COMPUTER FLOW VISUALIZATION AND EXPERIMENTAL INVESTIGATION OF COMPACT RING AND DUAL-SLOTTED LINEAR NOZZLES

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ABSTRACT: Both numerical and experimental flow research as well as thrust characteristics of a jet engine model thrust device equipped by a ring nozzle with the internal cavity in the form of a spherical segment are presented. For the dual-slotted linear nozzle, corresponding on geometrical parameters considered ring nozzle, numerical visualization of flow shadow picture inside of the cavity is executed. It is shown, that in a stationary mode the flow structure in the considered devices is similar to a flow in nozzles with the central body. The role of the gas central body thus plays the recirculation flow area, which is automatically formed in a nozzle cavity. The flow picture in dual-slotted linear nozzle on structure is similar to structure of ring nozzle. However, in case of dual-slotted linear nozzle a surface of the central body under the form appears more pointed at an axis in comparison with the ring nozzle. In both nozzles – ring and linear the primary turn of the stream that inlets from nozzle throat and moves along central body surface, occurs in the attached to a body oblique shock wave. Finally in a dual-slotted linear nozzle the stream is swivels along a thrust vector in an original four-shock configuration, and in a ring nozzle - in intensive hanging shock. Results of modeling of the non-stationary wave processes accompanying starting and an establishment of flow in experiments with models of similar nozzles devices are presented. Times of nozzle devices starting, formation and existence quasi-stationary regime of the expirations in a receiver are defined. In presented experimental and calculating results it was established that considered ring nozzle developed the thrust approximately twice exceeding corresponding values for sound nozzle.

INTRODUCTION: Ring and dual-slotted linear nozzles with the internal cavity on a number of characteristics represent a competition for traditional Laval nozzles as the thrust device of the jet engine. They have noticeably smaller length along thrust vector, possess property of auto adjustability at change of flight height and are considered as perspective for realization a pulsing valve less mode of fuels burning [1]. By present time some of them have found application at designing perspective samples of aviation and rocket technique.

The work is devoted to research of combustion products flow in ring and flat slotted nozzle devices with deflector in spherical segment form. The gas stream acts in the device with sound speed through ring nozzle in a radial direction and accelerates till supersonic speed, and then it turns and expires through outlet nozzle in the form of a supersonic expending jet. As it is shown in number of experiments and calculations, there exist stationary, considered in the work, high-frequency pulsation modes of flow in the devices [2-7]. The described geometry is ring nozzle with the central body which role is carried out the vortical zone formed in a deflector and giving the same effect as the central body in plug nozzles.

Here complex results are presented of numerical end experimental researches of flow structure and force characteristics of nozzle device model working on equilibrium combustion products of acetylene-air mixes when it is possible to perform precisely enough verification of mathematical model by results of comparison of experimental data with calculated one. Flow calculations in view of viscosity are performed with use of the numerical solution of non-stationary Navier-Stokes equations for multi component chemically non equilibrium model of the gas medium. The flow in non viscous approach was described due to the original computer system on the basis of Euler's equations, allowing to model two-dimensional non-stationary flows of the multi component inert and reacting gases. Experimental researches have been performed in the laboratory pulse aerodynamic setup equipped by measuring devices of pressure on deflector wall and thrust force [8-9].

NUMERICAL END EXPERIMENTAL RESEARCHES: Calculation was made on basis of numerical solution of non-stationary Navier-Stokes equations for multi-component chemically non-equilibrium model of gas/ New numerical technique and codes were developed to provide fulfillment this task due to application package HIGHTEMP [10]. In calculations the gas phase 10-componental model including all the basic combustion products of stochiometric acetylene-air mixture: O, H, O_2, H_2, OH, CO, CO_2, HO_2, H_2O, N_2 was used [8]. The kinetic scheme included 6 dissociation-recombination reactions and 13 exchange reactions. The flow scheme of combustion products was presented on Fig. 1.

