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Experimental investigation of acoustic self-oscillation influence on decay process for underexpanded supersonic jet in submerged space

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Intensification of mixing between the gaseous working body ejected through a jet nozzle with ambient medium is an important scientific and technical problem. Effective mixing can increase the total efficiency of power and propulsion apparatuses. The promising approach, although poorly studied, is generation of acoustic self-oscillation inside the jet nozzle: this impact might enhance the decay of a supersonic jet and improve the mixing parameters. The paper presents peculiar properties of acoustic self-excitation in jet nozzle. The paper presents results of experimental study performed for a model injector with a set of plates placed into the flow channel, enabling the excitation of acoustic self-oscillations. The study reveals the regularity of under-expanded supersonic jet decay in submerged space for different flow modes. Experimental data support the efficiency of using the jet nozzle with acoustic self-oscillation in application to the systems of gas fuel supply. Experimental results can be used for designing new power apparatuses for aviation and space industry and for process plants.

Keywords: mixing layer, jet nozzle, acoustic self-oscillations, spectral characteristics, shock wave structures.

Introduction

Development of aviation and space industry is driven by designing innovative power setups and propulsion engines. One field for this development is designing the ramjets for propulsion of vehicles flying at high supersonic and hypersonic speeds [1]. The efficiency of working process is important feature for ramjet efficiency, and it is based on complete combustion of the fuel mixture inside the combustion chamber (CC).

Simulation and experimental data [2, 3] demonstrate that completeness of fuel combustion can be achieved if the fuel is fed into the combustion chamber in gaseous state. The liquid fuel gasification (kerosene, ethanol, etc.) can be performed within the channels of regeneration cooling chamber [4]. As for gasification of solid fuel [5], it is performed in a gas generator through solid decomposition and pre-combustion [6]. A special interest was paid to using gaseous hydrogen [7, 8], which is stored aboard under high pressure (above 70 MPa). Note that traditionally the feeding of gaseous fuel to the CC (for most known designs of ramjet) is carried out via concurrent jet nozzles, where supercritical pressure drop takes place.

Because of mass and size restrictions to ramjet components, the engineers want to have short CC inside the ramjet. Under this restriction, the high completeness of fuel mixture combustion might be achieved through intensive mixing of gaseous fuel with input air inside the CC [9]. Therefore, intensification of gas-air mixing is an important technical and scientific

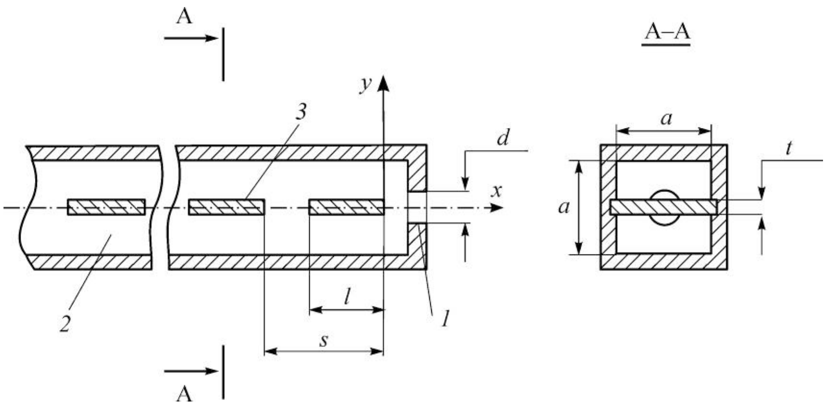

Fig. 1. Design of model injector.
1 — nozzle, *2* — cavity, *3* — plates.

problem. One of possible approaches to the problem solution is generation of acoustic-vortex self-oscillations within the jet nozzles: oscillations facilitate the decay of supersonic jet and improve the parameters of air-gas mixing [10].

The promising approach to the excitation of acoustic self-oscillations in model injector (Fig. 1) is arranging (before the nozzle *1* with diameter *d*) a cavity with cross section 2 and height *a*. This cavity comprises *N* periodic (placed with the pitch *s*) plates *3*: the plates have the thickness of *t* and the length of *l* [10].

The purpose of this research is experimental proof of efficiency of jet nozzles with generation of acoustic self-oscillations. We also study the law of decay of underexpanded supersonic jet in submerged space.

