Spectra Signals of Gas Pressure Pulsations in Nozzles

Vladimir A.Levin[1] Nataliya E.Afonina[1], Valeriy G.Gromov[1], Ivan S.Manuylovich[1], Aleksander N.Khmelevsky[1], Vladimir V.Markov[2]
[1]Institute of mechanics of the Moscow State University, 119192, Moscow, Russia
[2]V.A.Steklov Mathematical Institute, RAS, 119991, Moscow, Russia

1 Introduction

Annular and dual slotted linear nozzles with the internal deflector are considered as perspective for realization a pulsing, including the detonation regime of fuels combustion [1]. The study of pressure pulsation signals are topical to determination the dependence the spectral composition of pulsations from geometric nozzles parameters and the flow conditions in them in order to govern by frequency of a process. Also of interest is clarification the degree of influence of gas pressure pulsations in the flow on the thrust characteristics of these nozzles. The paper presents the results of computational and experimental study of dependences of frequency and oscillations amplitude of flow parameters in annular and dual slotted linear nozzles from the conditions at the inlet and the outlet of the nozzle and its geometry. Experiments with annular nozzles were conducted in a pulsed aerodynamic setup using as the working gas the combustion products of acetylene-air mixture. Calculations were made on the basis of the Navier-Stokes equations for multicomponent reactive gaseous medium using a single-temperature chemical nonequilibrium model including all main products of the combustion of a stoichiometric mixture of acetylene in air. As a result of investigation the dependences frequencies and oscillations amplitudes of the flow parameters in annular and equivalent gas flow dual slotted linear nozzles from the governing parameters were established. We dealt with different pressures at the inlet and exit of nozzles, different sizes of the critical cross-section and different diameters of the annular nozzle. Presented the comparison results of computational and measured spectral composition of quasi-periodic pulsating signal of pressure on the thrust wall of the annular nozzle obtained by the discrete Fourier transform on the time interval 0.5 to 2.5 ms. The calculation predicted the existence of quasi-periodic pulsating regimes of gas flow in a dual slotted linear nozzle and defined the spectral composition of pressure pulsations on the thrust wall and the thrust force developed by the such nozzle.

2 The gas-phase Model and the Method of Calculation

To describe the gas flow were used the Navier-Stokes equations for multi component reactive gas medium. It was assumed that the nozzle thrust surface is chemically neutral, has a predetermined

Correspondence to: gromov@imec.msu.ru

temperature and that flow is laminar. Numerical solution of equations obtained by the finite volume method on structured curvilinear grid, the cells are built by the intersection of two sets of discrete curves. Detailed description of the gas-phase model and the calculating methods was given in [2].

The calculations were performed for the flow region, including:

- deflector;
- dual slotted linear or annular nozzle with critical cross-section height *h;*
- exhaust conical nozzle with a half-angle 45º and a length of 15 mm;
- sufficiently large area of expansion .

Thrust wall deflector of annular nozzle has the shape of a spherical segment of radius R, height H and base diameter d. Thrust wall deflector of dual slotted linear nozzle has the shape of a cylindrical segment of radius R, height H and length L. Nozzle length L is chosen so that the area of the critical section of the nozzle coincides with the area of the critical section of the respective annular nozzle.

The calculations are performed on the grid with number of nodes 200x186.The nodes were condensed near the surface thrust wall. The computational domain boundaries and the nodes distribution of computation mesh for the base case of the model nozzle shown in Figure 1.

