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Pulsation Frequency Management of Thrust Force and Gas Pressure in Nozzles

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Abstract

Complex results in experimental and numerical flow dynamics and spectra of thrust force and gas pressure pulsations signals researches in annular and linear dual slotted nozzles are presented. Experiments were performed in a pulsed aerodynamic setup using the combustion products of acetylene-air mixture as working gas. Calculations of viscous flow are based on the Navier-Stokes equations for multicomponent reactive gaseous medium using a single-temperature chemical nonequilibrium model. Data of comparison calculated and measured spectral structure of pulsing pressure signals are presented. As a result, the dependences of frequency and amplitude of pressure, thrust force and flow parameters in annular and linear dual slotted nozzles from the throat and the deflector form sizes are established.

Keywords: annular (linear dual slotted) nozzle, Navier-Stokes equations, Fourier spectrum, pressure pulsations, dominant frequency

Nomenclature

L - Slots length
R - Segment radius
H - Segment height
h - Height of nozzle throat
d- Segment base diameter
Pe / Te - Opposite pressure/ temperature
Pa - pressure in center of thrust wall
D – thrust force
Po / To - Stagnation pressure/ temperature
Fp - Dominant (satellite in brackets) frequency of pressure pulsation spectrum
F_D - Dominant (satellite in brackets) frequency of thrust force pulsation spectrum

1. Introduction

The requirement of specific parameters improvement for aviation propulsion jet engines forced, in addition with perfection of traditional engines schemes designs, to search new, perspective schemes of engines and principles of their working process organization. The jet engines using technology of 2-Stage fuels combustion in the annular (or linear dual slotted) nozzle thrust device with internal deflector refer to this type of perspective engines. In this type of devices the first stage of combustion takes place in a special power-intensive medium subsonic generator from which the prepared components inject to supersonic annular (or linear dual slotted) nozzle with internal half-closed deflector cavity (the high-frequency chamber of combustion - the resonator) as a thrust wall. The similar thrust device scheme has greater potential opportunities for the valve less high-frequency 2-Stage pulsing detonation engine - PDE realization [1]. Application of PDE operating under the specified scheme, allows hope for substantial improvement of thrust-economic, overall-mass, specific characteristics as well as the reduction of thermal loads on the surface of combustion chambers in comparison with existing aviation engines for all types of aeroplanes. The first stage of works development on creation and application in aircraft of similar PDE thrust devices scheme is the

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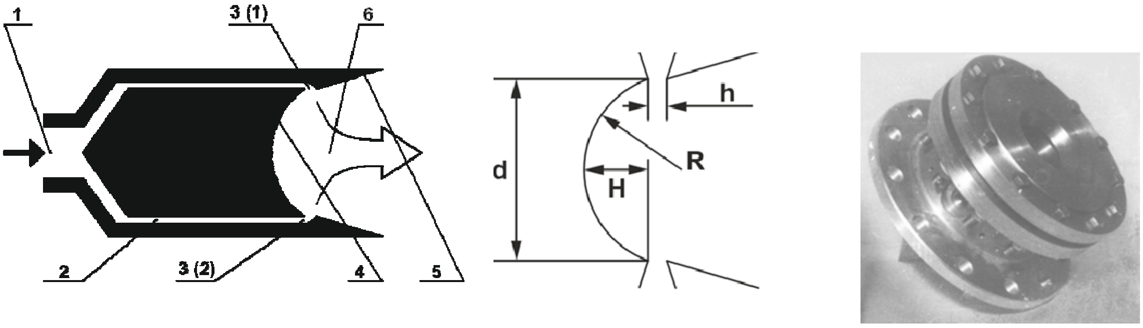
detailed experimental and calculation researches of physicochemical and gas dynamic processes, taking place in elements of its flowing path and also creation of the verified mathematical models describing non-stationary propagation processes of high-temperature waves of combustion and detonation in channels of such complex devices.

2-Stage PDE concept assumes injection of prepared (at the first stage) power-intensive medium into deflector cavity - gas dynamic resonator in which process of spontaneous ignition is periodically initiated and effective gas mixture detonation combustion takes place (at the second stage). Annular (or linear dual slotted nozzles) with the internal deflector cavity in the form of a spherical (cylindrical) segment are considered as perspective for realization of pulsing, including the detonation, regime of fuels combustion [1-3]. Presence of a high-frequency pulsing flow mode in annular (or linear dual slotted) nozzle resonator is a necessary condition of 2-Stage fuels combustion technology realization. As shown in experiments [4-14], there are different regimes of gas flow in such nozzle devices. In the steady-state regime they belong to the class of nozzles with a central body [9-11, 14]. In unsteady periodic pulsed regimes such nozzles are high-frequency (tens of kHz) pulsed output devices [4, 6, 12-13]. The study of thrust force and pressure pulsation signals is topical for determination the dependence of pulsations spectral composition from geometric nozzles parameters and their flow conditions in order to manage the process frequency. Pulsation frequency management is of interest at similar nozzle devices application to regulate frequency process of pulsing mode combustion in 2-stage PDE.

