Original article
DOI: https://doi.org/10.18721/JPM.16406

SIMULATION OF A SUPERSONIC NOZZLE OF A MASSIVE HELIUM JET INJECTOR

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Abstract. The paper describes the design and operating principle of a valve designed for testing the prototypes of key elements of a massive gas injection system: a seat and a supersonic nozzle. The calculation results for supersonic nozzle parameters close to optimal for the selected valve design have been presented. The simulation of gas flows through the seat and nozzle was carried out, the parameters of the formed jet at the injection system outlet in the nozzle near field were calculated. The choice of the “stepped” nozzle profile for the first tests was justified. An assessment was made of the requirements for the accuracy of manufacturing prototype nozzles.

Keywords: numerical simulation, magnetic confinement, high-temperature plasma, gas jets, discharge shutdown

Funding: The research was supported by "ROSATOM" State Corporation and the Ministry of Science and Higher Education of Russian Federation within the framework of the Federal Project 3 (U3) “Development and Creation of Jet & Pellet Injection Systems with Increased Performance and Resource” (No. FSEG-2023-0018).

Citation: Timokhin V. M., Korobko D. D., Nurtdinova L. I., Kapralov V. G., Sergeev V. Yu., Simulation of a supersonic nozzle of a massive helium jet injector, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 16 (4) (2023) 63–75. DOI: https://doi.org/10.18721/JPM.16406

Научная статья
УДК 533.17
DOI: https://doi.org/10.18721/JPM.16406

МОДЕЛИРОВАНИЕ СВЕРХЗВУКОВОГО СОПЛА ИНЖЕКТОРА МАССИВНОЙ ГЕЛИЕВОЙ СТРУИ

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Аннотация. В работе описана конструкция и принцип действия клапана, предназначенного для испытаний прототипов ключевых элементов системы массивной газовой инжекции: седла и сверхзвукового сопла. Приведены результаты расчетов параметров сверхзвукового сопла, близких к оптимальном для выбранной конструкции клапана. Выполнено моделирование газовых потоков через седло и сопло, рассчитаны параметры формируемой струи на выходе системы инжекции в ближнем поле сопла. Обоснован выбор «ступенчатой» формы профиля сопла для первых испытаний. Сделана оценка требований к точности изготовления прототипов сопел.

Ключевые слова: численное моделирование, магнитное удержание, высокотемпературная плазма, газовая струя, выключение разряда

Финансирование**.** Работа поддержана госкорпорацией «Росатом» и Министерством науки и высшего образования Российской Федерации в рамках Федерального проекта 3 (U3), № FSEG0018-2023- «Разработка и создание систем струйной и пеллет инжекции с повышенными производительностью и ресурсом».

Ссылка для цитирования: Тимохин В. М., Коробко Д. Д., Нуртдинова Л. И., Капралов В. Г., Сергеев В. Ю. Моделирование сверхзвукового сопла инжектора массивной гелиевой струи // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2023. Т. 4 № .16. С. 63–75. DOI: https://doi.org/10.18721/ JPM.16406

Introduction

One of the fundamental tasks in thermonuclear energy is to prevent or significantly reduce the probability of disruption of the tokamak discharge. Efforts are currently underway to solve this problem [1].

Let us briefly outline it. If disruption of the discharge current is unavoidable, rapid mitigation measures should be taken as a last resort to reduce the likelihood of significant damage to the vacuum chamber and other structural elements of the tokamak reactor. Since the thermal and magnetic energy of the plasma is effectively stored in the chamber during disruption, it can only be redistributed inside the chamber, but cannot be removed. This redistribution can be achieved, for example, by introducing a sufficiently large amount of impurities. A group of noble gases (helium, neon and argon) is commonly used as such impurities, which is designed to generate isotropic radiation of plasma energy on the first wall and is aimed at preventing concentrated loading.

The most common injection technology used for rapid delivery of impurities is massive gas injection (MGI). One of the prototypes of the MGI is described in the following section of this article.

An important element of the MGI system is the supersonic Laval nozzle, which ensures the formation of a jet of injected impurity into the tokamak vacuum chamber [2]. The nozzle parameters determine the velocity and distribution of the injected gas, which affects the penetration depth of the impurity and determines the distribution of the radiation source inside the plasma filament. Gas flow in the subcritical (tapering) section of the nozzle occurs at subsonic speeds. The local gas velocity in the critical (narrowest) section of the nozzle reaches sonic levels, and gas flow moves at supersonic speeds in the supercritical (expanding) section. The internal energy of the gas is converted into the kinetic energy of its directional motion. In addition, the gas passing through the nozzle at a significant speed does not have time to transfer a noticeable amount of its thermal energy to its walls. This feature of the process allows to consider it adiabatic, which greatly simplifies its modeling.