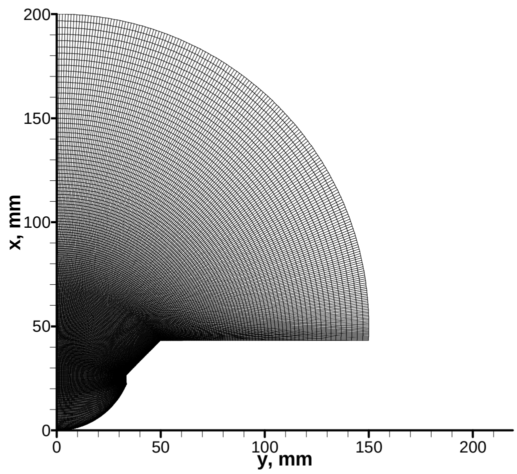


Figure 1

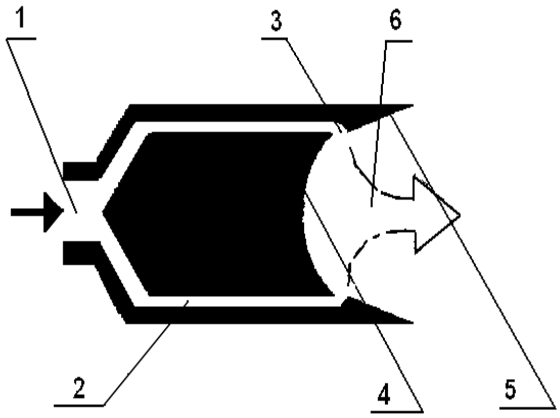


Figure 2

It was assumed that the insufflation of the acetylene combustion products through the critical section of the nozzle occurs with the sound speed *Us* at specified constant pressure and temperature of stagnation P_0 and T_0. The expiration from the device through a conical nozzle occurs in air gaseous medium with pressure *Pe* and temperature *Te*=300 K. In the calculations were varied conditions at the inlet and outlet of the nozzle and the size of the device.

3 An annular Nozzle and Aerodynamic Installation

Experimental researches of model of the annular nozzle, schematically represented in Figure 2, were performed in a pulsed aerodynamic setup. Its detailed description was given in [3, 4]. The investigated model was mounted in the setup on the adapter behind the bursting diaphragm, separating the high pressure chamber of setup - reactor (with burned acetylene-air mixture) from subsonic nozzle cavity. The subsonic cavity produced immediately behind the diaphragm a cylindrical channel with a diameter of

50 mm, marked with 1 in Figure 2, via which gas was supplied. A conical fairing was on the axis of cylindrical channel downstream. It provided the formation the annular flow, marked with 2 in Figure 2, at the entrance of the annular nozzle from the cylindrical stream coming out of the reactor setup. The outer and inner diameters of the annular channel were equal 140 and 100 mm respectively.

Then 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 4.4 mm parallel to the axis (designated by numeral 3 in Figure 2) was blown radial in a semi-closed cavity of the annular nozzle formed by the deflector in the form of a spherical segment. Its inner surface corresponded the thrust wall, was indicated by numeral 4 in Figure 2 and structurally designed as a piston having an axial freedom of movement. It was limited by the elastic deformation of a sensitive element attached to a strain gauge force transducer that measures the thrust force developed by the nozzle model during the tests. The increasing of pressure in the reactor resulted in rupture of the diaphragm and the inflow of combustion products in the inlet channel through which the gas was supplied to the entrance of the annular nozzle. Through the exhaust conical nozzle, indicated by numeral 5 in Figure 2, the outflow gas was occurred in the receiver pre-pumped to the forevacuum pressure. The direction of the expiry of the exhaust jet in the receiver was indicated number 6 in Figure 2. In the investigated regimes the blowing time was at least 50 ms.

In the process the experiment the changing of signals was controlled with high-frequency piezoelectric and strain gauge pressure sensors installed on the side wall at various points in a flow channel. The thrust, developed by the nozzle, was measured by a strain gauge force sensor. Signals were recorded by the oscilloscope. The specified set of measured parameters allowed to spend comparison of measured values of pressure and thrust with the corresponding calculated values.

4 Results of Calculations and Experiments

In the calculations were varied conditions at the inlet and outlet of the nozzle and the sizes of the device. Variants considered are shown in Tables 1 and 2. The parameters for the variant 1.1 were considered as basic, they correspond to the experiment conditions. The start-up of the device, initially filled with stationary air with pressure *Pe*, temperature *Te*, occurred suddenly that led to the generation of intense non-stationary gas dynamic processes and a significant increase in pressure. In all variants of calculation the starting perturbation caused the appearance of undamped quasiperiodic pulsations with different frequency and amplitude.