The purpose of the work is to present spectra researches of thrust force and gas pressure pulsations signals in declared nozzles using complex numerical and experimental approach assuming computational parametrical researches and a number of experimental measurements. The paper presents the results of frequency dependences and oscillations amplitude of flow parameters in annular and linear dual slotted nozzles from their geometry and inlet (outlet) conditions.

2. Annular (Dual slotted) nozzle and experimental setup

Experiments with annular nozzles were conducted in a pulsed aerodynamic setup using the combustion products of acetylene-air mixture as working gas. Its detailed description was given in [4, 9]. The setup includes the reactor, the dispensing channel, the nozzle device and the receiver. The studied model was mounted on the adapter behind the bursting diaphragm separating the high pressure chamber of the setup – the reactor (with burned acetylene-air mixture) - from subsonic nozzle cavity. The nozzle device consists of an entrance annular nozzle with internal deflector and an outlet conic (plane) nozzle, presented on "Fig. 1".



(a) (b) (c)

Fig 1. The gas flow scheme in the nozzle - **(a):** 1 – a cylindrical (plane) channel; 2 – an annular (plane) flow, 3(1) - 3(2) – an annular (dual slotted) nozzle critical section (for a linear dual slotted nozzle numbers 3 (1) and 3 (2) correspond to each of two linear slots with length L, located perpendicularly to the drawing plane); 4 – a thrust wall; 5 – an exhaust conical (plane) nozzle; 6 – an exhaust jet. Designations - **(b):** R, H and d – are segment radius, height and base diameter correspondingly; h – an annular (linear dual slotted) nozzle throat height. Annular nozzle photo – **(c)**

The deflector represents a spherical segment. The reactor is connected with the nozzle device by annular dispensing channel. The reactor is separated from the dispensing channel by the segmented diaphragm. Just before carrying out an experiment, the reactor is filled with a combustible acetylene-air mixture, and air from the receiver is pumped out up to a fore vacuum pressure. The fuel mixture is ignited by the special electric igniter made from thin explosive wire. The pressure in the reactor increases due to combustion until the level when the bursting of the diaphragm takes place. As result, the combustion products flow into the subsonic dispensing channel in a form of cylinder with a diameter of 0.05 m (marked with number 1 on "Fig. 1 a"), which was located over the diaphragm. A conical fairing was on the axis of cylindrical channel downstream. It provided the annular flow formation (marked with number 2) at the annular nozzle entrance from the cylindrical stream coming out of the setup reactor. The outer and inner diameters of the annular channel were equal to 0.14 and 0.10 m respectively. Later in the smoothly narrowed annular channel the flow made a 90-degree turn in the direction of the axis and through the annular critical section with size of 0.0044 m parallel to the axis (designated by number 3) was blown radial in a semi-closed cavity of the annular nozzle formed by the deflector of a spherical segment form. For the linear dual-slotted nozzle case the flow was blown through each of two linear slots (numbers 3 (1) and 3 (2)) with length L, located perpendicularly of the drawing plane. In this case the deflector surface has a cylindrical segment form. Its segmental surface corresponded with the thrust wall which was indicated by number 4 on "Fig. 1 a".

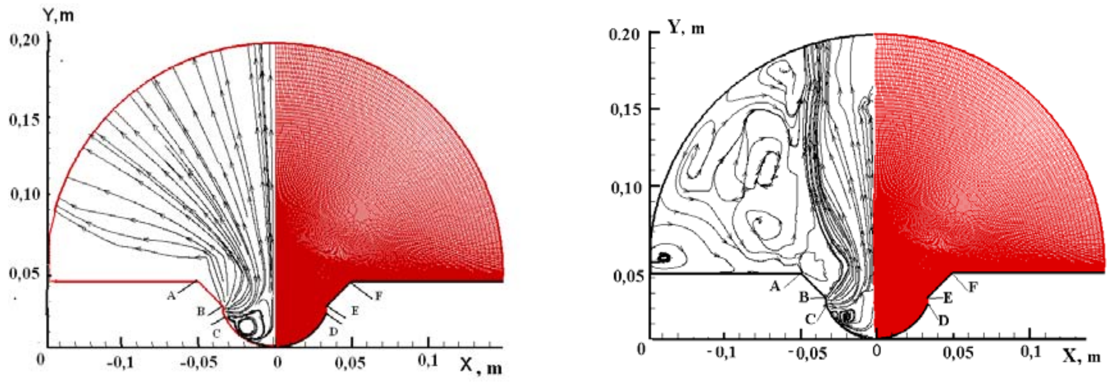
Designations of the nozzle segment characteristics and critical nozzle section used in presented paper are demonstrated on "Fig. 1 b". The basic variant geometrical sizes of annular nozzle model are as follows: $R = R_b = 0.036$ m; $H = H_b = 0.02213$ m; $d = d_b = 0.0664$ m; $h = h_b = 0.00044$ m.