Experimental setup description

Research was performed for a model injector (MI) with the photo presented in Fig. 2. The MI comprises a casing *1*, inlet channel *2*, cavity *3* with a periodic set of plates *4* and the lid *5*. The lid *5* has a centered cylindrical nozzle 6. The relative sizes and positions of plates within the cavity were selected after preliminary computations [10]. The model design has the following proportions: $d/a = 0.5–0.7$, $l/a = 1.25$, $s/a = 1.45$. The relative thickness of plates inside the nozzle cavity was $t/a = 0.75$, while the total number of plates was $N = 6$.

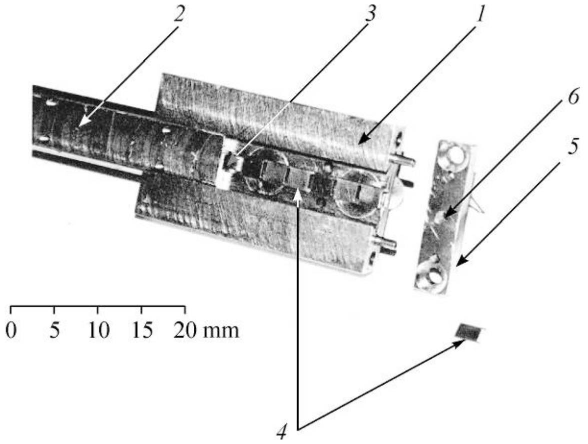

Fig. 2. Photo of model injector (MI): in disassembled view
1 — case, *2* — inlet channel, *3* — cavity,
4 — periodic plates, *5* — end plate, *6* — nozzle.

Experimental research was conducted at the setup with a diagram shown in Fig. 3. The working medium was air. The setup includes the high-pressure ramp *1* with the closure fitting and pressure safety lines, pressure reducer *2* equipped with command reducer *3*, the model of injector 5. The air input line before the nozzle has the pressure sensor *4*: the pressure data are collected with the data acquisition unit *12* and computer for data storage and processing *13*. The nozzle chamber is equipped with a pressure pulsation sensor *6* which feeds the signal through amplifier *7* to signal analyzer *8*. The system of flow visualization comprises the illumination part *9* and receiver part *10* of the shadow device IAB-451 as well as video signal recorder *11*.

This setup services flow experiments: the shadow method records the flow structure generated by the air jet; while the sensors measure the amplitude and pulsation of pressure in the cavity of the jet nozzle. An analysis of experimental data, which is presented in the following, gives the conclusion on the effect of amplitude and frequency of oscillations excited within the cavity on the efficiency of mixing of a supersonic jet with atmospheric air.

Experimental results and analysis of obtained data

The process of jet flow (Fig. 4) under the mode of underexpanded main stream *1* has specific features: the shock wave structure (SWS) is formed downstream the nozzle edge, and these features have been described in detail in [11–14]. The gas expansion downstream the nozzle exit occurs in the axis-centered rarefaction wave *3*, which interacts with the jet free boundary *4* and generates a compression wave *5*. The jet boundary has the tendency of bending to the jet axis. The compression waves form a hanging shock wave *6*. The shock wave reflection from the axis jet creates a Mach disk *7*. The gas flow behind the reflected shock has, as usually, a supersonic velocity, while the velocity behind the direct shock is subsonic. The reflected shock *8* interacts with the jet boundary and rebounds as a set of rarefaction waves. This complicated pattern of flow interactions facilitates the formation of a secondary barrel-type structure (but with lower intensity). Therefore, this flow occurs as a series of repeating (and attenuating with the distance from the nozzle exit) SWS. Ultimately, this creates zone *9*, where the turbulent mixing takes place [12, 14]: this mode of mixing is typical of a flow with low pressure gradients.

