Influence of outlet construction on thrust of pulse detonation engine

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Abstract
The possibility of using of an ejector and nozzle for increase of a thrust of a pulse detonation engine and influence of its geometrical parameters were investigated by experimentally and numerically. The influence of nozzle configuration on the thrust was studied experimentally in present work in a periodic regime. In present work thrust was created due to the periodic combustion of stoichiometric hydrogen-air mixture. Specific impulse was determined by ballistic method. The influence of the form of ejector on the thrust at single pulse operation was studied numerically in the work.

1. Introduction

In 1940 Y.B. Zel'dovich [1] showed that thermodynamic efficiency of fuel combustion at detonation regime is greater than at deflagration regimes [1]. The rates of energy release in detonation modes of gas combustion are three orders of magnitude higher than in deflagration combustion modes. This theoretical result gave rise to numerous studies of possibility of creation and utilization of a detonation engine for aviation needs [2,3].
In the last century it was proved that continuous stationary detonation combustion is impossible to achieve. The fact necessitates that for an energy converter pulsed operation mode should be used. It leads to the concept of a Pulse Detonation Engine (PDE). Operation of a 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.
Thrust of the pulse detonation engines can be sufficiently increased by nozzles and ejectors.
Result of experimental investigation of nozzles and ejectors can be found in [4,5], where the direct initiation of detonation was used. It was shown that there are an optimal dimensions of nozzle for the case of direct initiation of detonation in one-impulse regime. Authors showed that using of the ejector can lead to increase the specific impulse from 170-180 s to 265-277 s, that is up to 45%. Some aspects of ejectors with pulse jet are presented in [6], where gas-dynamics flow structure in ejector was investigated.
The use of direct initiation of detonation can be problematic for real engines. Thus, the thrust characteristics of a demonstrator of pulse detonation engine were investigated in this work at weak initiation with a transition from deflagration to detonation in a combustion chamber.
Aims of the work were:
1. Experimental investigation of influence of a nozzle on the thrust of a pulse detonation engine;
2. Numerical investigation of influence of an ejector on the thrust of a pulse detonation engine.

2. Influence of a nozzle on the thrust of a pulse detonation engine. Experimental investigation

2.1 Experimental setup

The scheme of model of the of pulse detonation engine is presented on Figure 1. It consisted of a detonation combustion chamber (1) with several sections of different diameters, block of injectors (2) for separate supply of oxidizer and fuel, ignition spark plug (3), nozzle (4), dynamometer (5) for measuring of the thrust, pressure transducers for registration of the detonation wave. Internal diameter of combustion chamber was equaled to 16 mm, the length – 2000 mm. Several sections of different diameters (20-40 mm) were used to accelerate the transition from deflagration to detonation in combustion chamber. Stoichiometric hydrogen-air mixture was used. The detonation

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cell size of the mixture was equaled to ~10 mm. Thus, the internal diameter of the combustion chamber was equaled to 1,6 tube diameter.
Nozzles compounded from conical and cylindrical parts were used. The length of nozzles were equalled to 150-170 mm. Diameter *d* of the cylindrical part was varied in the work. (Figure 2). Opening angle of the conical part of the nozzle equalled 90°.
Valve-less system of fuel feed was used to organize a periodic initiation of detonation. Principle of valve-less supply system was presented in [7]. The velocity of detonable mixture in the detonation combustion chamber equaled 5-10 m/s at fuel consumption 1.6-2.9 m^3/h.
Specific impulse was determined by ballistic method by dynamometer.