The deflector is constructively designed as a piston having an axial freedom of movement. It is limited by elastic deformation of the sensitive element attached to the strain gauge force transducer that measures the thrust force developed by the nozzle model during the tests. The outflow gas through the exhaust conical nozzle (indicated with number 5) occurs in the pre-pumped receiver to the fore vacuum pressure. The direction of exhaust jet expiry flow in the receiver is indicated with number 6 on "Fig. 1 a". The blowing time in the investigated regimes is at least 0.05 s.

In course of the experiment process the changing signals were controlled with high-frequency piezoelectric and strain gauge pressure sensors installed at various points of the side wall in the flow channel. Besides measuring the pressure on the lateral reactor wall, pressure measurements were also taken on a wall of the dispensing channel and at the center of the deflector by means of piezoelectric sensors. The thrust developed by the nozzle was measured by a strain gauge force sensor. The thrust force is created by excess pressure from working gas upon the deflector. For its measurement, the deflector has been established on the force sensor. Signals from sensors were recorded by high-speed digital electronic oscilloscopes and in parallel by a less high-speed digital multichannel amplifier. The specified set of measured parameters allowed the measured pressure and thrusting values to compare with the corresponding calculated values.

3. Mathematical flow model and the method of calculation

The 2-D Navier-Stokes equations for multi component reactive gas medium were used to describe the gas flow [9, 11, 13]. It was assumed that the flow is laminar, axially (or plane) symmetric, the nozzle thrust surface is under a predetermined temperature and chemically neutral. At modelling of the gas flow it is supposed, that gas represents an one-temperature multi component mix of the perfect gases, internal degrees of gas components freedom are excited equilibrium with translation degrees of freedoms, gas flow is chemically nonequilibrium and ionization of gas and radiative transfer are not considered. The unsteady gas dynamics equations are solved numerically by the implicit finite volume method on a structured single-block grid. In calculations schemes of the second order accuracy on spatial coordinates and grids with detailed enough resolving of a boundary layer have been used. The calculations were performed on the grid with 200x186 nodes. The nodes were condensed near the surface thrust wall. The configuration and sizes of the computational domain exactly correspond to the flow region and parameters of an annular nozzle used in experimental setup. The computational domain boundaries and the computation mesh nodes distribution for the annular nozzle basic variant amplitude. Calculated and the measured dominant (satellite in round brackets) frequency of thrust force and pressure pulsation signals spectra are presented in two last columns of the "Table".
are shown on "Fig. 2" (right). Here (left) the stream lines received in calculations on quasi-stationary flow phase are demonstrated. The contour of the



(a) **(b)**

Fig 2. Computational domain and mesh (to the right of an axis of symmetry) and stream lines (to the left) for the basic annular nozzle. Stagnation pressure $P_0 = 1.984$ MPa. Opposite pressure $Pe = 0.001$ MPa **(a)** , 0.1 MPa **(b)**. The contour of a nozzle cross-section is shown by line (A-B-C-0-D-E-F), a deflector thrust wall - (C-0-D), a nozzle critical section - (B-C)/(E-D) and an exhaust nozzle - (B-A)/(E-F)

axial annular nozzle cross-section is given on "Fig. 2" by curve line (A-B-C-0-D-E-F) which separates parts corresponding to the deflector thrust wall - (C-0-D), to the nozzle critical section - (B-C)/(E-D) and exhaust conical nozzle - (B-A)/(E-F). The computational domain is bounded below by the thrust wall of the deflector - line (0-D), from the left, by the axis of symmetry of the nozzle device; from the right, successively, by the critical cross section of the annular nozzle - line (D-E), the wall of the conical exhaust nozzle - line (E-F), and the horizontal grid of the vacuum chamber; and, from above, by the coordinate line of the curves set. The configuration and sizes of the computational domain exactly correspond to the parameters of the experimental setup.