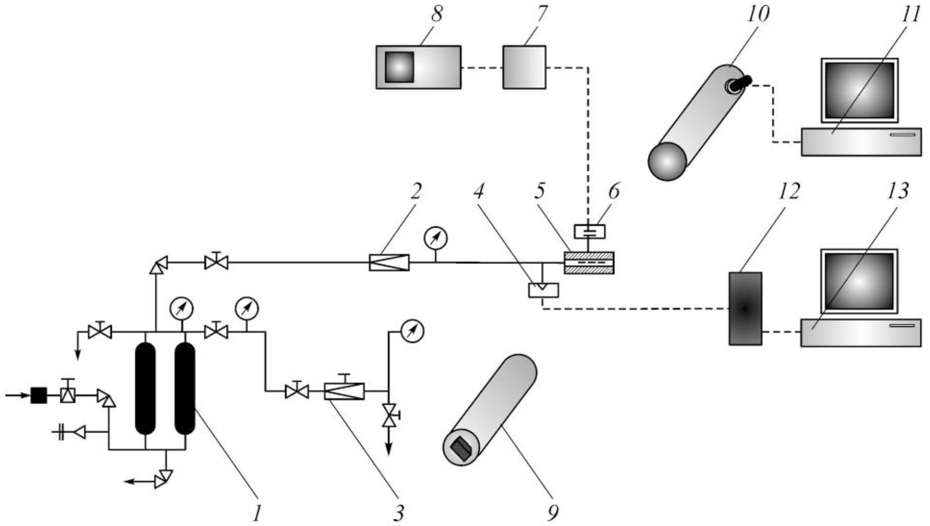

Fig. 3. Scheme of installation and measurement system for experimental investigation.
1 — high pressure ramp, *2* — pressure reducer, *3* — command reducer, *4* — pressure sensor, *5* — MI, *6* — pressure oscillation sensor, *7* — signal amplifier, *8* — signal analyzer, *9* — 10 shadow device, *11* — video signal recorder, *12* — data acquisition unit, *13* — information processing and storage device.

Now we have a configuration with a set of plates installed in the flow axis upstream the nozzle exit. This configuration excites a discrete component of pressure pulsation: this pulsation is related to periodic generation and separation of large-scale vortices in the turbulent wave behind the plates. The vortex separation from the plate surface induces pressure redistribution; this redistribution gives rise to a periodic transverse force applied to the main flow. Meanwhile, during a half-period, this force is directed to the side of separation vortex. The frequency of acting force is estimated by the formula [15]:

$$f = \mathrm{St} \cdot \mathrm{M} \cdot c/t,$$

where M is the Mach number for the flow through the cavity, c is the speed of sound. The Strouhal number for a plate for the Reynolds number in the range $10^2 < \mathrm{Re} < 5 \cdot 10^5$ is about $\mathrm{St} \approx 0.2$ [15].

The impact of these periodic pressure oscillation (driven by vortex separation) in the case of approaching this oscillation frequency to the resonant frequencies of gas flow in a cavity with plates generates the self-oscillations in the gas flow. The self-oscillation amplitude would be much higher than the pressure oscillation induced by vortex separation (for a situation of periodic set of plates in infinite space).

Simulation and experimental data [13] demonstrated that placing a plate inside the cavity creates a more complicated pressure distribution (as compared with smooth cavity). The plate-in-cavity changes the oscillation modes: oscillations in the plates-placement region has transversal oscillations, and free region beyond plates exhibits the exponent-decay transverse oscillations (standing waves) with the pressure node at the channel axis and zero velocities at the cavity walls. For a transverse cross section at the zone of plate installed, the options are symmetric and asymmetric distribution of pressure oscillations relative the plate center. The paper [13] gives the formulas for calculating the fundamental oscillation frequencies of gas flow f inside the cavity as a function of proportion between the plate length and cavity height. This relation is as follows:

$$\frac{f/f_m}{\sqrt{1-(f/f_m)^2}} = \begin{cases} \mathrm{ctg}\left(\dfrac{f}{f_m} \cdot \dfrac{\pi \cdot (2m-1)}{2} \cdot \dfrac{l}{a}\right), & \text{if } \dfrac{(2m-1)l}{a} < 1, \\ -\mathrm{tg}\left(\dfrac{f}{f_m} \cdot \dfrac{\pi \cdot (2m-1)}{2} \cdot \dfrac{l}{a}\right), & \text{if } \dfrac{(2m-1)l}{a} > 1, \end{cases}$$

here $f_m = (2m-1) \cdot c/(2a)$ is the fundamental frequency of transverse oscillations of gas inside free cavity (there is zero pressure amplitude at the axis and zero velocity at the walls), c is

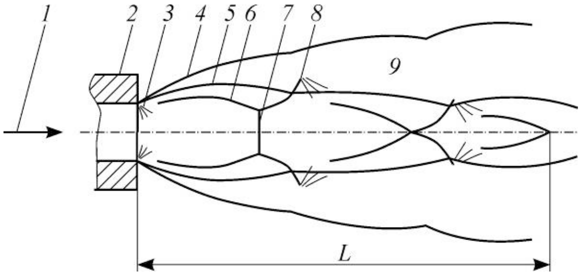

Fig. 4. Shock-wave structure (SWS) of the jet in the underexpansion mode.