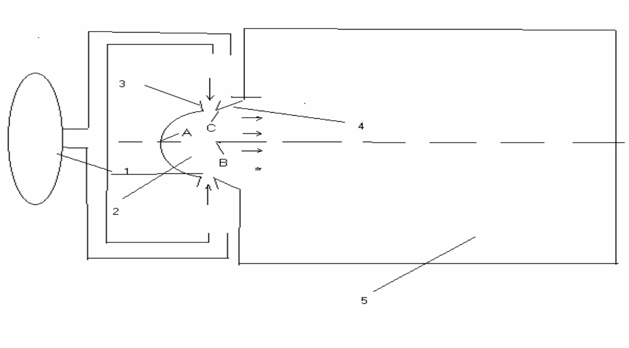

Fig. 1. The scheme of experimental setup: 1 - reactor, 2 - deflector, 3 - entrance radial ring nozzle, 4 - outlet nozzle, 5 - receiver for burning products, A, B and C - points of pressure control at numerical modeling.

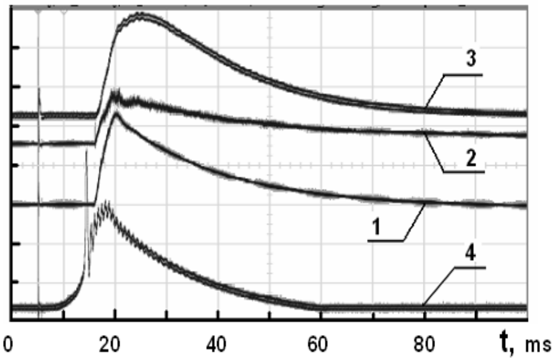

Fig. 2. Typical oscillograms (1-4) of signals from pressure and force gauges.

The stoichiometric mixture of acetylene-air with set initial values of pressure - Pin, temperatures – Tin = 300K and different mole concentrations of components - Xin burned down in a reactor at constant volume formatting of a gas mix with parameters P, T, X. Products of burning acted on the bringing channel in ring nozzle and flowed out with sound speed in deflector from which gas through outlet nozzle – a conical nozzle with half angle 45^0, initial diameter d = 66.4 mm and length 16.6 mm along the thrust vector followed in a receiver filled by motionless air at constants on time parameters Pe=0.01 atm, Te = 300K. Movement of gas in the bringing subsonic channel was defined under formulas of one-dimensional gas dynamics in the assumption of «frozen» chemical compound. Deflector represented a spherical segment with height 22 mm and basis diameter d = 66.4 mm. The critical section height of ring nozzle was equal h = 4.4 mm. Four variants for different values of stagnation pressure on an input ring nozzle have been counted: P = 4.81, 9.77, 14.78 and 19.83 atm. Total thrust value D was calculated on the pressure distribution received in calculations along thrust wall surface:

$$D = 2\pi \int_0^{s_n} (p_w - p_e)\,|x|\,n_y ds; I = D / gG.$$

Here p_w - pressure upon thrust wall surface, n_y - a vertical component of a vector of a normal to a surface, s - the distance measured along a contour of the cavity surface from point A (Fig. 1), s_n - distance up to an edge ring nozzle, G - the total gas flow rate through nozzle, g - acceleration of gravity.

Experimental researches of conditions of the expiration and trust characteristics were spent with an original design of the model, allowed to measure pressure in several points on a trust wall surface, and also near critical section in subsonic stream area. Typical working time of a near stationary flow mode was nearby 50 ms. Pressure was measured by high-frequency piezoelectric and special - with stability of zero and a constancy of calibration at change of temperatures of the measured environment, strain gauges. Simultaneously during experiences the trust force was registered by the strain gauge of force. Signals were recorded by digital oscillographs HP-54624A and multichannel amplifier MGCplus. For calibration of gauges the dynamic method was used in conditions as much as possible approached to conditions of their operation at measurements. The set of measured parameters was allowed spending in the unequivocal image their comparison to calculated values of corresponding sizes.

Typical oscillograms of signals from several gauges during one full cycle of the high-temperature flowing, registered by one of oscillographs, are presented on Fig. 2. Number 1 corresponds to a signal from a piezoelectric pressure sensor established in the bringing channel at a distance of 80 mm from the critical section of ring nozzle, 2 - to a signal from piezoelectric pressure sensor in the center deflector (in point A jn Fig. 1), 3 - to a signal from the strain sensor of thrust force, 4 - to a signal from piezoelectric pressure sensor upon the wall of combustion chamber - a reactor.