The goals of this study included modeling the process of outflow of a massive gas jet from the MGI system for various types of nozzle and choosing its optimal type.

The criterion for the effectiveness of the nozzle is to achieve the maximum gas velocity with a minimum jet angle at the nozzle outlet (this allows increasing the penetration depth of the injected gas into the plasma).

Another important criterion for choosing a prototype nozzle is the simplicity of its manufacturing technology. The small size of the critical section and the complex shape of the nozzle profile require laser and electroplating technologies. The possibility of manufacturing a nozzle without complex metalworking procedures creates a significant advantage with comparable parameters of the jet formed by the nozzle.

The simulation was performed to support bench tests of a prototype valve for massive gas injection and did not involve changes in gas flow parameters and nozzle geometry over a wide range.

The main purpose of the calculations was to find the optimal distribution of gas flow parameters in the near field at the nozzle outlet. The optimal values of the set of parameters are necessary for designing the diagnostics of the MGI test system, as well as for modeling the interaction of gas jets with high-temperature plasma of magnetic confinement setups.

The obtained results are presented as follows. First, the operating principles and configuration of the gas valve designed to form a supersonic jet are described. Then the calculation results of the main parameters of the supersonic nozzle are presented. Next, we describe the algorithm for constructing the computational grid and the results obtained during the simulation, as well as analyze the gas flow through a supersonic nozzle. In conclusion, the main conclusions of the work are formulated.

Gas valve for testing seat and nozzle prototypes

The MGI method is relatively simple to implement, but tends to form a local source of impurity radiation in the peripheral regions of the plasma, which can lead to low efficiency of impurity injection into the central regions of the plasma cord [3]. According to the original design [4], the positioning of the MGI valve allows it to be brought closer to the plasma, which increases the efficiency of impurity injection. The main idea of the design is to ensure the mobility of the valve at a considerable distance from the actuator, which allows to shift the outlet section of the valve nozzle up to the last closed magnetic surface (LCMS). The valve system allows for it to move from a position outside the gate valve to the nozzle to a position next to the LCMS. The movement of the nozzle can reach a distance of more than a meter, which usually exceeds the size of the neutron protection of neutron setups, including the ITER reactor (International Thermonuclear Experimental Reactor). Such movement can be quite fast, which opens up prospects for using such a configuration of MGI in the radiation environment of a tokamak reactor. This eliminates the need for guide tubes to deliver the jet from the valve nozzle to the plasma, reduces the system response time, and reduces the angular expansion of the gas jet.

The following calculated characteristics of a massive helium gas jet injector are set:

gas flow is at least 10^{23} atm/s (maximum);

total number of injected particles is at least $5 \cdot 10^{23}$;

response time of the system (appearance of gas at the nozzle outlet after receiving the trigger signal from the system predicting the disruption of the discharge current) is no more than 3 ms;

gas delivery time from the nozzle outlet to the plasma is less than 1 ms (when the nozzle is located at a distance of less than 10 cm from the LCMS).

For the purpose of experimental studies of the formation of a gas jet, a special valve was developed that provides relatively easy access to the nozzle, as well as to the seat that is a structural element designed to securely attach the nozzle and block the gas flow.

Fig. 1 shows a general view of the valve for testing the seat and nozzle prototypes. Both a replaceable seat *4* and a replaceable nozzle *2* can be independently installed in the valve. The valve allows operation with gas pressures up to several tens of atmospheres. Outlet nozzle *1* provides connection to the vacuum circuit of the setup through a port with a poppet valve, used to install vacuum sensors of the PMT-6M type.

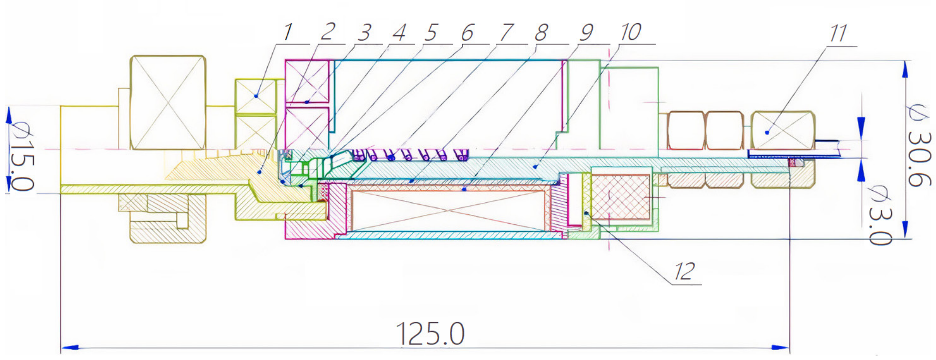

Fig. 1. Gas valve circuit for testing seat and nozzle prototypes:
outlet nozzle *1*, replaceable nozzle *2*, lower magnetic core *3*, replaceable seat *4*, separator *5*, armature with plate *6*, spring *7*, stainless separation tube *8*, solenoid coil *9*, stop *10*, gas inlet *11*, printed circuit board *12*

The valve design includes a solenoid, whose magnetic circuit consists of armature *6*, stop *10* and a set of magnetic cores. The working gap of the magnetic circuit is located between the armature and the stop. Solenoid *9* is mounted on stainless tube *8*, into which the stop is soldered. The coil is connected to an external switching power supply via terminals mounted on the printed circuit board *12*. External gas line *11* is connected to the inlet fitting of the stop to supply the working gas to the valve. Spring *7* is located inside the stop and armature, which ensures that the valve closes at the end of the electrical pulse.

