Investigation of the effect of the ejector on the performance of the pulse detonation engine nozzle extension

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Abstract. Influence of an ejector nozzle extension on gas flow at a pulse detonation engine was investigated numerically and experimentally. Detonation formation was organized in stoichiometric hydrogen-oxygen mixture in cylindrical detonation tube. Cylindrical ejector was constructed and mounted at the open end of the tube. Thrust, air consumption and parameters of the detonation were measured in single and multiple regimes of operation. Axisymmetric model was used in numerical investigation. Equations of Navies–Stokes were solved using a finite-difference scheme Roe of second order of accuracy. Initial conditions were estimated on a base of experimental data. Numerical results were validated with experiments data.

1. Introduction

In the year of 1940, Y B Zel'dovich [1] showed that thermodynamic efficiency of fuel combustion at a detonation regime is greater than at a deflagration regimes [1]. The rates of energy release in the detonation modes of gas combustion are three orders of magnitude higher than in the deflagration combustion modes. This theoretical result gave rise to numerous studies of possibility of creation and utilization of a detonation engine for aviation needs [2].

It leads to the concept of a pulse detonation engine (PDE). Operation of the PDE relies on pressure-rise detonation combustion rather than constant-pressure deflagration currently used in conventional engines, for instance, piston engines, gas turbine engines and scramjets. High thermal efficiency of PDE attracts researchers to apply it as a new technology for aerospace propulsion. However, detonation combustion is not performed throughout the combustion chamber simultaneously but in a narrow edge. This edge is usually much smaller than that of the combustion chamber and the propagation velocity exceeds the velocity of sound in the unburned mixture 4–6 times. Therefore, in the combustion chamber the local regions of high pressure and low-pressure range can be formed. So the detonation combustion should not be considered as quasi-stationary.

One of the main features of the pulse engine is that the nozzle produces a variable thrust during a period. One stage of combustion can be effective; other is regressive. Thus, it is necessary to investigate each stage of the detonation combustion for the thrust to be maximal during the period.

Thrust of the pulse detonation engines can be sufficiently increased by nozzles and ejectors. The ejector in a pulsed mode is shown in figure 1. The detonation wave, coming out of the

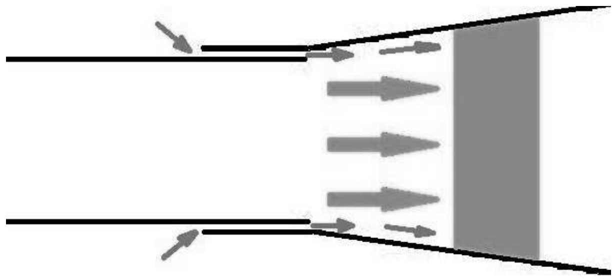

Figure 1. Pulse ejector.

combustion chamber, is followed by the expansion wave, the phase of which is much higher than in the compression phase of the wave front. The increase in thrust results from the growing mass of the working gas by entraining a secondary flow of the external air induced by a primary flow. This is due to two factors:

(i) due to the turbulent mixed flow coming from the combustion chamber and ambient air. This mechanism is also valid for the steady ejector;

(ii) due to the gas pressure in wave can be smaller than the external air pressure at the phase of the expansion wave. This mechanism is valid only for the pulse ejector.

As known, a divergent nozzle increases the thrust of the engine, which produces supersonic flow. Thus, the tapered ejector can produce the thrust augmentation higher, than the ejector without divergence.

1.1. Steady ejector

In [3] the relationship between the thrust augmentation ratios and ejection coefficient n for steady ejector is given:

$$P/P_0 = \sqrt{(n+1)\eta},$$

where P—the engine thrust with the ejector, P_0—engine thrust without ejector, $n = G_{eg}/G_0$—ejection coefficient, where G_{eg}—ejected air consumption, G_0—gas flow from the combustion chamber consumption, η—efficiency of the ejector. It was shown that using of the ejector can lead to increase the specific impulse up to 35% in [3], and up to 50% in [4] for the steady ejector.