The ignition moment in the combustion chamber is registered on all beams by vertical "splash" in signals of pick up from the short-term high-voltage impulse submitted on an electric igniter. From this time, continuous pressure growth in the combustion chamber, registered by the pressure sensor established in reactor wall (beam 4 on the screen of the oscillograph) is observed. At approximately 12 ms the diaphragm separating the reactor from an entrance cavity of model bursts. That leads to pressure growth on the sensors established in the bringing channel and on deflector wall. Also the strain sensor of force (beam 3) registers the pressure increase. Through 4-6 ms after the bursting of diaphragm the pressures on an input of the nozzle device and on a thrust wall reach a maximum and after that their continuous reduction begins due to gas pressure drop through critical section of ring nozzle. Estimations and results of calculations show that establishment time of flow stationary regime in the device is essential less than characteristic time of the out flowing of combustion products from the reactor.

MAIN RESULTS: The full picture of flow dynamics in the deflector cavity from the beginning moment in the ring jet till the formation resulting stream conditions is investigated. The analysis of process development has allowed establishing its two stages with different qualitative and quantitative parameters. The initial stage is characterized by short time and strong pulsations of characteristics of flow. Eventually the amplitude of pulsations decreases.

Using of non-viscous gas environment model it is established resulting flow mode with periodic pulsations concerning small amplitude of all stream parameters. Taking into account viscous effects the steady state is established with similar to non-viscous calculation model parameters. Thus establishment time depends on problem parameters and varies within the limits of 0.5-1.0 ms. Pulsations have most intensive after start and gradually fade in the allotted time. The most intensive pulsations pressure P(A), presented on Fig. 3, tests in ground area on cavity wall (point A on Fig. 1), the time is counted from the beginning of gas entering in the cavity.

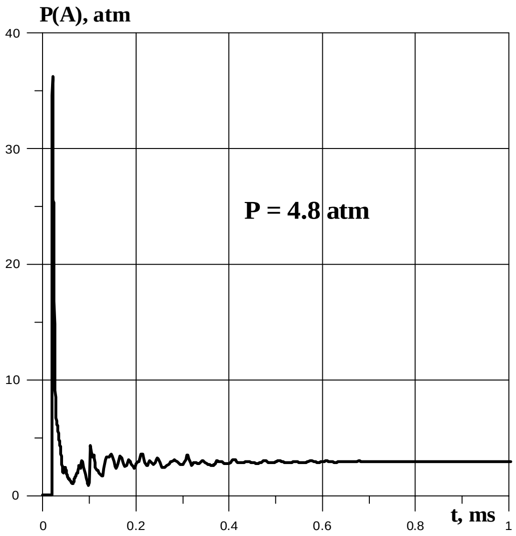

Fig. 3.

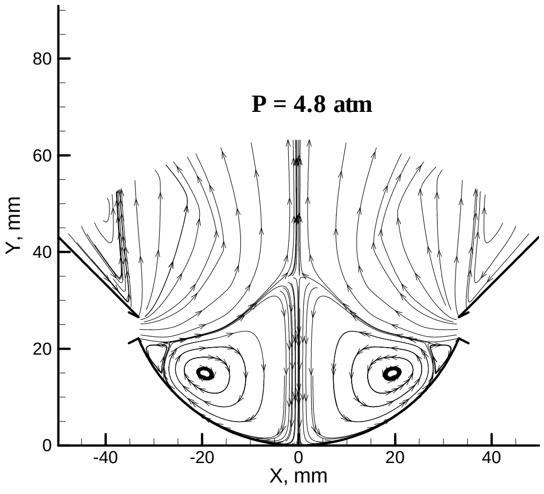

Fig. 4

In all considered variants initial flow disturbances connected with start of the nozzle device quickly dump and approximately through 0.6 ms steady state flow is formed. On Fig. 4 particles trajectories for the first case of calculations are shown. Corresponding steady state two-dimensional pictures of flow pressure and dimensionless gradient of density - $|\mathrm{grad}\ \rho|$, in meridian plane of cross section for this case is shown on Fig. 5 and Fig. 6 accordingly. The streamlines picture (Fig. 4) shows that in the nozzle device recirculation flow in the form of two annular vortexes is formed. Entering in the cavity working gas flows out from device in the form of extending axis symmetric jet. These two flow areas are divided by the stream dome-shaped surface starting from the bottom edge of the ring nozzle. The dividing surface acts inherently as the central body surface in the plug nozzle.