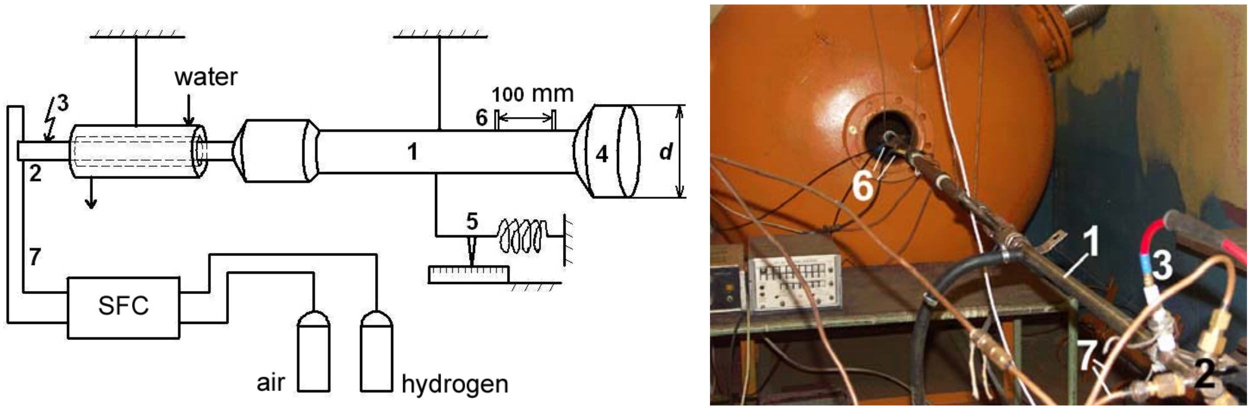


Figure 1: Model of pulse detonation engine. 1 – detonation combustion chamber, 2 – block of injectors, 3 – electric spark plug, 4 – nozzle, 5 – dynamometer, 6 – pressure transducers, 7 – fuel tubes, SFC – stand of flow control

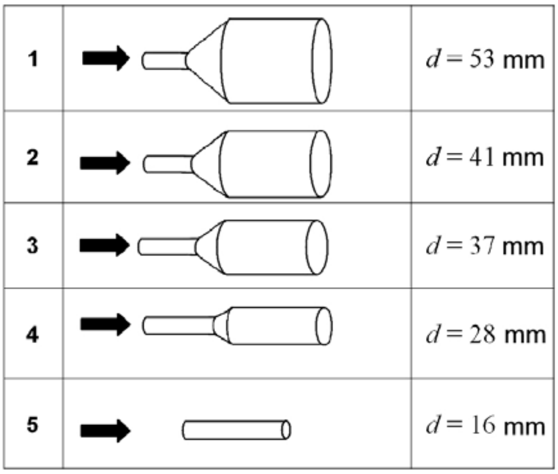


Figure 2: Nozzles. *d* – internal diameter of nozzle

2.2 Experimental results

Experiments showed that in the combustion chamber the transition from deflagration to detonation was registered at 100 tube diameters from the spark plug. Figure 3 gives pressure profiles at the open end of the combustion chamber directly before the nozzle. The velocity of detonation wave equaled 1900-2000 m/s, pressure at the front – 20 atm.
An average thrust *F* (solid line) during the period in dependence of outlet area of the nozzle ($\pi d^2/4$) is presented on Figure 4. Data obtained is presented for diameters of nozzle 1 tube diameter (16 mm), 1.75 tube diameters (28 mm), 2.31 tube diameters (37 mm), 2.56 tube diameters (41 mm) and 3.19 tube diameters (53 mm). It worth to note that significant increasing in the thrust was achieved by increasing of the volume of combustion chamber due to volume of the nozzle.
Figure 4 also gives the dependence of specific impulse on the outlet area of the nozzle (dot line). Because of the impulse combustion of fuel the thrust was changed considerably during the period. Average meaning of the impulse

was measured by equation (1), where Q – mass fuel consumption, T – period, Δm – mass of gas during period. As expected, there is an optimal diameter of the nozzle at which the specific impulse is maximal. Increasing of the outlet area of nozzle leaded to increase in fuel consumption. The optimal diameter was founded to be equaled 1.8 tube diameters (28 mm).

$$\langle J \rangle = \langle F \rangle \big/ \langle Q \rangle = \frac{1}{T}\int_0^T F(t)dt \Bigg/ \frac{\Delta m}{T} \tag{1}$$