It is assumed that the insufflations of acetylene combustion products through the nozzle critical section occur with the sound speed at specified constant stagnation pressure P_0 and temperature T_0. The gaseous medium expiration in air from the device through the conical nozzle occurs with pressure $Pe = 0.001$ MPa and temperature $Te = 300^0$ K. "Soft" boundary conditions extrapolation are used to close the problem on the outer boundary. It was assumed that the surface of the thrust unit was cooled to a temperature $T_w = 300^0$ K. The gas parameters on the nozzle critical section were derived from the arbitrary discontinuity condition determined by breakdown problem; on the one hand, by the outflow conditions with the sound speed at given constant stagnation pressure P_0 and temperature $T_{0,}$ and, on the other hand, by the parameters of gas in the cells adjacent to the nozzle. The computational spectral composition of quasi-periodic pulsating thrust force and pressure signals in the annular (linear dual slotted) nozzles were obtained by usage of the discrete Fourier transform.

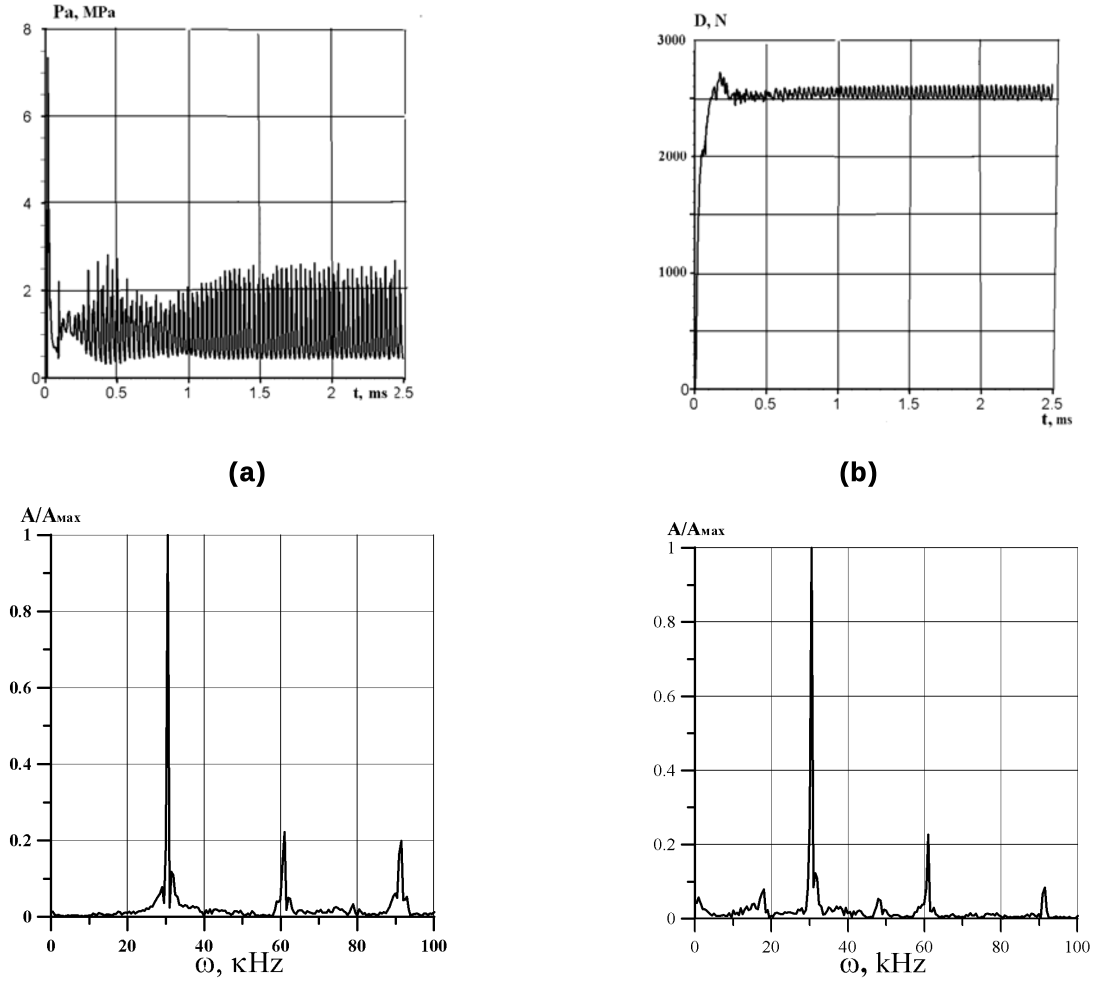
4. Main results of calculations and experiments

Varied conditions at the nozzle inlet and outlet and different sizes of the nozzle device were used in the calculations. Variants 1.1-1.5 for annular (1.7-1.8 for dual slotted) nozzles are noted in "Table". The parameters for the variant 1.1 were considered as basic (on the geometrical sizes); they correspond to the experiment conditions – variant 1.6. The start-up of the device initially filled with stationary air with pressure Pe and room temperature Te suddenly led to the generation of intense non-stationary gas dynamic processes and to significant pressure increase. In all calculation variants the starting perturbation caused the appearance of undamped quasi periodic pulsations with different frequency and amplitude. Calculated and the measured dominant (satellite in round brackets) frequency of thrust force and pressure pulsation signals spectra are presented in two last columns of the "Table". On "Fig. 3-4" below one can see: p_a *(t)* - the pressure in the center of the thrust wall (a), *D(t)* – thrust force (b) as well as spectra of pressure - p_a *(t)* (c) and thrust force - *D(t)* - (d) pulsations obtained by method discrete Fourier transform (DFT) on a time interval of 0.5 - 2.5 ms.

