas, entropy index γ = 1.4, total flow temperature T_0=300 K, turbulence model – kω-SST. In Fig. 3 – 5 number designations are used the same as following: 1 – shortened Laval nozzle; 2 – bell shaped tip; 3 – hanging jump; 4 – Mach disk; 5 – reflected shock; 6 – secondary hanging jump; 7 – separation zone; 8 – zone of low speeds



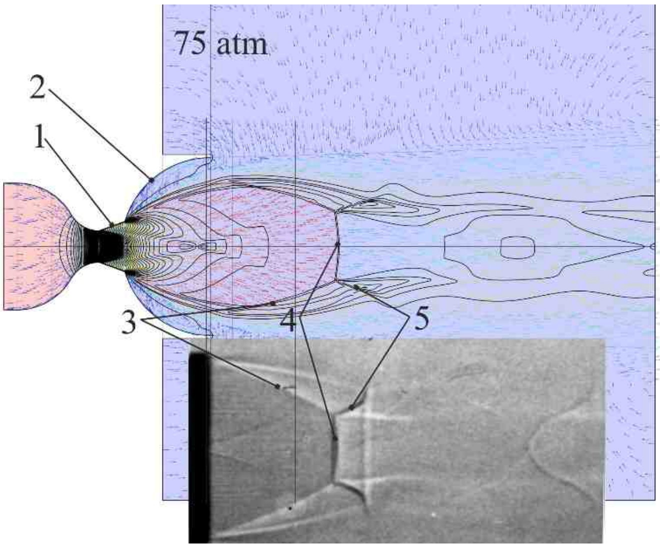
b)

Fig. 3 – Flow in a shortened Laval nozzle with a bell shaped tip (p_0 = 50 bar)

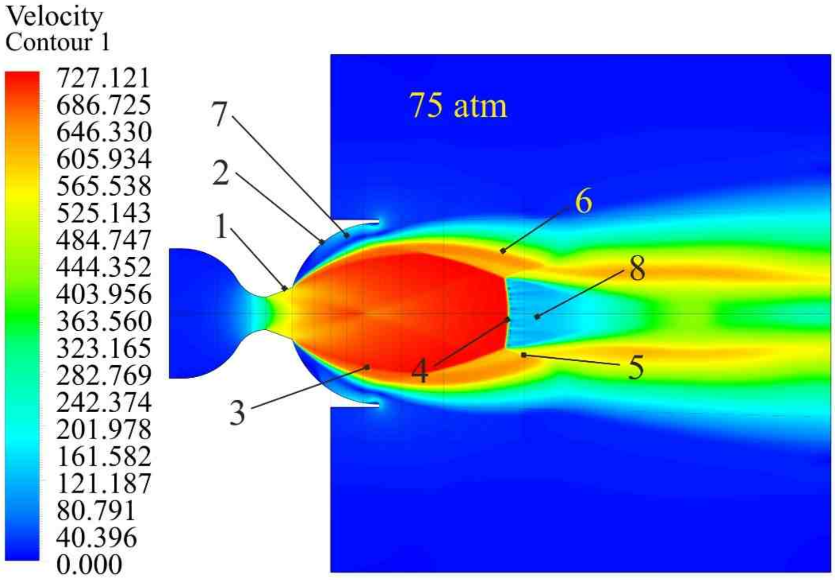
In the gas flow from a nozzle with a tip the Mach disk 4 (see Fig. 3) is separated from the cut (end) of the shortened nozzle at a distance 3.5 $d_{a,\ sh}$ (where $d_{a,\ sh}$ – cut diameter of the shortened Laval nozzle). It means that the length of the first "cask" when the gas jet flows from the Laval nozzle into the nozzle decreases by about 20% compared to the value 4.57 $d_{a,\ Laval}$ for Laval nozzle without tip. The maximum diameter of the first "cask" is reduced by 1.35 times. That is, the longitudinal and transverse dimensions of the “cask” decrease approximately proportionally (taking into account the measurement inaccuracies in the calculated and experimental flow patterns). The Mach disk in the flow from the nozzle increases in diameter compared to the flow behind the nozzle without a tip (see Fig. 2a) and shocks 3 and 5 are more intense. The same is observed in the shadow photograph of the flow behind the cut of the bell shaped tip (see the photo in Fig. 3a). Hanging shocks 4 and 6 originate almost from the edge of the shortened Laval nozzle (Fig. 3b). Separation zone 7 is formed by the free penetration of the surrounding atmosphere into the area between the free boundary of the gas flow from the nozzle and the tip wall.

The Mach number of the expanded flow in front of the Mach disk 4 is $M \approx 5.4$. The value of the velocity in front of the Mach disk calculated according to the one-dimensional theory is M ≈ 5.32 (for $q(\lambda_a)=\frac{F_*}{F_a}=0.0319$). Behind the Mach disk, there is a developed zone 8 with a low flow velocity (see Fig. 3b).