The operating principle of the gas valve is as follows. The working gas flows from the inlet line into the inner channel of the stop, then through the channels in the armature, enters the volume surrounding the armature inside the stainless tube and is fed through separator *5* to replaceable seat *4*, whose channel is closed by the plate of armature *6*. When the solenoid is triggered, the valve plate moves away from the seat and the gas passes through the seat into replaceable nozzle *2*, in which a supersonic gas jet is formed, flowing through nozzle *1* into the vacuum volume on which the valve is installed. To replace the seat and/or nozzle, it is enough to turn off the gas line and fill the vacuum volume with atmosphere, then unscrewing the outlet nozzle from lower magnetic core *3*. After that, new seat and nozzle can be inserted, replacing the seals (if necessary).

The operating cycle of the valve includes the following sequence of actions.

At the stage of preparing the valve for operation, it is necessary to connect it to a switching power source and check the operation of the solenoid.

The next step is to connect inlet gas line *11* and pump it out and the internal volume of the valve, consisting of channels in stop *10*, anchor *6* and separator *5*, to remove the working gas and air that filled the main and the internal volume of the valve before operation starts.

After pumping, the inlet gas line and the inlet internal volume of the valve should be filled with new working gas.

Then, in compliance with safety procedures, it is necessary to check the operation of the valve with the working gas and its exhaust into the atmosphere.

Next, the valve is installed on a vacuum volume, into which the working gas is injected, and it is necessary to pump out the vacuum volume.

During operation, the switching power supply discharges the capacitor bank to solenoid *9*. As a result, magnetic flux is formed through a chain of magnetic conductors, stop *10* and armature *6*. The armature is attracted to the stop and detaches the plate from seat *4*. At the outlet of the seat, the leading edge of the gas flow is formed, which passes through replaceable nozzle *2*, where a supersonic gas jet is formed.

The calculation of parameters and optimization of gas flows formed by these structural elements is the subject of this study. As the source battery is discharged, the magnetic field in the solenoid weakens and the valve closes with spring *7*, which forms the trailing edge of the gas pulse and completes the operating cycle of the valve.

Calculation of supersonic nozzle parameters for MGI

The Laval nozzle parameters were calculated using methods and formulas for one-dimensional steady flows of ideal gas in channels [5, 6]. A variant of the Laval nozzle with a conical profile was calculated, which was taken as a basis for the manufacture of prototypes of the nozzle and seat. Well-known gas-dynamic relations and conservation laws were used:

$$\frac{T}{T_0} = 1 - \frac{\gamma - 1}{\gamma + 1}\lambda^2, \quad (1)$$

$$\frac{\rho}{\rho_0} = \left(1 - \frac{\gamma - 1}{\gamma + 1}\lambda^2\right)^{\frac{1}{\gamma - 1}}, \quad (2)$$

$$\frac{p}{p_0} = \left(1 - \frac{\gamma - 1}{\gamma + 1}\lambda^2\right)^{\frac{\gamma}{\gamma - 1}}, \quad (3)$$

where p_0, ρ_0, T_0 are the pressure, density and temperature of the resting gas; γ is the adiabatic index; λ is the reduced velocity,

$$\lambda = \frac{v}{c_{S*}} = \frac{v}{\sqrt{\frac{2\gamma R}{(\gamma + 1)M}T_0}}$$

(c_{S*} is the speed of sound at critical values of the parameters ρ_*, T_*, p_*).

The parameters ρ_*, T_*, p_* follow the expressions:

$$T_* = \frac{2}{\gamma + 1}T_0, \; \rho_* = \left(\frac{2}{\gamma + 1}\right)^{\frac{1}{\gamma - 1}}\rho_0, \; p_* = \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma}{\gamma - 1}}p_0.$$

The gas parameters should take their extreme values in the narrowest section of the Laval nozzle, called the "critical section". The designed nozzle should provide a mass flow of helium $G = 3{,}8 \cdot 10^{-4}$ kg/s. In accordance with the law of conservation of flow and the set values of pressure, temperature and flow at the nozzle inlet, the diameter of the critical section is determined:

$$d_{crit} = 2\sqrt{\frac{G\sqrt{T_0}}{B\pi p_0}}, \quad (4)$$

where $B = \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma + 1}{2(\gamma - 1)}}\sqrt{\gamma\frac{m_{He}}{R}} = 0.016\,\frac{\mathrm{K}^{0.5}\mathrm{s}}{\mathrm{m}}.$

We obtain the value d_{crit} = 0.73 mm in this simulation for helium.