Two zones of raised pressure with peak value of 2.9 atm are formed near stagnation region on the axes and at the cavity bottom (Fig. 5). This value approximately coincides with the critical pressure p^* and almost twice bellows of the total pressure P. One more local peak of pressure is formed practically on a dividing surface in near confluence of two neighboring boundary jets of the big and the small ring vortexes and the jet following along central body from the ring nozzle. In this point (point B on Fig. 6) the oblique shock BC of small intensity is formed where first step of the inlet jet turn is realized. Second step of the jet turn is realized in more intensive hanging shock DG located below on the stream. Hanging shock divides the outlet jet on internal area with high gas density and external area where gas is more rarefied and the velocity is greater.

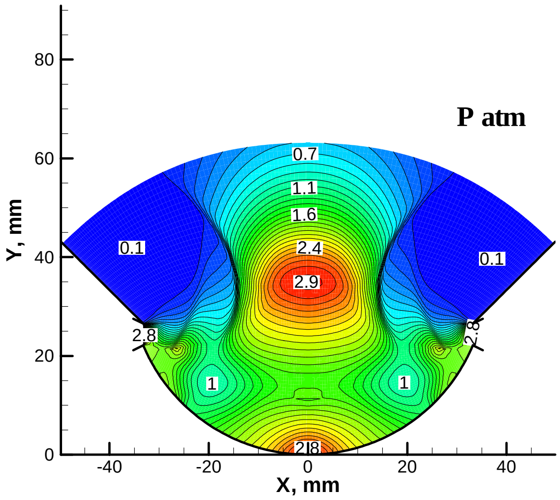

Fig. 5

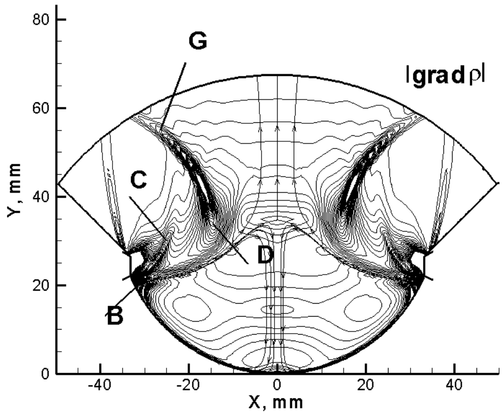

Fig. 6

The gas temperature in recirculation zone varies within the limits of 2500-2800 K. Temperature peak here are close to the stagnation temperature Tt. Along of outlet conic jet axis the pressure and temperature fall, and Mach number increases. Flow in the external area of outlet jet has character of Prandtl - Meyer flow. The stream is turned on the limiting corner defined by the ratio Pe /P. So, on Fig. 5 it is visible the structure of the ring stream consisting of areas rarefaction and compression with shocks which provide a ring jet turns which are flowing round the central body, and formation in the field of jets closing behind a conic outlet jet body divided by ring hanging shock on two areas - internal and external which border is defined by opposite pressure in outflow space.

During researches a series of calculations with duel-slotted linear nozzle of special form has been executed. The form and the sizes of its thrust wall, the sizes of a throat of linear nozzle, and also the form and the sizes of exhaust nozzle in accuracy coincided with corresponding parameters of axial section considered above mentioned axis symmetric ring nozzle. Such duel-slotted linear nozzle is more convenient to use in experiments on visualization of a stream by a shadow method.

In figures 7 and 8 calculation examples of a field with current lines and pressure isolines in the established mode in similar nozzle in its cross-section plane are presented. From figure 7 it is visible, that the picture of current lines in duel-slotted linear nozzle on structure is close to a structure in ring nozzle, presented on figure 4. In both nozzles in a stationary phase near to a thrust wall the recirculation zone is automatically formed. It is carrying out the central body role where the gas flow is accelerated. However, in case of duel-slotted linear nozzle the section of a surface of the central body by the form appears more pointed near to an axis of symmetry in comparison with ring nozzle and is characterized by presence enough extensive section (BD in figure 7) close to rectilinear.