Figure 4 shows the results of flow calculation in a nozzle with a tip at a pressure of 75 bar and ambient pressure $p_н$=1 bar. The shadow pattern of the flow behind the tip exit (see the photo in Fig. 4a) corresponds to the calculated density distribution in the flow.



a)

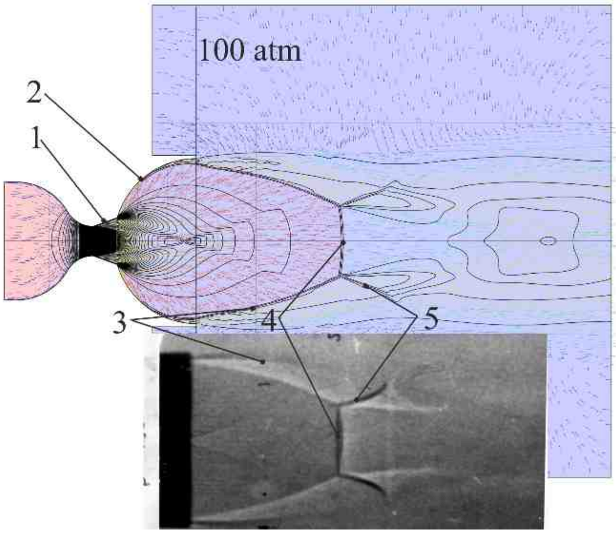


b)

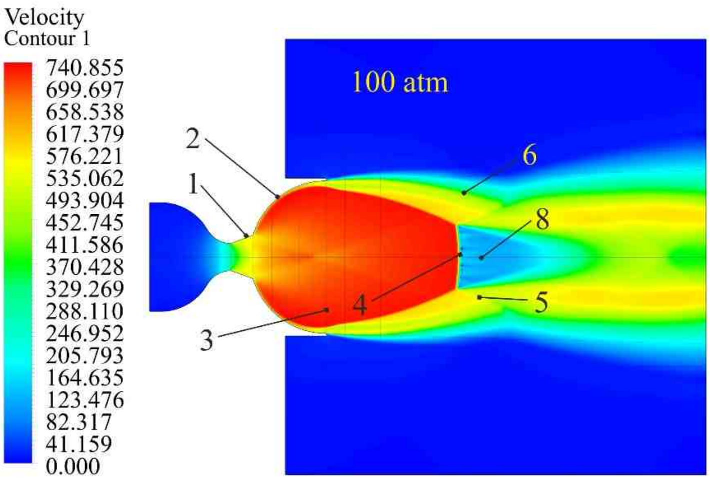
Fig. 4 – Flow in a shortened Laval nozzle with a bell shaped tip (p_0 = 75 bar)

With an increase in pressure from 50 to 75 bars, the characteristic dimensions of the first "cask" increase by 10%. As well as at a pressure of 50 bar, the jet boundary does not adjoin the tip wall. The velocity distribution in the jet flowing out of a nozzle with a tip (Fig. 4b) is similar to the distribution at a pressure of 50 bar. The size of the subsonic region behind the Mach disk (blue color in Fig. 4b) also increases by 10% compared to the size at a pressure of 50 bar (see Fig. 3b). In separation zone 7 (see Fig. 4b), the flow entering from the outer atmosphere near the packing exit flows onto the packing wall, causing a local increase in static pressure (see Fig. 4, line 2).

Figure 5 shows the results of flow calculations in a shortened nozzle with a tip at a nozzle inlet pressure of 100 bar and an external pressure of 1 bar. In this case, the jet boundary in the tip is adjacent to the tip wall. The additional force caused by the gas viscosity presses the jet against the nozzle wall. At the same time, at the edge of the nozzle cut, there is a breaking point of the hanging shock 3 caused by the indicated force (Fig. 5b).



a)



b)

Fig. 5 – Flow in a shortened Laval nozzle with a bell shaped tip (p_0 = 100 bar)

Figure 5 shows the results of flow calculations in a shortened nozzle with a nozzle at a nozzle inlet pressure of 100 bar and an external pressure of 1 bar. In this case, the boundary of the jet in the nozzle is adjacent to the nozzle stack. The additional force caused by the viscosity of the gas presses the jet against the nozzle wall. At the same time, at the edge of the cut of the nozzle, there is a breaking point of the hanging shock 3 caused by the indicated force (see Fig. 5b). The shock 3 penetrates into the nozzle almost along its wall up to the cut of the shortened Laval nozzle (see Fig. 5a, 5b).

The dimensions of the first "cask" are increased by 10% compared to the case p_0 = 75 bar. The flow behind the primary hanging shock 3 to the secondary (weakly expressed) 6 has a lower velocity in comparison with the case of flow at pressures of 50 and 75 bar.

The performed analysis shows a good coincidence the gas flow characteristics obtained in the calculation and at experimental cold air blows. Thus, the above indicates a qualitative and quantitative verification of the calculation results in a shortened Laval nozzle with a bell shaped tip.

Conclusions. The flow pattern in a shortened Laval nozzle with a bell shaped tip has been studied. The shortened nozzle forms a flow in the bell shaped tip. Behind the cut of the shortened nozzle the flow, maintaining a cask-shaped shape, depends on the ambient pressure. The underexpanded gas flow behind the cut of the shortened nozzle does not adjoin the nozzle wall, and the geometrical characteristics of the “cask” depend on the expansion degree of the gas jet flowing from the shortened nozzle. A developed separation zone is observed between the jet boundary and the tip wall, which propagates against the flow from the nozzle exit to the cut of the shortened nozzle. The characteristics of this zone depend on the flow expansion degree in the shortened nozzle. With a high degree of flow underexpansion the jet boundary in the nozzle adjoins the nozzle wall, distorting the shape of the first jet “cask”. In this case, the perturbation from the external environment is transmitted along the boundary layer of the jet attached to the wall.

Numerical calculations using the ANSYS package are compared with the results of calculations based on the one-dimensional theory of the Laval nozzle and with the results of experimental studies performed at the Institute of Technical Mechanics of NASU and SSAU. Thus, based on the results of the study, we can conclude that the results of numerical calculations are verified by the results of experimental studies and calculations according to the one-dimensional theory of flow characteristics in a shortened nozzle with a bell shaped tip.

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