Table. Annular and dual slotted linear nozzles

Variant	P_0, MPa	T_0, K	*Pe*, MPa	R, m	H, m	d/L, m	h, m	Fp, kHz	F_D, kHz
1.1	1.984	2991	0.001	0.036	0.02213	0.0664	0.0044	30 (60;90)	30 (60;90)
1.2	1.984	2991	0.001	0.072	0.04426	0.1328	0.0088	15 (-)	15 (7;23)
1.3	1.984	2991	0.001	0.1107	0.02213	0.1328	0.0044	7 (22)	7 (22)
1.4	1.984	2991	0.10	0.036	0.02213	0.0664	0.0044	30 (60;90)	30 (60;90)
1.5	0.978	2991	0.001	0.036	0.02213	0.0664	0.0044	30 (60;90)	30 (60)
1.6	1.948	2991	0.001	0.036	0.02213	0.0664	0.0044	22 (44)	-
1.7	1.984	2991	0.001	0.036	0.02213	0.1042	0.0044	25 (50;41)	25 (50;41)
1.8	1.984	2991	0.10	0.036	0.02213	0.1042	0.0044	25 (32;39)	25 (7;13)

For the basic variant 1.1approximately with 1 ms, the quasi-periodic regime was set for the pressure in the thrust wall central point with the main dominant frequency equal *Fp* = 30 kHz ("Fig. 3 c").