1 — main stream, *2* — MI, *3* — axial rarefaction wave, *4* — jet boundary, *5* — compression wave, *6* — hanging shock wave, *7* — Mach disk, *8* — reflected shock wave, *9* — mixing region.

the speed of sound inside the cavity, $m = 1, 2 \div N$ is the number of fundamental transversal mode.

Note also that the asymmetric distribution occurs only under condition $(2m-1)\cdot l/a > 1$, and the oscillation frequency is defined by function –tg in the right-hand side of the equation.

Experiments from [16] demonstrated that the amplitude of oscillation in cavities with two or free plates (arranged with step s) is much higher than for a single-plate configuration. The possible explanation of this fact is the following. Generation of pressure oscillations by a flow streamlining a plate in cavity might be considered as phenomenon of self-oscillation generation with mechanisms of feedback. The paper [13] studied the flow in a cavity with a single plate: the authors proposed the scheme of feedback: oscillation of transversal acoustic velocity in the vicinity of back edge of the plate due to a delay time τ induces an acoustic dipole source caused by alternate vortex separations from different sides. For a cavity with several plates arranged with an interval, additional resonant mechanism of oscillation generation is possible. According to this mechanism, the interaction of vortices (generated at the back edge) produces acoustic waves: these waves can travel upstream. Impact of acoustic waves on unstable shear layer near the back edge of the plate might enhance the vortex formation (and it, in due turn, enhances acoustic oscillations).

The shape of oscillations (if localized near the plate) ensures high levels of acoustic pressure amplitude (up to ~ 180 dB). This method of excitation of powerful acoustic self-oscillations needs no external energy sources. This makes this approach feasible for the applications requiring intensive mixing of gas flows. The experimental data for spectral characteristics of pressure oscillation inside the MI cavity are plotted in Fig. 5.

If the cavity lacks of plates, the pressure pulsation sensor demonstrates a high-band spectrum, which is typical of turbulent flows [17–19]. In this case, the maximal level of oscillation amplitude is not higher than $\Delta p/p_0 = 0.01$ (Fig. 5*a*). Here p_0 is the time averaged pressure inside the cavity.