1.2. Pulse ejector

Improving the efficiency of the nozzle in ejecting the outside air can also be caused by the reduction of resistance oncoming flow. The external oncoming flow slows down on the outer wall of the engine due to the viscosity and nozzle geometry. That leads to increased flow resistance force. In using the ejector, the external oncoming flow partly rush through the gaps in the combustion chamber.

The phenomenon of abnormally high thrust boost in gas ejection process with pulsed active jet was opened in 1951 [5]. It was shown by Slobotkina and Evtuhin [6] that using of the ejector can lead to increase the thrust up to 100% for the pulse engines for the pressure much less than the detonation combustion, produced in PDE. In [6] was shown the dependence of the ratio of thrust (P_3/P_1) and kinetic energy (K_3/K_1) for pulse ejector on the ratio of the time of impulse to the time of period (see figure 2). Slobotkina and Evtuhin received maximum increase of thrust for the ratio of the time of impulse to the time of period equaled 0.1. However, they did not research the case with less magnitude of that ratio (for PDE this ratio equal about 0.001-0.01). These data show that the ejector for the PDE may be significantly more effective than for the conventional pulse engine.

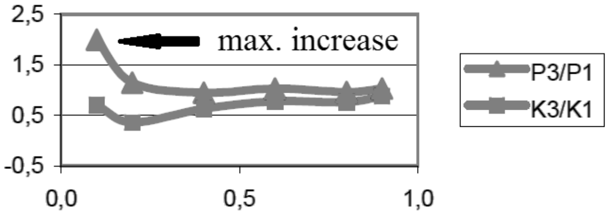

Figure 2. Ratio of thrust (P_3/P_1) and kinetic energy (K_3/K_1) for pulse ejector on the ratio of the time of impulse to the time of period [6].

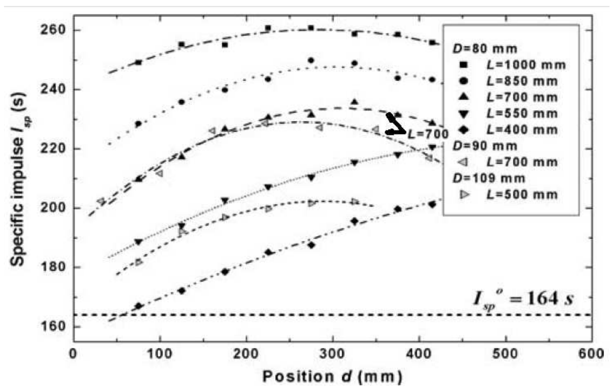

Figure 3. Specific impulse Isp versus the ejector position d for different ejector inner diameters D and lengths L [8].

1.3. Ejector for PDE

Thrust augmentation ratios above a factor of 2 were measured by Wilson *et al* [7] for the PDE using a tapered ejector. However, Wilson used the combustion tube with thick walls. Thus, Wilson cannot use the ejectors with small diameters (minimum ratio of the diameter of the ejector to the diameter of the detonation tube was 2.2). Large sizes of the ejector reduce aerodynamic performance of the engine, thereby increasing of the speed lead to significantly reducing of efficiency of the ejector. As have been shown by Canteins *et al* [8], the addition of an ejector increases the specific impulse up to 60% for the ration of the ejector diameter to the tube diameter 1.6 (D = 80 mm, figure 3). However, Canteins *et al* used the ejector without the divergence. Canteins *et al* also have shown that the ejector with larger diameter less effective in some conditions (see figure 3). Therefore, for this reason, we investigate ejectors with small diameter.

The aim was to determine the dynamics of thrust and enhancement in the thrust due to the ejector in the pulse regime of combustion. The influence of the cylindrical ejector on the thrust was investigated experimentally.