When designing a conical nozzle, it is also necessary to choose the correct opening angle of the subsonic and supersonic sections of the nozzle [7–9]. The recommended values of the opening angle β of the supersonic section of the nozzle in conical nozzles should not exceed 15° [9].

For the calculations presented below, the angles of the subsonic and supersonic sections of the nozzle were selected (α and β, respectively: α = 26°, β = 12°), which determined the lengths of these sections as 10 and 20 mm, respectively.

When calculating the diameter of the outlet section, the gas dynamic function of the reduced flow rate is commonly used:

$$q(\lambda)=\frac{\rho v}{\rho_* c_{S*}}=\left(\frac{\gamma+1}{2}\right)^{\frac{1}{\gamma-1}}\lambda\frac{\rho}{\rho_0}=\left(\frac{\gamma+1}{2}\right)^{\frac{1}{\gamma-1}}\lambda\left(1-\frac{\gamma-1}{\gamma+1}\lambda^2\right)^{\frac{1}{\gamma-1}}. \quad (5)$$

It follows from the condition of conservation at steady flow that

$$\rho_2 v_2 S_2=\rho_* c_{S*} S_{crit}\rightarrow S_2=\frac{\rho_* c_{S*}}{\rho_2 v_2}S_{crit}=\frac{S_{crit}}{q(\lambda_2)}, \quad (6)$$

and the cross section at the nozzle outlet is expressed as

$$d_2=d_{crit}\sqrt{\frac{1}{q(\lambda_2)}}. \quad (7)$$

In the case under consideration, the diameter of the outlet section d_2 = 4 mm was set by the design parameters of the valve (see Fig. 1). Therefore, the value of the gas-dynamic function of the reduced flow rate, found from equations (5), allows to obtain the value of the reduced velocity λ_2 and the velocity v_2 at the nozzle outlet:

$$q(\lambda_2)=\left(\frac{d_{crit}}{d_2}\right)^2=0.014\rightarrow\lambda_2=1.97\rightarrow v_2=c_{S*}\lambda_2=1.74\ \text{km/s}. \quad (8)$$

Simulation results

The conical profile of the Laval nozzle calculated in the above manner had the following parameters:

diameter of inlet section d_1 = 4.0 mm;
diameter of critical section d_{crit} = 0.7 mm;
diameter of outlet section d_2 = 4.0 mm;
length of supersonic section of the nozzle l_2 = 20 mm;
total opening angle of the walls β = 12°;
length of subsonic section l_1 = 10 mm;
total opening angle of the walls α = 26°.

We chose the geometry of the conical nozzle with these parameters for the first experiments with the prototype of the MGI valve, simplified for manufacturing. A nozzle with stepped subsonic and supersonic sections, close to a conical profile, was designed, which can be achieved technologically by sequential drilling of the workpiece (the term «stepped nozzle» is used from now on for brevity). Seven steps were set for both sections of the nozzle. The step diameter was chosen to be 0.5 mm, the step length was 1.4 mm for the subsonic section and 2.8 mm for the supersonic section. A cylindrical seat was installed in front of the inlet section of the nozzle, with the length equal to the diameter of the inlet section, 4 mm, necessary to lock the gas flow and anchor this element in the valve structure.

A sketch of the nozzle with the seat and an example of a constructed computational grid for simulation is shown in Fig. 2. The computational domain was divided into two zones. A more refined grid was built near the nozzle and seat, where the gas flow parameters change faster, with the element size of 0.05 mm; the size of the grid cell was reduced to 0.01 mm for 10 cells adjacent to the wall to improve the resolution of the boundary layer in the main volume in the near-wall region. The size of the grid element was 0.15 mm in the area of the diagnostic chamber, where the jet is injected.

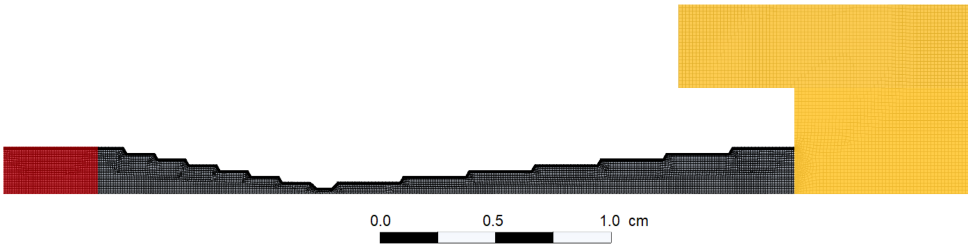

Fig. 2. Example of computational grid for stepped Laval nozzle with seat (highlighted in red). The region with the diagnostic chamber (highlighted in yellow) is shown

This section presents the results of numerical simulation of helium flow through such a nozzle. The computational domain was divided into similar zones, with the same characteristic dimensions of the grid element for calculations with other nozzle profiles (their main results are given in the next section).