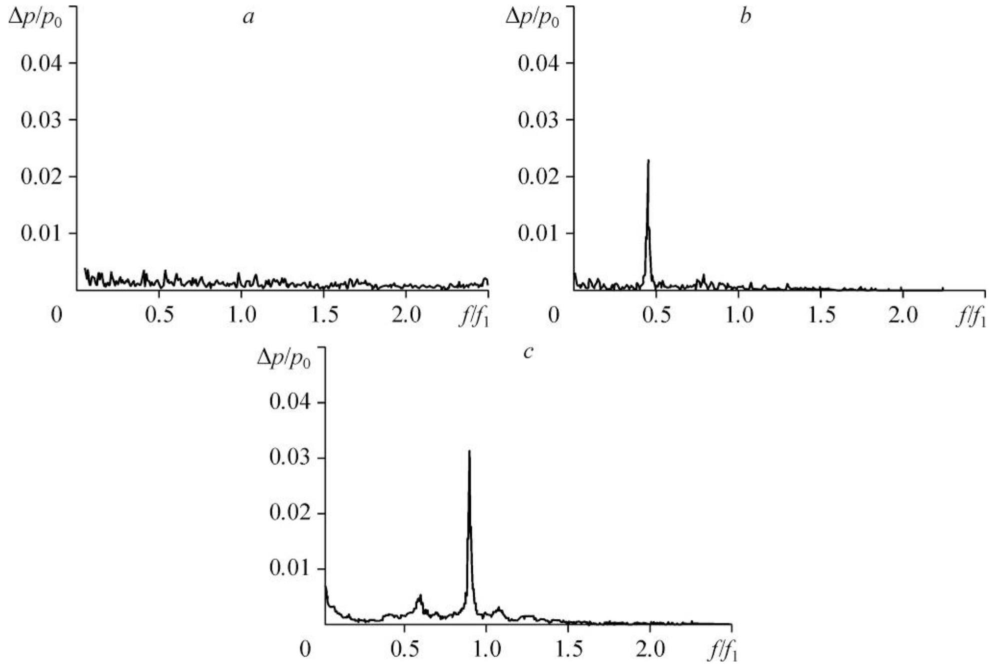

Fig. 5. Spectral characteristics of pressure oscillation in the cavity.
No plates (*a*), symmetric distribution of pressure oscillation amplitude (*b*), asymmetric distribution of pressure oscillation amplitude (*c*).

For the flow with self-excitation mode (a set of plates placed with an interval), the oscillation signal exhibits resonance-mode view (Figs. 5*b* and 5*c*): the spectrum has a visible discrete component with a high amplitude of pressure oscillation [20]. As was shown, the space behind the set of plates exhibits a transverse mode with a pressure minimum ("node") on the device axis. The amplitude decays exponentially over the length of MI cavity. This feature ensures high amplitudes of pressure oscillation about $\Delta p/p_0 = 0.25–0.35$ (Figs. 5*b* and 5*c*), while the pressure drop for oscillation generation remains low.

We should note that for the asymmetric excitation, the recorded values of oscillation amplitude reach the maximal level. The spectral line within the self-oscillation frequencies can be by factor of 2,000 higher than for a similar spectrum for free-space cavity. The symmetric distribution is typical of gas flow velocity with M ~ 0.1, while asymmetric distribution develops for M ~ 0.2. In our experiments, the variation of Mach number was regulated through variation of exit diameter d of the MI.

For the case of symmetric distribution of pressure oscillation amplitude, the relative value of peak frequencies was $f/f_1 = 0.52$, and for asymmetric mode, it was $f/f_1 = 0.91$. Here $f_1 = f_m$ at $m = 1$. These frequencies are rather close to the calculated frequencies (Fig. 6), and to the experimental data for a channel with a single plate. Comparison of our experiments with empirical data [13, 16] for a case of a channel with a single plate demonstrated that placing of several plates with periodic order gives enhancement of pulsation amplitude by 2–3 times. Meanwhile, the value of ratio f/f_1 does not change even for scaled-up dimensions of the setup (experiments described in [13] were carried out for a setup with the transversal size of cavity by ~30 times bigger than for the setup depicted in Fig. 2). This testifies that the mechanism of self-oscillation excitation due to periodic generation and separation of large-scale vortices in a turbulent wave behind a plate in a channel takes place for a broad range of channel dimensions and frequency f_1.

According to publications [13, 14], one of indicators of effective mixing of a supersonic jet with ambient air is the span of SWS decay pattern, which is defined as distance L between the nozzle outlet and the last hanging shock wave (Fig. 4). For generalization of experimental results, we can use the relative value of SWS span L/d. In this aspect, the most intensive jet mixing takes place for a situation with a minimal relative span of the SWS. Therefore, the efficiency of external impact on the process of jet mixing with atmospheric air through the mechanism of acoustic self-oscillations in the presented research was estimated through comparison of values L/d for different geometries of MI and operation modes.

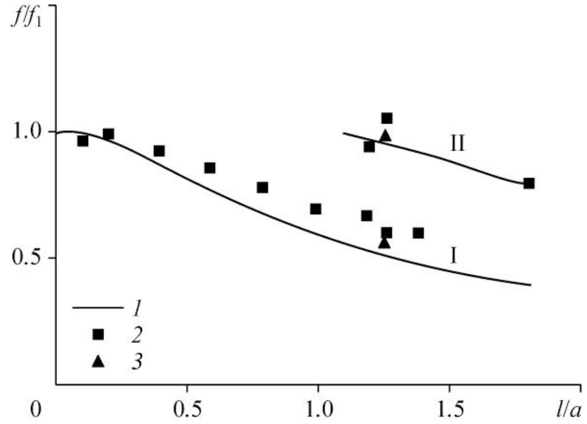

Fig. 6. Relative frequency of pressure oscillation for the cases of symmetric (I) and asymmetric (II) distributions.