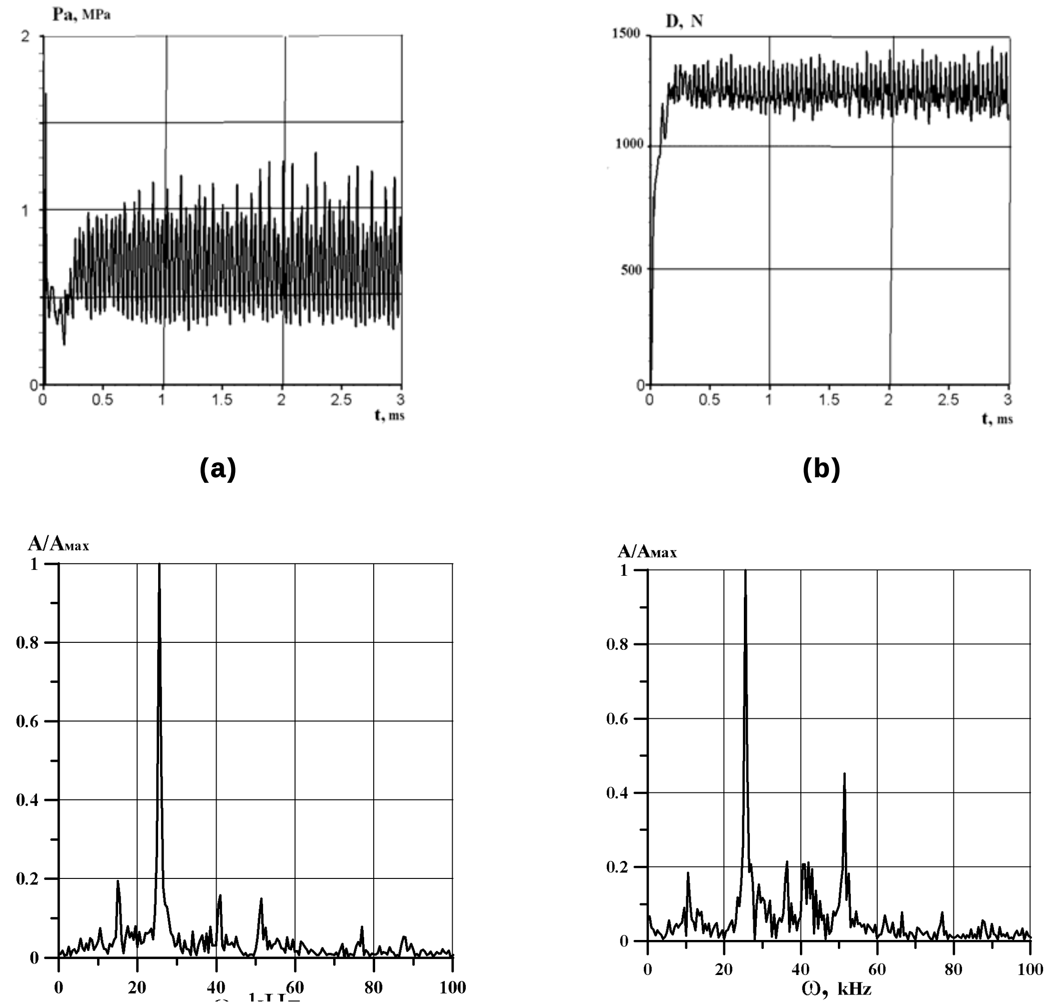
(a) **(b)**

(c) **(d)**

Fig 3. Calculation data for basic variant 1.1 of annular nozzle: $R = R_b = 0.036$ m; $H = H_b = 0.02213$ m; $d = d_b = 0.0664$ m; $h = h_b = 0.0044$ m. Stagnation pressure $P_0 = 1.984$ MPa. Opposite pressure $Pe = 0.001$ MPa. **(a)** - pressure p_a *(t)* in the center of the thrust wall, **(b)** - thrust force - *D(t)*, **(c)** - spectra p_a *(t)*, **(d)** – spectra *D(t)*

There are emissions at frequencies of 60 and 90 kHz (they are given in parentheses in *Fp* column of the "Table") in addition to the dominant frequency in the pulsations spectrum. The pressure changed approximately from 0.5 to 2.5 MPa, the thrust force - from 2500 to 2600 N.

In variant 1.7 from "Table" was considered linear dual slotted nozzle equivalent under the form and the geometrical sizes of nozzle cross-section, gas flow rate, a magnitude of the critical section area and the conditions at the input and output with the annular nozzle in the basic variant 1.1: $R = R_b = 0.036$ m; $H = H_b = 0.02213$ m; $h = h_b = 0.0044$ m; $L = 0.1042$ m. The results are presented on "Fig. 4". Qualitatively, the results for the linear dual slotted and corresponding annular nozzles are the same, but there are some quantitative differences. The pressure on the thrust wall varies approximately from 0.4 to 1.2 MPa that is lower than for the annular nozzle. Accordingly, the thrust is lower too. The dominant frequency in the spectrum of p_a (*t*) and *D(t)* corresponded to value ≈ 25 kHz.



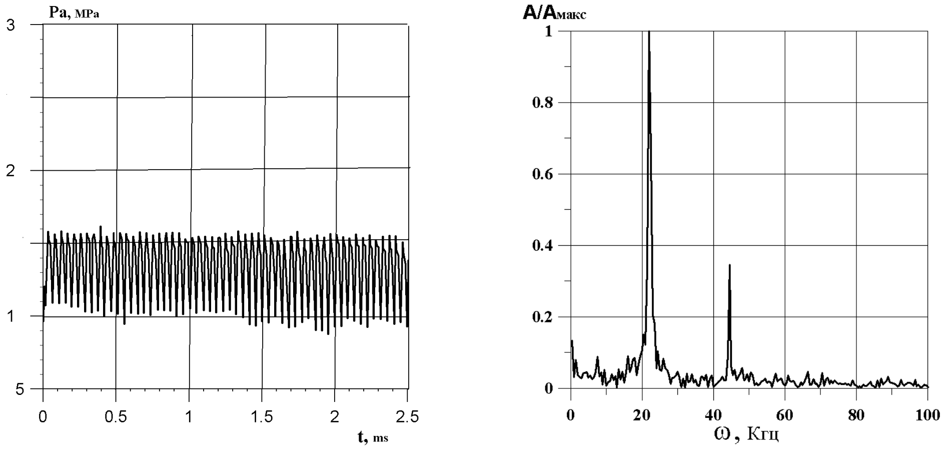
(a) **(b)**

(c) **(d)**

Fig 4. Calculation data for basic on the geometrical sizes variant 1.7 of linear dual slotted nozzle. Stagnation pressure $P_0 = 1.984$ MPa. Opposite pressure $Pe = 0.001$ Mpa. **(a)** - pressure p_a *(t)* in the center of the thrust wall, **(b)** - thrust force - *D(t),* **(c)** - spectra p_a *(t),* **(d)** – spectra *D(t)*

The results of experimental pressure measurements and spectrum of $p_a(t)$ for the basic variant of the annular nozzle (variant 1.6) are presented on "Fig. 5". They demonstrate a qualitative agreement with the calculation results on "Fig. 3". In both cases, the main dominant and additional frequencies – satellites, the main frequency multiples, are present in spectra of $p_a(t)$. The quantitative differences are observed in the main dominant frequency $Fp = 22$ kHz values measured in the experiment with one satellite frequency on a multiple frequency of 44 kHz, and from the calculated main dominant frequency Fp = 30 kHz with two satellites on multiple frequencies in the 60 and 90 kHz respectively. It should be noted that the main dominant frequency is easily determined by the calculation of the peaks repetition period in the signal $p_a\ (t)$ without using the DFT method.