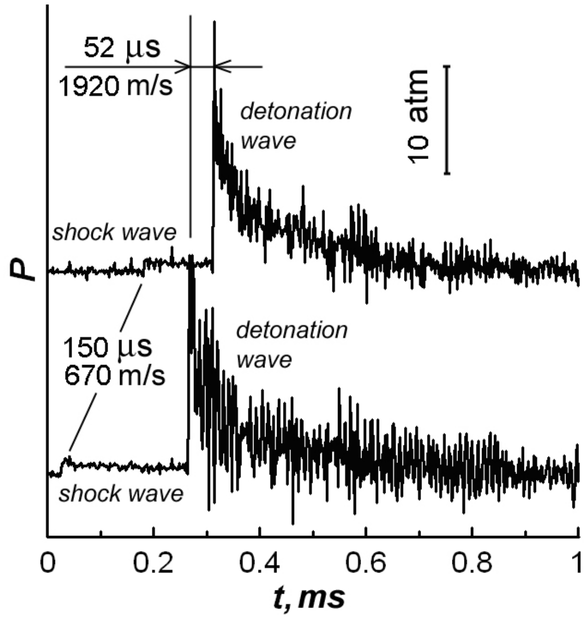


Figure 3: Pressure profiles at the end of the detonation combustion chamber. Distance between pressure transducers was 100 mm

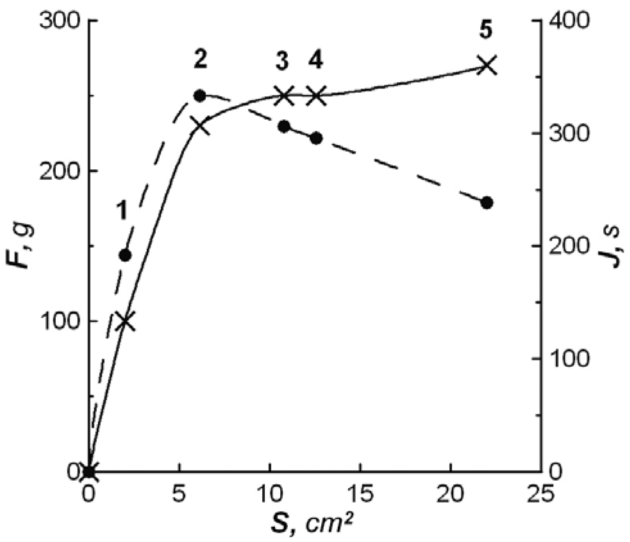


Figure 4: Dependences of thrust (*F*) and specific impulse (*J*) on cross section area of nozzle outlet (*S*)

3. Influence of an ejector on the thrust of a pulse detonation engine. Numerical investigation

3.1 Numerical model

Geometrical model of an ejector and flow of gases in the ejector are presented on Figure 5. In the calculations the ejector was connected with open end of the detonation chamber. Axisymmetric model was used.
Equations of Navies-Stokes were solved using finite-difference scheme Roe of second order of accuracy. k-ε-model of turbulence was used. Triangular and rectangular calculation grids are presented on Figure 6.
Outflow of detonation combustion products was established as a constant during definite period of time. Pressure of the products was established as 10 atm, velocity – 1000 m/s. Ambient pressure was 1 atm, ambient air was stationary. Figure 5 shows flow of detonation products and ambient air through the ejector.

3.2 Numerical results

At first, an optimal gap between detonation tube and simply cylindrical ejector was determined. Diameter of the tube was 20 mm. Several positions of ejector were considered, the gap was equaled to 4%, 6%, 8%, 10% and 12% of the tube diameter (Figure 7). Dependence of air consumption on the gap is presented on Figure 8. Maximal consumption of air was found to be at the gap 8% from the diameter of tube.
At second, the optimal profile of ejector was calculated. Two type of the ejector were investigated and compared with conical nozzle: conical ejector and ejector like a Laval nozzle (Figure 9). The thrust was calculated in simulations. In was obtained the thrust 8.5 kg for the ejector (1), 8.8 kg for the nozzle (2) and 9.4 kg for the ejector (3). Considering the flow structure through the ejector on Figure 10 the optimal profile of the ejector can be obtained.