2. Experimental set-up and results

Figure 4 shows an experimental installation. The detonation chamber is an aluminum tube with length of 2000 mm, an external diameter of 20 mm, an inner diameter of 16 mm with one closed end and one open end (1). We used aluminum tube for minimization of weight of construction. The ejector is a stainless steel tube 150 mm long and 22 mm in inner diameter (2). Fuel and air were supported into the detonation tube wia two elastic pipes at the closed end of the detonation

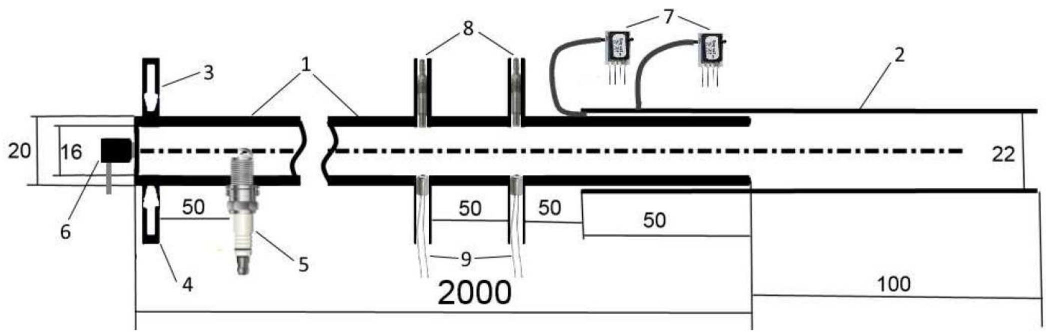

Figure 4. Experimental installation. 1—detonation tube; 2—ejector; 3, 4—gas supply system; 5—the spark plug; 6—force sensor; 7—Differential pressure sensors; 8—piezoelectric transducers; 9—photodiodes.

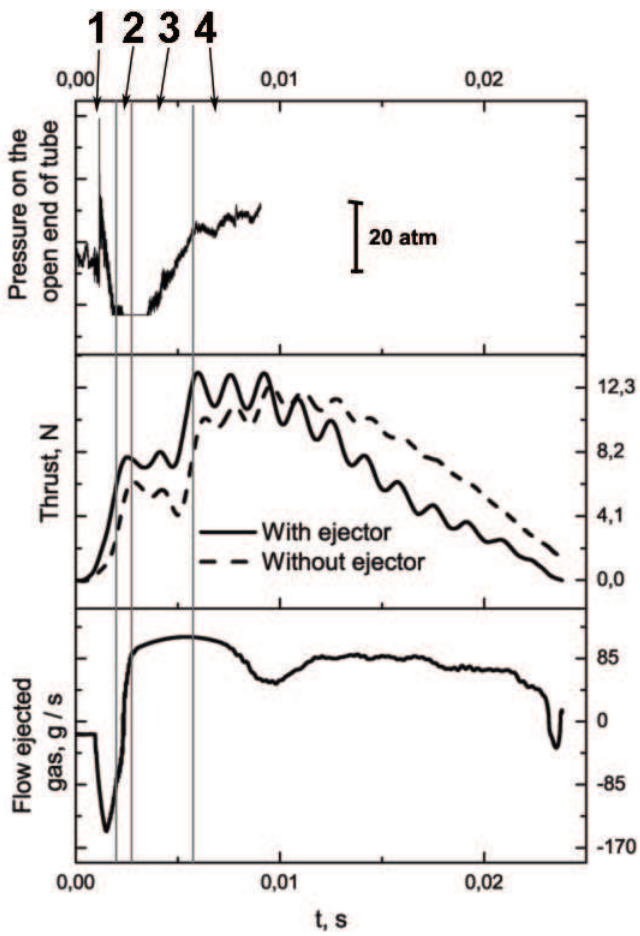

Figure 5. Experimentally measured pressure before the open end of the detonation tube, thrust and flow rate of the ejected air: 1–4—stages of operation, see below.

tubes (3, 4). Ignition system consists of a spark plug (5). We used a force sensor FSG15N1A for measuring the instantaneous thrust (6). We used a system of two pressure sensors DUXL05 for