Variant 1.2 from "Table" differs from the basic case (variant 1.1) as all sizes are doubled: $R = 2R_b = 0.0720$ m; $H = 2H_b = 0.04426$ m; $d = 2d_b = 0.1328$ m; $h = 2h_b = 0.0088$ m. The analysis shows that this modification leads to some increase in time for an output on quasi-periodic mode and the change in pressure and thrust mean values within the considered time interval. As in the basic case, there is a dominant oscillation frequency equal to 15 kHz, which is twice less than the main frequency for the basic case.



(a) **(b)**

Fig 5. Experimental results for basic variant 1.1 of the annular nozzle. Stagnation pressure $P_0 = 1.984$ MPa. Opposite pressure $Pe = 0.001$ MPa. **(a)** - pressure $p_a\ (t)$ in the center of the thrust wall, **(b)** - spectra $p_a(t)$

Variant 1.3 is different from the basic one by the annular nozzle configuration: basic diameter is increased twice at constant altitude of the spherical segment and critical section: $R = 3{,}075R_b = 0.1107$ m; $H = H_b = 0.02213$ m; $d = 2d_b = 0.1328$ m; $h = h_b = 0.0044$ m. As seen, the magnitude of the pressure fluctuations varies. The oscillation dominant frequency is reduced to 7 kHz. The pressure changes approximately within the range of 0.5 to 1.5 MPa, the thrust force - from 5000 to 5400 N. The emissions values in pressure spectrum (two to three times above average) are observed rarely.

In variant 1.4 the gas flow from the base annular nozzle occurs in the air at atmospheric pressure. The opposite pressure increase leads to a sharp increase of initial perturbation (up to 100 MPa). Dominant frequencies 30 (main), 60 and 90 (satellites) kHz remain in a quasi periodic mode in the spectrum of $p_a\ (t)$. It leads to the oscillation amplitude increase in the range of few kilohertz. The pressure fluctuations interval in this time period changes approximately from 0.7 – 1.2 MPa to 0.5 - 3 MPa. The thrust force after 1,5 ms is established at a level approximately 2200 N.

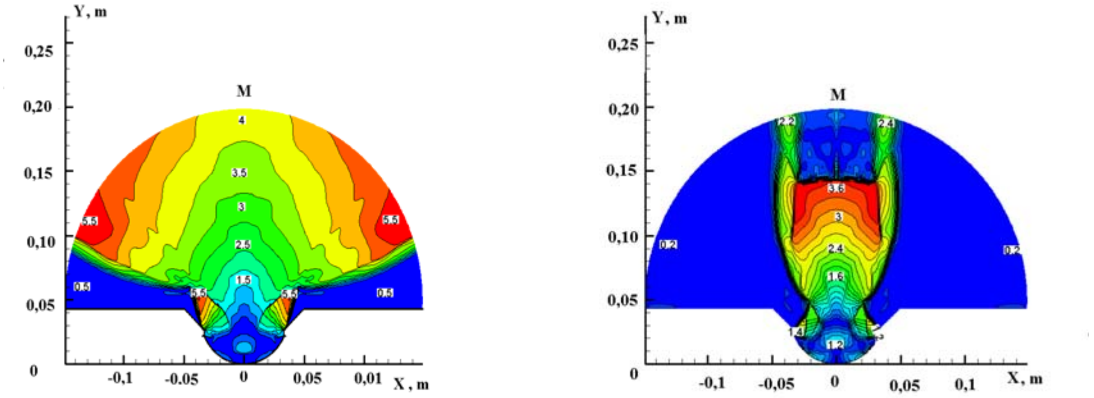
In variant 1.5 the stagnation pressure on the input of the annular base nozzle is reduced twice compared to the basic variant. The pressure also decreases in about two times and changes approximately from 0.2 – 1.5 MPa, the thrust force - from 1200 to 1300 N. The main frequencies in the spectrum of $p_a\ (t)$ are practically unchanged.

In variant 1.8 linear dual slotted nozzle was considered with equivalent under the form and the geometrical sizes of nozzle cross-section, gas flow rate, the critical section area size and the input conditions with the annular nozzle in the basic variant 1.1. But in variant 2.2 the gas flow from the nozzle occurs in the air at atmospheric pressure. Variant 1.8 for linear dual slotted nozzle corresponds to the variant 1.4 for the base annular nozzle. In this case pressure changes approximately from 0.5 to 1 MPa, and the spectrum of $p_a\ (t)$ has one dominant frequency equal 24 kHz. The thrust force after 1,5 ms is established at a level approximately 1100 N.