The simulation was performed using the ANSYS Fluent CFD package, where a stationary system of continuity and momentum balance equations was numerically solved. An axisymmetric problem was solved using an implicit integration scheme, with second order approximation. The k-ε Realizable turbulence model was included in the calculations [10]. The following boundary conditions were imposed for solving the problem:

nozzle inlet pressure..10 atm (1 MPa);
nozzle outlet pressure..1 Pa;
temperature at the inlet and outlet of the nozzle.......300 K;
no-slip condition for the walls assumed to be smooth.

The choice of the calculation method was based on the following considerations. The estimation of the Knudsen number for the given problem parameters gives values not exceeding $2 \cdot 10^{-3}$ inside the nozzle and $3 \cdot 10^{-2}$at a distance of 5 cm from the nozzle, which allows using a continuum approach for this problem with reasonable accuracy at sufficiently small distances from the nozzle exit. The valve design assumes it is placed in close proximity to the plasma, at a distance of no more than 10 cm from the LCMS of the setup, which allows to expect a high degree of reliability of the calculated results obtained.

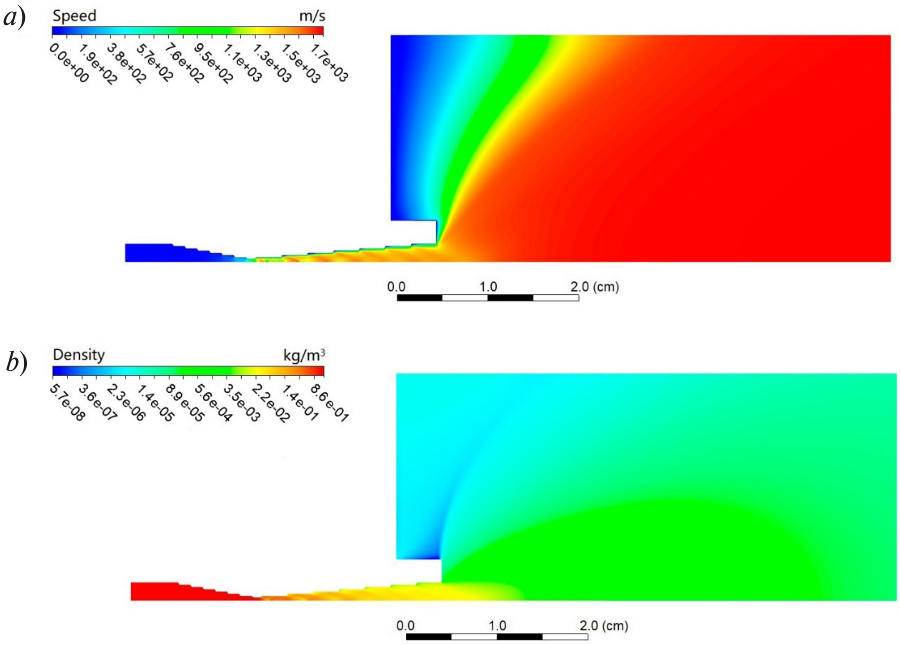

Fig. 3. Calculated distributions of velocity (*a*) and density (*b*) of helium jet at steady flow from stepped nozzle with seat

Fig. 3 shows the calculated velocity and density distributions for the stepped prototype of the Laval nozzle after steady flow is established. Inside the supersonic section of the nozzle, periodic jumps in gas parameters can be observed, resulting from the reflection of shock waves from the steps inside the nozzle. This behavior of gas outflow can lead to a turbulent gas flow regime inside the nozzle and affect its performance.

It is logical to assume that an increase in the number of steps in the nozzle profile will cause a decrease in the amplitude of these jumps and, accordingly, a more uniform behavior of the gas flow inside the nozzle. In this case, the risk of transition to a turbulent gas flow regime will be reduced. It should be noted that a jet with uniform outflow profiles of gas velocity and density is obtained at the outlet of the nozzle with such a profile with 7 steps, and the divergence of the jet is not large.

The velocity and density distributions along the jet injection axis are shown in Fig. 4. The figure clearly shows the nature of the flow parameter jumps along the injection axis inside the nozzle. The amplitude of fluctuations in density does not exceed 80% of the maximum value, and in terms of flow velocity it is about 40%. The maximum oscillations are concentrated near the critical region of the supersonic section of the nozzle. The oscillation amplitude decreases approaching the nozzle outlet.