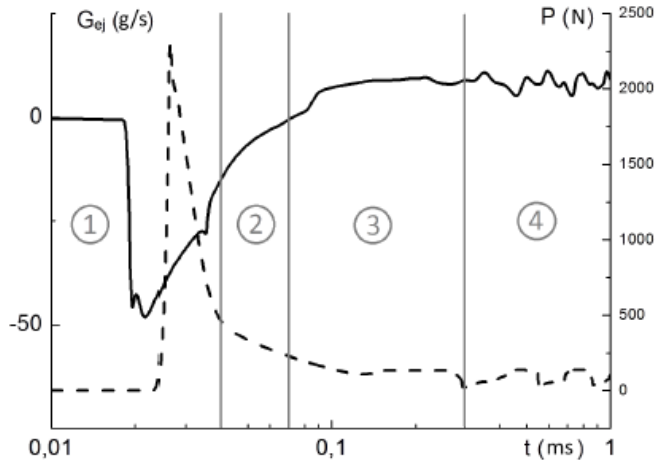

Figure 6. The dependence of the gas flow rate in the ejector gap and the thrust at the ejector outlet on the time: 1–4 stages of one pulse.

determining the gas flow in the gap between the ejector and the detonation tube (7). We used a system of two piezoelectric transducers (8) and two photodiodes (9) to determine the velocity and profile of the detonation wave.

Figure 5 shows experimentally measured pressure before the open end of the detonation tube, thrust and flow rate of the ejected air.

3. Numerical investigations

Mathematical model numerical investigation was presented by us in [9].

Axisymmetric model was used in numerical investigation. Equations of Navies–Stokes were solved using a finite-difference scheme Roe of second order of accuracy. Initial conditions were estimated on a base of experimental data. Mathematical simulation of the first two pulses of the engine for three different ejectors was carried out.

Figure 6 presents the numerically dependences of flow rate of the air through the ejector clearance and thrust generated by the ejector section. Pressure profile is the similar to the measured pressure inside the detonation tube. However, the characteristic times of the thrust and flow rate are several times smaller, then measured in experiment. It is explained by the resolution of the resistive pressure gauges FSG15N1A and DUXL05. In numerical calculation the mass of the detonation tube and ejector was not considered. Thus, one can assume the qualitative similarity in numerical and measured data. It can explain the qualitative differences in the thrust graph. But the questions about the differences in scale are still opened.

In this case, four time stages of one pulse were singled out.

3.1. Stage I. The detonation wave is coming out of the detonation tube

When leaving the detonation tube channel, the detonation wave front propagates not only along the tube axis but also in radial directions. When rounding the open end of the detonation tube, the detonation wave front moves partly in the reverse direction through the ejector clearance (figure 7—1). This results in the flow rate of the air added through the ejector clearances having a negative value for about 20 μs. The maximum value for is 48 g/s. In the thrust, a sharp peak of 2.3 kN is observed that is caused by the detonation wave front passing through the ejector section.