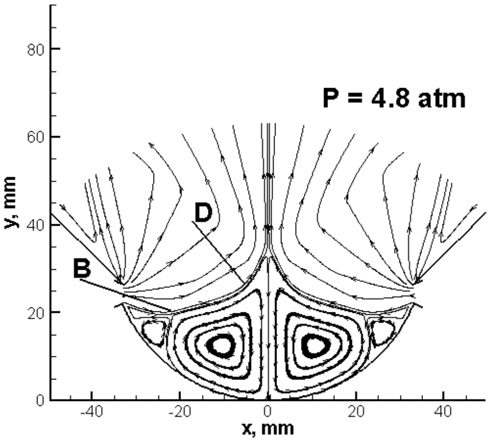

Fig. 7

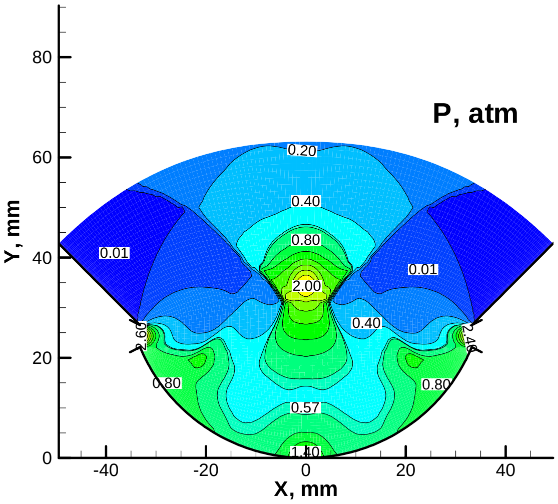

Fig. 8

In both nozzles-linear and ring - the primary turn of the stream acting from a nozzle throat and moving along a surface of the central body, occurs attached to central body (BC in figure 9 or figure 6 accordingly). Finally in duel-slotted linear nozzle the stream, moving along a surface of the central body, is turned in a direction of thrust vector in original four-shock configuration FD-FE-FH-FG which is distinctly looked through in figures of 9 and 10. Dimensionless gradients of stream density along axes Y and X accordingly are presented in figures of 9 and 10.

It is visible, that the first of shock waves (DF in figure 9) a four-shock configuration is formed close to surface of the central body near to a confluence point a rectilinear section of the central body with its pointed top.

Second shock wave EF also is formed close to surface of the central body below on a stream. Both specified shock waves provide a final turn of a stream that runs near central body close to 90° concerning a direction of a stream in a nozzle throat.

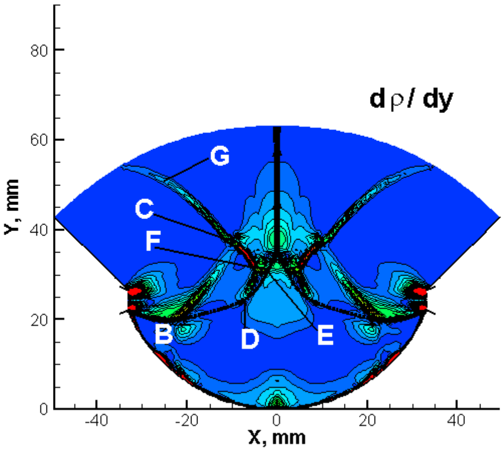

Fig. 9

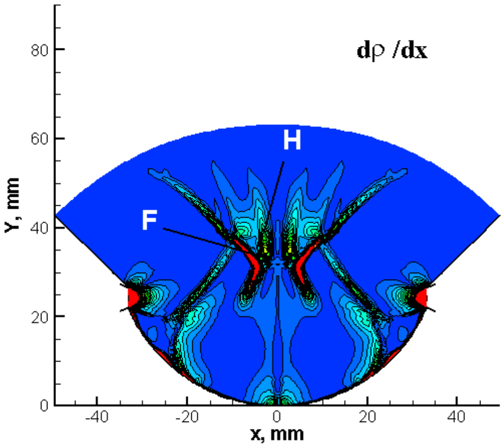

Fig. 10

The third shock wave FG is adjoined to point F of crossing of two specified shock waves – DF and EF which provide a turn up to corners of greater 90° current jets more remote from a surface of the central body, than a point of crossing of two primary shock waves. Interaction of third shock wave FG with the weakness shock wave BC leads to occurrence of a characteristic break on third wave FG in point C, observable on figure 9.

The fourth shock wave FH steps aside from point F (FH in figure 10) also. It quickly enough fades downwards on a stream and provides the coordination of current parameters in kernel field behind shock FC near to point F with parameters of current what was reflected from nozzle plane of symmetry near to top of a gas central body.

In figures 11and 6 the calculated field of the dimensionless module of density stream gradient in cross-section plane of duel-slotted linear nozzle and ring nozzle are presented. Here simultaneously there are all shock waves structures considered above.