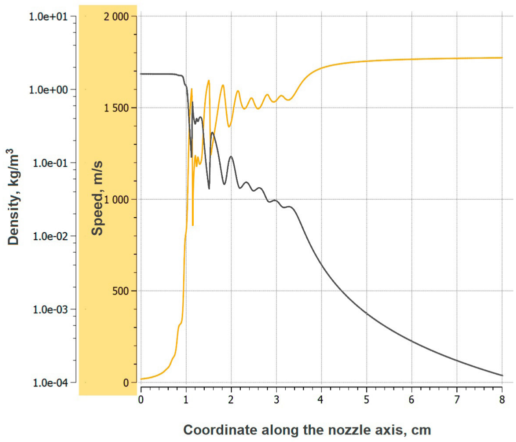

Fig. 4. Distributions of velocity (yellow curve) and density (black curve) of the jet along the nozzle axis for stepped nozzle with seat

Despite the peculiarities of the distribution of gas flow parameters inside the stepped nozzle, the general pattern of the distribution of jet parameters behind the nozzle remains the same as that of a conventional conical nozzle, except for a slightly larger gas expansion angle. The velocity directly at the nozzle outlet decreases to about 1.5 km/s, but the jet in the diagnostic chamber accelerates to the velocities v_{max} = 1.7 km/s, which is close to the theoretical maximum (see equations (8)). The pressure at the nozzle exit at the problem parameters set is about 800 Pa, which leads to a significantly underexpanded jet flow mode [11]. The characteristic dimensions of the hanging bow shock, obtained from empirical formulas [12], are about 10 cm and are comparable to the dimensions of the diagnostic chamber, which fully corresponds to the calculated flow pattern. Studies of the large-scale structure of the jet are beyond the scope of this work. The calculation results for nozzles with other profiles, including smooth conical ones, are given in the next section of the study.

Optimization of the nozzle profile

The conical shape of the nozzle is the limit for a nozzle with a stepped profile, with an increase in the number of steps to infinity. Theoretically, a parabolic nozzle should give optimal values of the velocity and gas expansion angle at the outlet [7]. The computational grid for the parabolic nozzle was constructed as follows: the dimensions of the inlet, outlet and critical sections were assumed to be the same as when designing a conical nozzle (to preserve mass flow), and the shapes of the profiles of the subsonic and supersonic sections were parabolical along the axis of the nozzle. The shape of the profiles of the subsonic and supersonic parts was «merged» near the critical section, using the method with the first derivative of the shape of the nozzle profile tending to zero along its axis. Otherwise, a kink appear in the nozzle profile, which can lead to shock waves in this region.

To compare the angle of expansion for three types of nozzle, the half-width of the jet was estimated. The distribution of the jet density was calculated in the plane transverse to the axis of the jet injection, at a distance of 3 cm from the outlet section of the nozzle. Next, the distance from the injection axis was determined, at which the gas density drops by half relative to its maximum value, which determines the half-width of the jet, characterizing the scale of gas expansion at the nozzle outlet.

Density distributions along the cross section of the jet for the three types of nozzle for which calculations were performed are shown in Fig. 5, and the main characteristics of the jet in the diagnostic chamber are shown in the table. The results obtained indicate the smallest expansion of the helium jet and its highest exit velocity for a smooth conical nozzle. The parabolic shape of the nozzle section gives intermediate values of speed and width, which is apparently due to the suboptimal choice of the profile of this type of nozzle at given cross-section values.

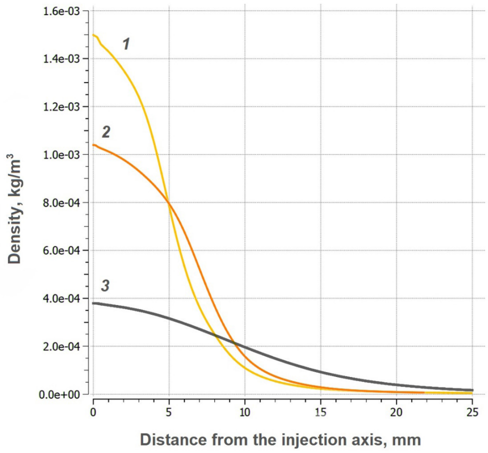

Fig. 5. Density distribution of helium jet along its cross-section for three types of nozzles at a distance of 3 cm from the exit from the outlet section.
The calculations were carried out for conical (curve *1*), parabolic (*2*) and stepped (*3*) nozzle shapes

The selection of the optimal nozzle profile with a parabolic cross section is a complex multi-parameter problem, whose solution is beyond the scope of this study. The stepped nozzle provides a less than 10% decrease in the jet velocity at the outlet and leads to an increase in the jet angle of expansion by about half, compared with the conical nozzle profile. Such a deterioration in the parameters of the jet is acceptable and is fully compensated by the technological simplicity of its manufacturing.