Table 1: Annular nozzle

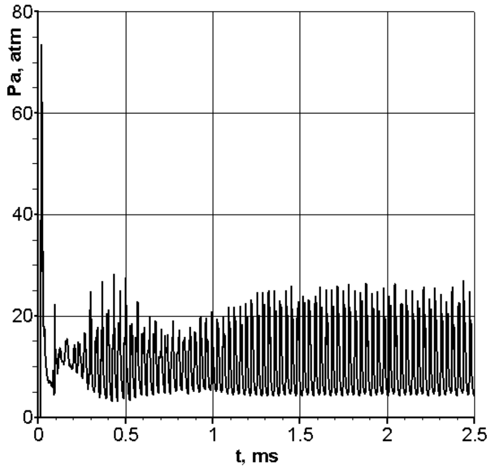
Variant	P_0, atm	T_0, K	*Pe,* atm	*R, mm*	*H, mm*	*d, mm*	*h,mm*	*Fp,* kHz
1.1	19.84	2991	0.01	36.0	22.13	66.4	4.4	30 (60;90)
1.2	19.84	2991	0.01	72.0	44.26	132.8	8.8	15 (-)
1.3	19.84	2991	0.01	110.7	22.13	132.8	4.4	7 (22)
1.4	19.84	2991	1.0	36.0	22.13	66.4	4.4	30 (60;90)
1.5	9.78	2991	0.01	36.0	22.13	66.4	4.4	30 (60;90)

Table 2: Dual slotted linear nozzle

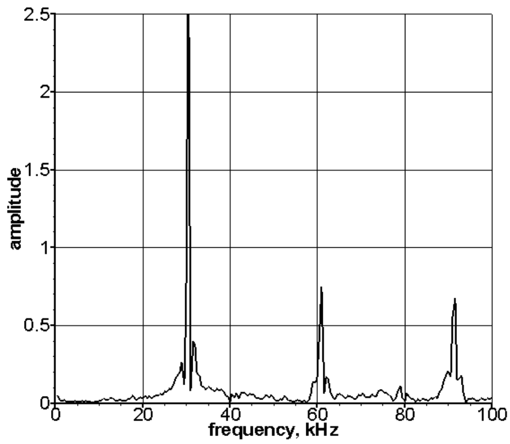
Variant	P_0, atm	T_0, K	*Pe,* atm	*R, mm*	*H,mm*	*L, mm*	*h, mm*	*Fp,* kHz
2.1	19.84	2991	0.01	36.0	22.13	104.2	4.4	≈ 25 (-)
2.2	19.84	2991	1.0	36.0	22.13	104.2	4.4	24 (<2)

For each variants were calculated the following parameters, partially shown in the figures 3-5 below: $p_a\ (t)$ - the pressure in the center of the thrust walls (a), *D (t)* - thrust, as well as spectra of pressure fluctuations

$p_a\ (t)$ (b) and thrust $D\ (t)$, obtained by method discrete Fourier transform (DFT) on a time interval of 0.5 - 2.5 ms. In Figure 3 were shown the calculation results for the basic variants case 1.1.