1 — simulation date, *2* — experimental data [12, 15] for a single plate placed in channel, *3* — experimental data for a set of plates in channel.

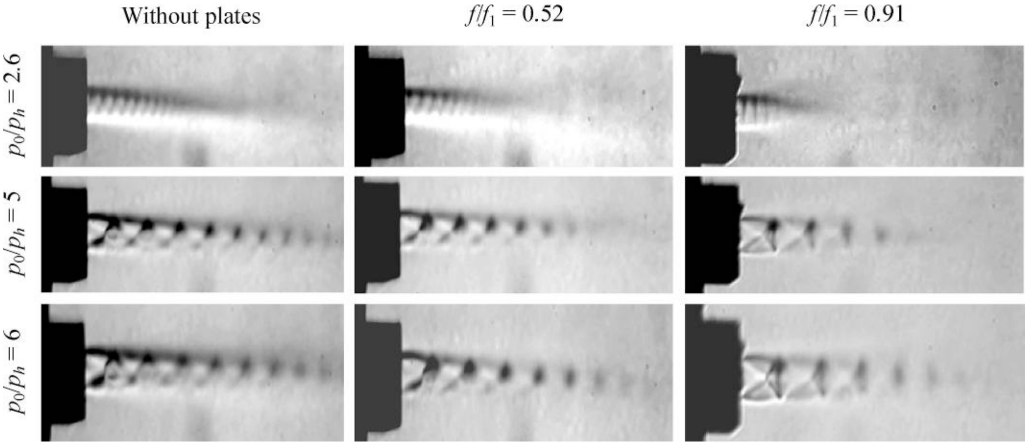

Рис. 7. Shadow picture for different values of p_0/p_h and f.

To find the L/d ratio, we analyzed the shadow pictures of the flows for different geometry configurations of MI and for pressure drop range $p_0/p_h = 2.6–6$, where p_h is the pressure in the ambient medium. Typical shadow pictures are presented in Fig. 7.

The results for a MI without plates in the cavity correspond to classical ideas about flow structure in underexpanded jet in submerged space [12, 13]: the pattern shows enlarging (in transverse direction) turbulent mixing layer with the distance from the nozzle exit.

Figure 8*a* shows the relation between L/d and p_0/p_h for different flow modes for a jet from the MI. These data are instrumental in comparative analysis of mixing efficiency for different versions of generating the self-oscillations. For a MI without the plates installed in the cavity with some interval, the SWS of the jet (for the tested pressure range) has the longest relative span: $L/d = 5–8$. Then the flow mode assumes generation of acoustic self-oscillations (due to subsonic flow past a series of plates in the cavity), the relative span of SWS reduces by factor of 1.5–1.9. Thus, for the case of symmetric distribution of pressure oscillation amplitude, the relative span was $L/d = 4–6.5$, and for asymmetric distribution, $L/d = 3.5–5.5$.

It should be noted that for the tested range of parameters, the value of ratio L/d has almost linear dependency on the relative pressure drop in the MI. The increase in relative amplitude of pressure oscillation inside the cavity allows to reduce the span of SWS. Figure 8*b* presents the average (for different relative pressure drops in the MI) dependency L/L_0 on $\Delta p/p_0$. Here L_0 is the span for the SWS for a jet from MI without acoustic self-oscillations. According to experimental data, for the relative pressure drop $\Delta p/p_0 = 0.35$, the decrease in L relative L_0 is by factor of two.

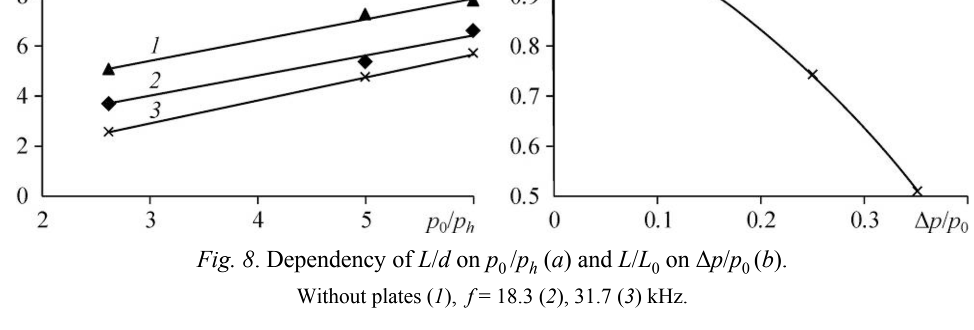

Fig. 8. Dependency of L/d on p_0/p_h (*a*) and L/L_0 on $\Delta p/p_0$ (*b*).