Analysis of Fig. 5 allows us to conclude that the density distributions of the jet in the cross section are monotonous, with maxima on the injection axis for all types of nozzles. The absolute density value on the injection axis for a stepped nozzle drops by 4 times relative to a conical one. There is also a significant increase in the angle of expansion of the jet for the case of a stepped nozzle.

During the simulation, the diameter of the critical section for the stepped nozzle was also varied to assess the effect of the nozzle manufacturing accuracy on the parameters of the formed jet. The computational grid corresponded to the one shown in Fig. 2, with accuracy up to the diameter of the critical section, which was set to ± 0.2 mm from the calculated optimal value of 0.7 mm (obtained by formula (4). As a result, the velocity and density distributions of the gas at the outlet of the nozzle were calculated. The main parameters of the jet are summarized in the same table.

Table

Calculated key parameters of the nozzle

Nozzle type	Jet outlet velocity, m/s	Jet half-width, mm	Mass flow rate, g/s
Conical	1715	5.0	0.32
Parabolic	1666	7.0	0.32
Stepped ....standard	1551	10.3	0.32
....with seat	1549	11.0	0.32
...with critical section increased to 0.9 mm	1551	10.6	0.55
...with critical sectiondecreased to 0.5 mm	1531	10.9	0.17

Thus, an increase in the mass flow rate of gas by 1.7 times was obtained with an increase in the diameter of the critical section to 0.9 mm. If this diameter was decreased to 0.5 mm, the mass flow rate decreased by 1.9 times. Calculations also show that the jet velocity in the diagnostic chamber does not significantly depend on the type of nozzle, while the smallest jet angle is obtained for a standard stepped nozzle. The drop in velocity at the nozzle outlet and the broadening of the jet profile with varying critical cross-sectional area do not exceed several percent. However, a significant change in the mass flow rate of gas with varying critical cross-sectional area indicates that high manufacturing accuracy is required for the dimensions of the stepped nozzle profile (diameter tolerance should be at least 0.01 mm).

Conclusion

The optimal parameters of the supersonic nozzle were calculated for a given mass flow rate of helium of $3.8 \cdot 10^{-4}$kg/s. The diameters of the inlet and outlet sections were 4 mm, the diameter of the critical section was 0.7 mm, the lengths of the subsonic and supersonic sections of the nozzle were 10 and 20 mm, respectively; the total opening angle of the walls for the subsonic section was 26°, and 12° for the supersonic section. The outflow of gas through nozzles of various profiles into the diagnostic chamber was simulated using the ANSYS Fluent CFD package. The parameters of the gas flow through a stepped nozzle with a seat in the near field of the jet were calculated in detail. It was found that such a nozzle allows to obtain a gas flow rate of about 1550 m/s on the injection axis, with a half-width of the jet of 11 mm at a distance of 3 cm from the nozzle exit.

The simulation confirmed that a stepped nozzle with a seat gives an insignificant difference in the values of the velocity and half-width of the jet, compared with a nozzle without a seat. The maximum outlet velocity and the minimum jet angle can be achieved at the given cross-sectional values with a nozzle with a conical profile shape, while a stepped nozzle with a seat shows a decrease in quality by no more than 10% in terms of the jet velocity parameter, and a decrease by about 3 times in terms of the half-width of the jet, which is quite acceptable if the technological simplicity of manufacturing is taken into account.

Thus, the best option is the design and manufacturing of a stepped nozzle with a seat to be used in the first experiments with the prototype of the MGI valve in setups with magnetic plasma retention.

The critical cross-sectional area of a stepped nozzle with a seat was varied during the simulation. The calculation results showed a strong dependence of the mass flow rate on the critical section of the nozzle; the velocity and half-width of the jet at the outlet changed insignificantly.

In general, the conducted study confirms the stringent requirements for the manufacturing accuracy of nozzle profiles. The diameter tolerances of the nozzle profile must be no worse than the grade of 10.

REFERENCES

1. **Eidietis N. W.,** Prospects for disruption handling in a tokamak-based fusion reactor, Fusion Sci. Technol. 77 (7–8) (2021) 738–744.

2. **Landau L. D., Lifshitz E. M.,** Fluid mechanics (§ 97. Flow of gas through a nozzle), Second Ed. Vol. 6 of Course of Theoretical Physics. Pergamon Press, Oxford, New York, 1987.

Hollmann E. M., Aleynikov P. B., Fьщр T., et al., Status of research toward the ITER disruption mitigation system, Phys. Plasmas. 22 (2) (2015) 021802.

4. **Dremin M. M., Kapralov V. G., Kislov A. Ya., et al.,** Effect of noble gas injection on discharge disruption in T-10 tokamak, Probl. At. Sci. Technol. Ser. "Thermonucl. Fusion" (4) (2012) 58–70 (in Russian).