The analysis of spectra has shown also, that in a spectrum of thrust force pulsations besides satellites on frequencies multiple to dominant frequency additional emissions of smaller amplitude on frequencies not multiple the basic frequency were observed. Presence of additional frequencies in a spectrum of thrust force pulsations is caused by integrated character of a total signal of thrust force, defined not only a kind of pressure signal in the center of thrust wall *Pa (t),* but also changes of pressure on other sites of its surface. Therefore the spectrum of thrust force pulsations had more complex appearance.

The presented results allow revealing the parameters defining the spectrum of thrust force and gas pressure pulsation signals in the center of the nozzle thrust wall. There are parameters defining the geometrical form of internal half-closed nozzle cavity - spherical segment: diameter of its basis, height and radius and the height of nozzle critical section. The main specified parameters characterize the nozzle configuration features. As seen from "Table", it is possible to operate the spectrum of gas pressure and thrust pulsations signals by means of their changes: for dominating frequency in the spectrum within the limits of from 7 up to 30 kHz, practically irrespective of opposite pressure in the expiration space (the height of flight) and stagnation pressure.

During numerical modeling the quasi-stationary 2-D isolines pictures of flow parameters in calculated area have been received. So in variants 1.1 and 1.4 for the base annular nozzle on the pulsing period phase of pressure growth the flow picture with the streamlines is shown on "Fig. 2 a, 2 b" (left). It is visible, that the recirculation flow zone in the internal cavity of the annular nozzle - area (C-0-D) has the form of torus vortex, and the gas flowing through annular nozzle critical section (B-C)/(E-D) flows around recirculation zone - a gas central body of the annular nozzle, is turned and expires in surrounding space in the form of axial-symmetric jet. Depending on the opposite pressure in the expiration space the jet thermo and gas dynamic parameters change. As an example, 2-D fields of Mach number M isolines are presented in jets behind the nozzle exit section of the basic annular nozzle out flowing in high-altitude conditions (for *Pe* = 0.001 MPa on "Fig. 6 a" for variant 1.1) and ground conditions (for *Pe* = 0.1 MPa on "Fig. 6 b" for variant 1.4).



(a) **(b)**

Fig 6. Quasi-steady state 2-D pictures of Mach number M isolines in a meridian plane of base annular nozzle for the case calculations variant 1.1: **(a)** - stagnation pressure *Po* = 1.984 MPa, opposite pressure *Pe* = 0.001 MPa, **(b)** - stagnation pressure *P0* = 1.984 MPa, opposite pressure *Pe* = 0.1 MPa

2-D flow fields of a stream Mach number M on "Fig. 6" evidently show remarkable property declared nozzle - auto adjustability or change of the form of a jet depending on height of flight (conditions in space of the expiration), inherent to nozzles with the central body. It is visible that with the opposite pressure increase appreciable expansion of the jet (presented on "Fig. 6 a") is decreased and it also gets specific structure of a "barrel" (on "Fig. 6 b") with the advent of Mach disk on distance of several calibers from the exit section of the nozzle.

With the further time increase on an interval of the pulsations period counted from the moment of the minimal pressure attained on the trust wall, the pulsations amplitude reaches a maximum for the period and there is the flow reorganization and the pressure falls up to a minimum. After that the process repeats.

5. Conclusion

Complex of computational parametrical researches and certain experimental measurements of flow pulsation parameters in the annular and linear dual slotted nozzles were performed. For the basic configuration of the annular nozzle the main dominant spectrum frequency - 22 kHz qualitatively confirmed by calculations (30 kHz) was experimentally established. The spectrum of thrust force pulsations had more complex appearance in comparison with a spectrum of pressure pulsations in the center of a thrust wall. The numerical research of frequency dependence and oscillation amplitude of flow parameters in these nozzles showed that the management of the main dominant frequency of pressure and thrust force pulsations can be most effectively carried out both by proportional increase of the nozzle size (the frequency decreases proportionally) and also by changing the critical section size and the deflector height regardless to the opposite pressure in the outflow space (the flight altitude). The application of these adjustments helps to demonstrate the variation possibility of the main dominant pressure pulsation in the studied nozzles in the range of 7 to 30 kHz. The existence of quasi-periodic plane symmetric pulsating regimes of laminar gas flow in the linear dual slotted nozzles has been predicted in calculations. The dominant pulsation frequency of thrust force and pressure - 25 kHz for such nozzle has been determined.

6. Acknowlegment

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