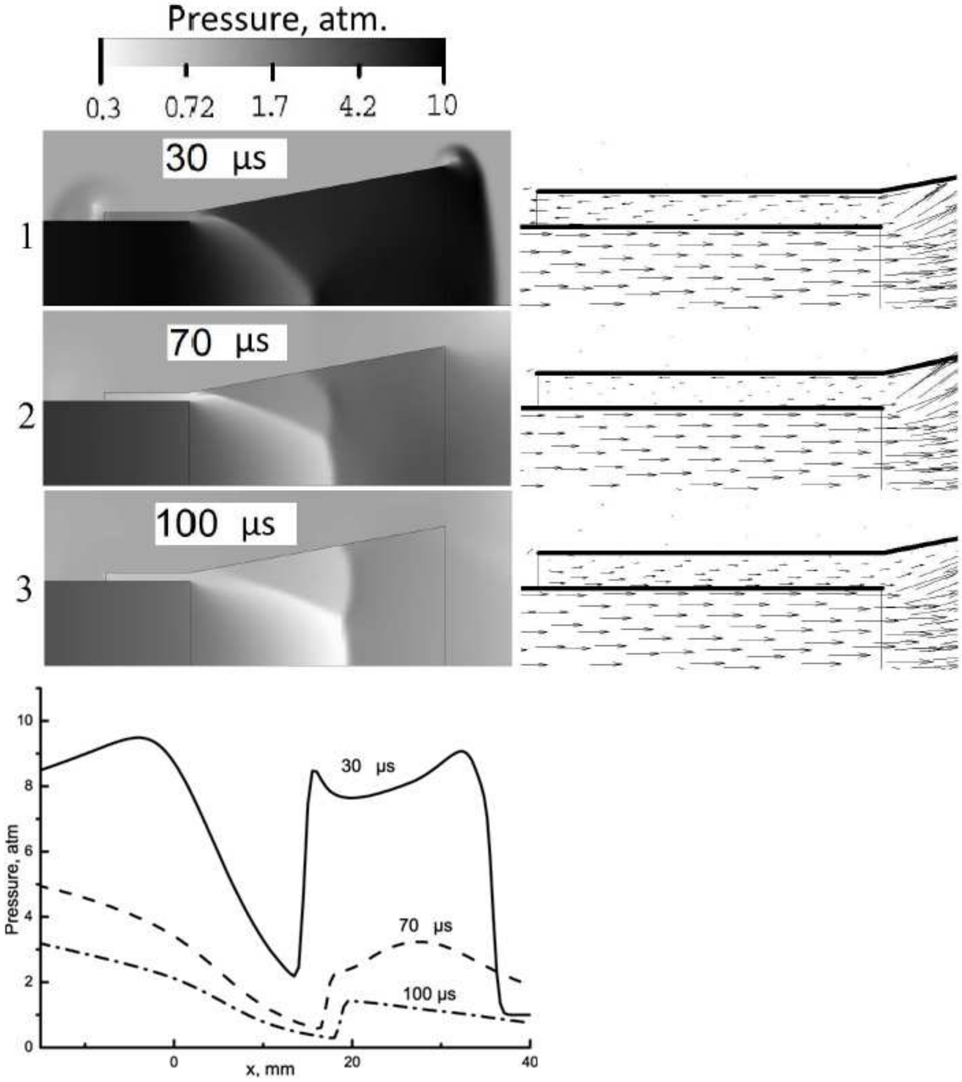

Figure 7. The pressure field in the ejector, the velocity field and pressure along the axis in the clearance between the combustion tube and the ejector 30, 70 and 100 μs after the detonation wave leaves the combustion tube.

3.2. Stage II. Attenuation of the detonation wave intensity and decrease in the negative ejection

The pressure behind the detonation wave front falls to 0.6 atm during 70 μs starting from the moment the detonation wave front passes the open end of the combustion tube. Therefore, after a sharp negative peak, a decrease in the module of the added air rate to 0 g/s is observed starting from 20 μs to 70 μs (see figure 7—2). The thrust also decreases but remains positive.

3.3. Stage III. The expansion wave leads to the positive ejection of the external air

When the pressure behind the detonation wave falls, the ambient air is sucked in. As a result, the direction of the ejected air changes to the positive sign, the rate reaches 10 g/s, and the direction does not change to the end of the period. The thrust, starting from 0.1 to 0.2 ms, becomes almost constant at 110–130 N.

3.4. Stage IV. Fluctuations
Further, the pressure at the detonation tube outlet falls more rapidly than the pressure outside the tube, and, as a consequence, the flow of the ejected air decreases and can even become negative. This results in fluctuations in the ejected air flow (see figure 6). The fluctuations in the gas flow rate in the clearance between the ejector and the combustion tube vary from 5 to 11 g/s. Because of fluctuations in the ejected air, the thrust is also subject to fluctuations within the range 20–140 N.

4. Summary
Experimentally the increase in thrust and air consumption were determined during the pulse regime of operation. Increase in thrust with the ejector was obtained 2–4 N. Air consumption was obtained 100 g/s.

Numerical and experimental data give qualitatively the same results. Experimental and numerical data presents the same stages in operation: detonation, attenuation of the detonation wave intensity and the decrease in the negative rate, the effect of the depression wave and the increase in the positive rate and fluctuation in thrust and flow rate.

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