5. **Dulov V. G., Lukyanov G. A.,** Gazodinamika protsessov istecheniya [Gas dynamics of outflow processes], Nauka, Novosibirsk,1984 (in Russian).

6. **Izotov B. A.,** Raschet i postroyeniye profilya sopla Lavalya [Calculation and profiling of De Laval nozzle], Orenburg State University Publishing, Orenburg, 2009 (in Russian).

7. **Kirillov A. B., Rotinyan E. M.,** Mekhanika zhidkosti i gaza. Soplo Lavalya [Fluid-flow mechanics. De Laval nozzle], Polytechnical Institute Publishing, St. Petersburg, 2017 (in Russian).

8. **Pipko A. I., Pliskovskii V. Ya., Penchko E. A.,** Konstruirovaniye i raschet vakuumnykh system [Design and calculation of vacuum systems], Energiya, Moscow, 1979 (in Russian).

9. **Shishkov A. A., Panin S. D., Rumyantsev B. V.,** Rabochiye protsessy v raketnykh dvigatelyakh tverdogo topliva: Spravochnik [Operation processes in solid rocket motors: Handbook], Mashinostroyeniye, Moscow, 1988 (in Russian).

10. **Shih T. H., Liou W. W., Shabbir A., et al.,** A new k-ε eddy-viscosity model for high Reynolds number turbulent flows, Comput. Fluids. 24 (3) (1995) 227–238.

11. **Volkov K. N., Emelyanov V. N., Zazimko V. A.,** Turbulentnyye strui: staticheskiye modeli i modelirovaniye krupnykh vikhrey [Turbulent jet flows: Statistical models and simulation of large vortices], Fizmatlit, Moscow, 2014. (in Russian).

12. **Shelukhin N. N.**, Issledovaniye kharakteristik sverkhzvukovoy nedorasshirennoy strui [Study of characteristics of a supersonic underexpanded jet flow], TsaGI Sci. J. 26 (1–2) (1995) 78–87 (in Russian).

СПИСОК ЛИТЕРАТУРЫ

1. **Eidietis N. W.** Prospects for disruption handling in a tokamak-based fusion reactor // Fusion Science and Technology. 2021. Vol. 77. No. 7–8. Pp. 738–744.

2. **Ландау Л. Д., Лифшиц Е. М.** Теоретическая физика. В 10 тт. Т. 6. Гидродинамика (§ 97. Истечение газа через сопло). М.: Физматлит, 728 .2021 с.

3. **Hollmann E. M., Aleynikov P. B., Fьщр T., et al.** Status of research toward the ITER disruption mitigation system // Physics of Plasmas. 2015. Vol. 22. No. 2. P. 021802.

4. **Дремин М. М.**, **Капралов В. Г., Кислов А. Я. и др**. Влияние напуска благородных газов на срыв разряда в токамаке Т-10 // Вопросы атомной науки и техники (ВАНТ). Серия. Термоядерный синтез. 2012. № 4. С. 58–70.

5. **Дулов В. Г., Лукьянов Г. А.** Газодинамика процессов истечения. Новосибирск: Наука, 1984. 226 с.

6. **Изотов Б. А.** Расчет и построение профиля сопла Лаваля. Оренбург: Изд-во Государственного Оренбургского университета, 20 .2009 с.

7. **Кириллов А. В., Ротинян Е. М.** Механика жидкости и газа. Сопло Лаваля. СПб.: Изд-во Политехнического университета, 2017. 22 с.

8. **Пипко А. И., Плисковский В. Я., Пенчко Е. А.** Конструирование и расчет вакуумных систем. -3е изд., перераб. и доп. М.: Энергия, 504 .1979 с.

9. **Шишков А. А., Панин С. Д., Румянцев Б. В.** Рабочие процессы в ракетных двигателях твердого топлива: Справочник. М.: Машиностроение, 240 .1988 с.

10. **Shih T. H., Liou W. W., Shabbir A., Yang Z. Zhu J.** A new k-ε eddy-viscosity model for high Reynolds number turbulent flows // Computers & Fluids. 1995. Vol. 24. No. 3. Pp. 227–238.

11. **Волков К. Н., Емельянов В. Н., Зазимко В. А.** Турбулентные струи: статические модели и моделирование крупных вихрей. М.: Физматлит, 360 .2014 с.

12. **Шелухин Н. Н.** Исследование характеристик сверхзвуковой недорасширенной струи // Ученые записки ЦАГИ (Центральный аэрогидродинамический институт). 1995. Т. 26. № 1–2. С. 78–87.

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Статья поступила в редакцию 05.09.2023. Одобрена после рецензирования 04.10.2023. Принята 04.10.2023.
Received 05.09.2023. Approved after reviewing 04.10.2023. Accepted 04.10.2023.