Without plates (*1*), $f = 18.3$ (*2*), 31.7 (*3*) kHz.

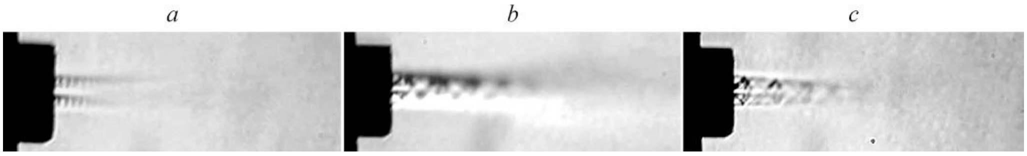

Fig. 9. Flow structure in the case of locating the last plate directly at the MI exit. $p_0/p_h = 2.6$ (a), 6 (*b*, *c*).

Some change in the flow pattern (Fig. 9) is observed when the last plate is installed directly in the nozzle: this divides the MI into two sectors. At small relative pressure drops, the flow pattern is presented by two jets (Fig. 9*a*). The gain in p_0/p_h causes merger of two jets (Figs. 9*b* and 9*c*), but the span of SWS decreases by 15–25 % (compared with the configuration when all plates are inside the cavity). The spectral analysis of pressure oscillations inside the MI cavity demonstrated that for this configuration, the excited self-oscillations have the frequencies $f/f_1 = 0.5–0.7$, which corresponds to symmetric distribution of amplitudes.

This effect can be explained by influence of two factors. If the plate separates the nozzle into two sectors, the distribution of pressure amplitude in the nozzle corresponds to the longitudinal mode of acoustic oscillations [13]. Under these conditions, the oscillation amplitude is higher compared to the alternative arrangement (the space between the end edge of the last plate and the nozzle exit has the distribution as an eigenmode with exponential decline of amplitude in downstream direction). The other mechanism is that the last plate splits the nozzle into two independent sectors: every sector is considered as a nozzle of smaller area. Since the dimensions of SWS depends in linear manner on the nozzle diameter [17], the value of L/d decreases considerably.

The presented data can be used for designing the new generations of power and propulsion plants suitable for using in aviation and space technology.

Conclusions

The set of model experiments was aimed at the study of influence of acoustic self-oscillations on the process of decay of underexpanded supersonic jet in submerged space.

It was demonstrated that through excitation of acoustic and vortex self-oscillations in jet nozzle, it is possible to enhance the decay of the jet: this improves the efficiency of mixing. One of promising methods for generation of that type of self-oscillations is arranging of a cavity with a set of transversal plates placed with a certain interval.

When acoustic self-oscillations are excited in the cavity upstream the nozzle exit, this generates pressure pulsations with symmetric or asymmetric distribution of amplitude in the zones above and below the set of plates. Symmetric distribution in the tested MI is characterized by the relative frequency of pressure oscillation $f/f_1 = 0.52$, but asymmetric mode has $f/f_1 = 0.91$. The maximum amplitudes of pressure oscillations correspond in this case to an asymmetric distribution and may amount up to 35 % of the full pressure ahead of the nozzle.

Data analysis demonstrates that for flow modes with generation of acoustic self-oscillations (developing in the cavity of jet nozzle with a set of plates streamlined by subsonic flow), the relative jet length reduces by 1.5–1.9 times. The maximum reduction of jet span through the mechanism of acoustic self-oscillations (up to values $L/d = 3.5–5.5$) was recorded for asymmetric distribution of pressure oscillation. The extra reduction in the span of jet decay by 15–25 % can be achieved if the last (downstream) plate is fixed directly in the nozzle: this plate divides the nozzle into two sectors.

The data presented allow us to draw a conclusion that mixing intensification can be achieved by impact of acoustic self-oscillations on the jet. Self-oscillations are generated by placing a set of plates with an interval; this approach is easy and feasible design solution.