(a) $p_a(t)$

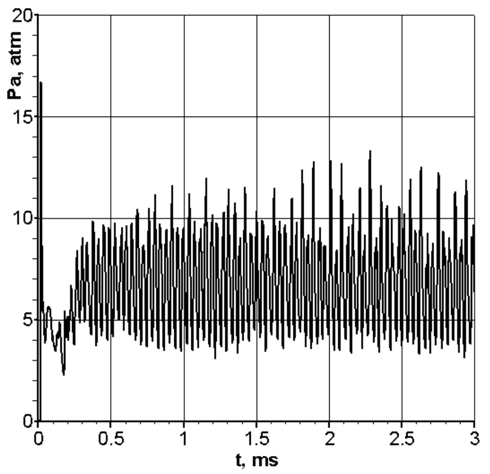


(b) Spectrum $p_a(t)$

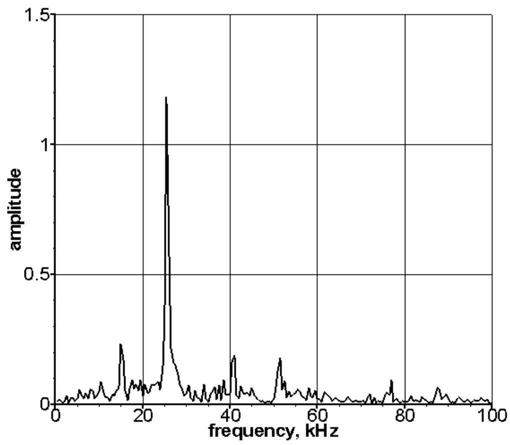
Figure 3. Calculation data for variant 1.1

Under these conditions, starting approximately with 1 ms, the quasi-periodic regime was set as for the pressure in the central point of thrust wall and for thrust in general with the main dominant frequency equal Fp = 30 kHz. In addition to this frequency in the spectrum of the pulsations there are emissions at frequencies of 60 and 90 kHz (they are given in parentheses in the Fp column of tables). Pressure changed from 5 to 25 atm, thrust – 2500 – 2600 N.

In variant 2.1 we considered dual slotted linear nozzle, equivalent under gas consumption, the magnitude of the critical section area and the conditions at the inlet and outlet with the annular nozzle in the basic variant 1.1. The calculation results for the variant 2.1 was shown in Figure 4.



(a) $p_a(t)$

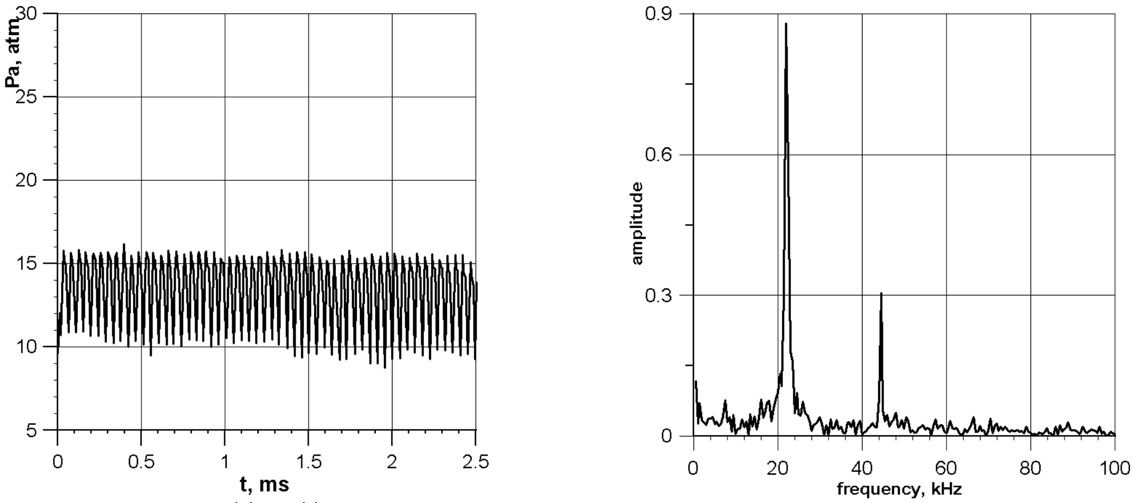


(b) Spectrum $p_a(t)$

Figure 4. Calculation data for variant 2.1

Qualitatively, the results for the dual slotted linear and corresponding annular nozzles were the same, but there were some quantitative differences. Pressure on the thrust wall varied from 8 to 12 atm that was lower than for the annular nozzle. Accordingly, the thrust was lower at an equal area of the output section. The dominant frequency in the spectrum of p_a *(t)* corresponded to value ≈ 25 kHz.