Thus, the results presented in figures 4 - 11 :

1. Show opportunities of computer visualization of the complex currents formed by duel-slotted linear nozzle and ring axis symmetry nozzle;

2. Show, that the character change of current symmetry from axis symmetric for ring nozzle to flat for duel-slotted linear nozzle leads to cardinal change of details of the jet currents formed specified nozzles, despite of geometrical identity of cross-section sections of their supersonic flowing parts.

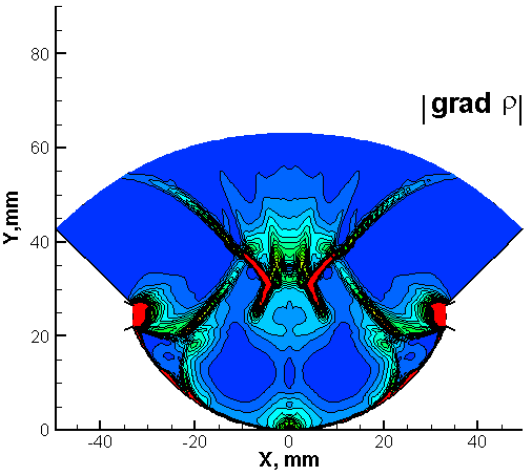

Fig. 11

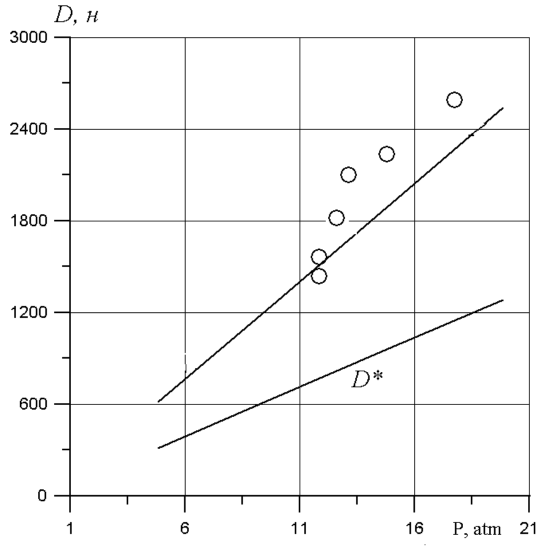

Fig. 12

The dependence of thrust D from stagnation pressure P (continuous) that obtained in numerical research after an establishment of steady state for ring nozzle device with outlet part in form of a conical outlet nozzle is compared with corresponding thrust values D^* for equivalent gas flow sound nozzle and also with the corresponding data measured in experiments (solid circles). Results are presented on Fig. 12. Satisfactory agreement of behavior tendency and quantitative values of the specified sizes is observed, that allows verifying adequacy of the created original mathematical model. It is visible, that considered nozzle device develops the thrust (and specific impulse as it is easy to show) approximately twice exceeding corresponding values for the sound nozzle.

CONCLUSION: Gas dynamic and thermo-chemical structure of the flow field generated by the considered nozzle device in the steady state mode was investigated. Data about time of an establishment of a stationary mode are obtained. It is determined, that in stationary mode the flow field structure in the ring or flat slotted nozzle devices is similar to flow field in nozzles with the central body. The central body role plays the recirculation flow area, which formed automatically in nozzle cavity. The gas stream entering in the device through the ring or flat slotted nozzle in radial direction, is accelerated till supersonic velocity, then turns and expires through the outlet nozzle in the form of supersonic extending jet, at first in ring form, and then in conic. The jet structure includes areas of rarefaction, compression and shocks where stream turning from radial to axial direction takes place. The jet angle expansion is defined by the pressure attitude on device input and in surrounding space.

Computer flow visualization and experimental investigation of compact ring and dual-slotted linear nozzles was made. It was established that the character change of current symmetry from axis symmetric for ring nozzle to flat for duel-slotted linear nozzle leads to cardinal change of details of the jet currents formed specified nozzles, despite of geometrical identity of cross-section sections of their supersonic flowing parts. If in duel-slotted linear nozzle the stream is turned to thrust vector direction in original four-shock configuration, so in ring axis symmetrical nozzle the stream is turned to thrust vector direction in strong hanging shock.

Comparison of results obtained in numerical research with experimental data on measurement of thrust force has allowed to verify numerical model and also to convince that it is reliable enough to predict expected values of the thrust developed by the nozzle device. In the investigated variation interval of stagnation pressure calculated values of thrust linearly depend on pressure and will be well corresponded with measured which approximately twice exceed calculated values for gas flow equivalent sound nozzle.

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