References

1. **V.S. Zuev and V.S. Makaron,** Theory of Direct Jet and Ramjet Engines, Mashinostroenie, Moscow, 1971.
2. **O.V. Guskov and V.I. Kopchenov,** Simulation of flow structure in a channel with supersonic inlet conditions, Aeromechanics and Gasdynamics, 2001, No. 1, P. 28–39.
3. **S.I. Baranovsky, V.M. Levin, A.S. Nadvorsky, and A.I. Turishchev,** Experimental and theoretical study for co-current supersonic jets with interaction, Int. school-seminar "Turbulent Flows in Interacting Flows", Minsk, ITMO AS BSSR, 1986, P. 84–98.
4. **V.Yu. Aleksandrov, K.Yu. Arefyev, and A.V. Voronetsky,** Study of effective regenerative cooling system in supersonic ramjet engines using hydrocarbon fuel, Teplovye Processy v Tekhnike, 2014, Vol. 6, No. 11, P. 489–495.
5. **V.I. Tsutsuran, N.V. Petrukhin, and S.A. Gusev,** Military and Technical Analysis of State of Art and Perspectives in Field of Rocket Fuel, DM RF, Moscow, 1999.
6. **N.P. Dulepov, G.K. Kotenkov, and L.S. Yanovskii,** Ramjet with solid fuel, Aktualnye Problemy Aviatsionnyh i Aerokosmicheskih System, 2001, Vol. 6, No. 2, P. 1–21.
7. **S.S. Vorontsov, V.A. Zabaikin, V.V. Pikalov, P.K. Tret'yakov, and N.V. Chugunova,** Investigation of the structure of a diffusion hydrogen plume in a supersonic high-enthalpy air jet, Combustion, Explosion and Shock Waves, 1999, Vol. 35, No. 5, P. 465–467.
8. **L.G. Vinogradov, V.L. Semenov, and Yu.M. Shikhman,** On 15th anniversary of first flight test of ramjet apparatus fueled by liquid hydrogen, Dvigatel, 2006, Vol. 48, No. 6, P. 28–29.
9. **E.A. Meshcheryakov and V.A. Sabel'nikov,** Reduced heat production due to mixing and kinetics factors in supersonic combustion on unmixed gases in an expanding channel, Combustion, Explosion and Shock Waves, 1988, Vol. 24, No. 5, P. 526–533.
10. **A.N. Antonov, V.M. Kuptsov, and V.V. Komarov,** Pressure Oscillations in Jets and Separation Flows, Mashinostroenie, Moscow, 1990.
11. **D.A. Gubanov,** Impact of microjets on structure and acoustic emission from a supersonic underexpanded jet, PhD thesis, Novosibirsk, 2014.
12. **K.S. Pyankov,** Simulation of features of ideal gas flow and two-phase gas-particle mixture, PhD thesis, Moscow, 2011.
13. **M.A. Ilchenko, V.V. Krutchenko, and Yu.S. Mnatsakanyan,** Stability of Operation in Aircraft Engines, Mashinostroenie, Moscow, 1995.
14. **V.S. Avduevskii, E.D. Ashratov, A.V. Ivanov, and U.G. Pirumov,** Gas Dynamics of Supersonic Nonisobaric Jets, Mashinostroenie, Moscow, 1989.
15. **D.I. Blokhintsev,** Acoustics in Nonuniform Moving Medium, Nauka, Moscow, 1981.
16. **E.A. Folomeev, M.A. Ilchenko, and N.I. Selin,** Heat transfer intensification in channels under self-oscillations of gas flow, Thermal Engineering, 1995, No. 4, P. 151–159.
17. **G.N. Abramovich,** Applied Gas Dynamics, Foreign Technol. Div. Wright-Patterson Air Force Systems Command, Ohio, 1970.
18. **A.S. Ginevskii, E.V. Vlasov, and R.K. Karavosov,** Acoustic Control of Turbulent Jets, Fizmatlit, Moscow, 2001.
19. **G. Bendat and A. Piersol,** Engineering Application of Correlational and Spectral Analysis, Wiley-Interscience, New York, 1980.
20. **G.I. Eremin and V.I. Kondratyev,** Acoustic impact on flow and noise spectrum for supersonic jets, Aero Acoustics, Nauka, Moscow, 1980, P. 119–123.