The results of experimental pressure measurements and spectrum of p_a (*t)* for the base variant of the annular nozzle were presented in Figure 5. They demonstrate a qualitative agreement with the calculations in Figure 3.



(a) $p_a(t)$ (b) Spectrum $p_a(t)$

Figure 5. The experimental data for the flow conditions in the base variant 1.1.

In both cases, in spectra of p_a *(t)* was presented the main dominant and additional frequencies - satellites, multiples of the main. The quantitative differences were observed in the values of the main dominant frequency *Fp* = 22 kHz, measured in the experiment with one satellite on a multiple frequency of 44 kHz, 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 repetition period of the peaks in the signal p_a *(t)* without using the DFT method.

Variant 1.2 differed from the basic case in that all sizes are doubled. The analysis shown that this modification leads to some increase in time of an output on quasi-periodic mode and the changed in mean values of pressure and thrust on the considered time interval. As in the basic case, there was a dominant oscillation frequency equal to 15 kHz, as for pressure so for thrust force, which twice less than the main frequency for basic case.

Variant 1.3 differed from the basic by configuration of the thrust module. The diameter of the annular nozzle was increased twice at constant altitude of a spherical segment. As shown by the analysis, the nature of the pressure fluctuations and thrust varied. The dominant frequency of oscillation was reduced to 7 kHz. The pressure changes in the range of 5 to 15 atm the thrust 4900 - 5400 N. Rarely were observed the emissions values in pressure spectrum, two to three times above average.

In variant 1.4 gas flow from the annular nozzle occurs in air at atmospheric pressure. The increase of the backpressure leads to a sharp increase of the initial perturbation (up to 1000 atm). In a quasi periodic mode in the spectrum of p_a *(t)* remained dominant frequencies 30 (main), 60 and 90 kHz. It increased the oscillation amplitude in the range of a few kilohertz. The pressure fluctuations interval in the considered time range changed from 7 – 12 atm to 5 – 30 atm. In the spectrum of *D(t)* on oscillations with frequencies up to 10 kHz are imposed oscillations of relatively small amplitude with a frequency of 30 kHz. The average value of the thrust force was equal ≈ 2200 N, which was slightly lower than in the basic case.

In variant 1.5 the total inlet pressure in the annular nozzle was reduced twice compared to the basic variant. The pressure and the thrust were also decreased about twice times. The main frequencies in the spectrum of $p_a(t)$ and *D(t)* practically unchanged.

Variant 2.2 for dual slotted linear nozzle corresponded to the variant 1.4 for the annular nozzle. The comparison showed that there was not only quantitative but also qualitative difference between the results of the calculations for these options. Pressure changed from 5 to 10 atm, the thrust value fluctuated around the level of 1000 N. The spectrum of $p_a(t)$ has one dominant frequency of 24 kHz. In the spectrum of *D(t)* in addition to this frequency there were emissions at frequencies 10 and 13 kHz.

Conclusions

Numerical and experimental study of spectrum signals of pressure pulsations on thrust wall in the annular and dual slotted linear nozzles were performed. For the basic configuration of the annular nozzle was experimentally established the main dominant spectrum frequency (22 kHz), qualitatively confirmed by calculations (30 kHz). The numerical research of dependence of frequency and oscillation amplitude of flow parameters in these nozzles showed that the management of the main dominant frequency can most effectively be carried out as due to of a proportional increase in nozzle scale (frequency decreases proportionally), and the size of critical section and height of the deflector, regardless of flight altitude – backpressure in the space of outflow. Usage these adjustments helped to demonstrate the variation ability the main dominant pressure pulsation in the studied nozzles in the range of 7 to 30 kHz. In calculations first were predicted the existence quasi-periodic pulsating regimes of laminar gas flow in dual slotted linear nozzles and was established the dominant pulsation frequency (≈ 25 kHz) of pressure on the nozzle thrust wall.

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