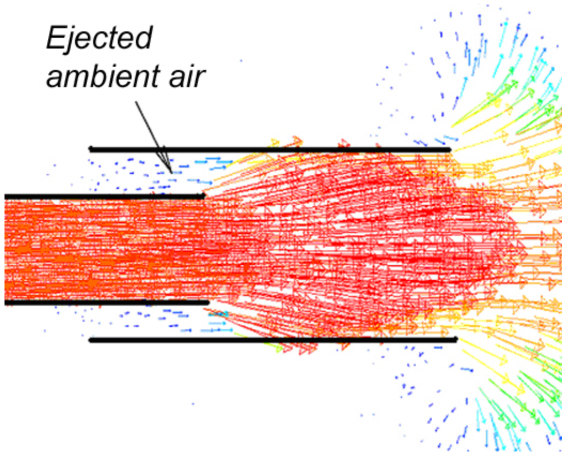


Figure 5: Ejector and flow of gases

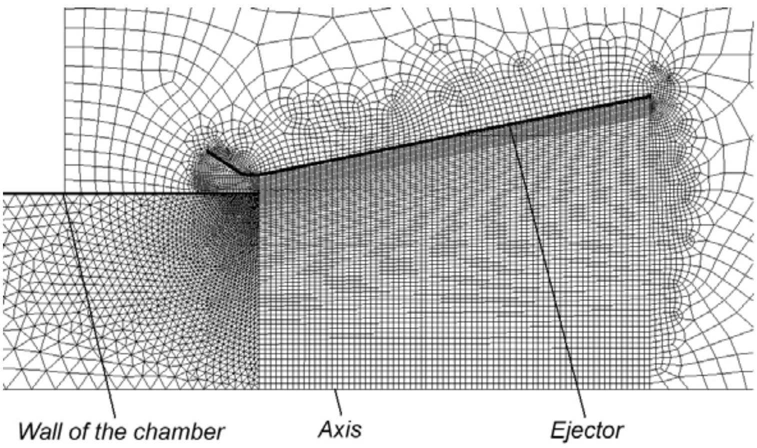


Figure 6: Triangular calculation grid

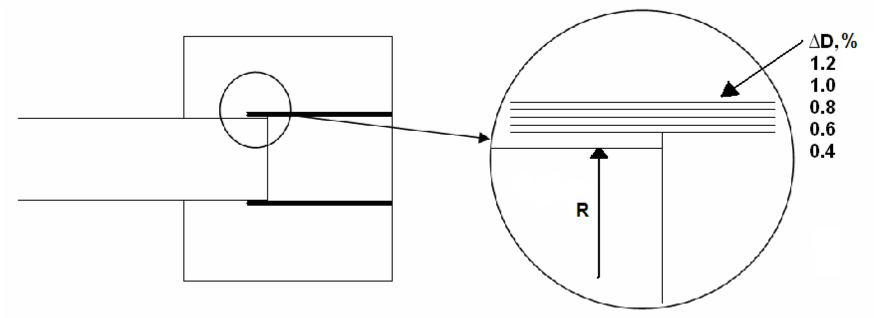


Figure 7: Positions of the ejector relative to the detonation combustion chamber. ΔD – gap in percents

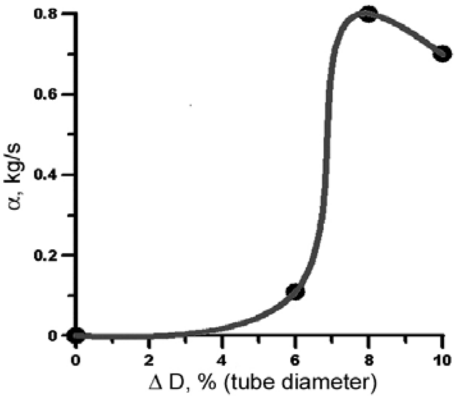
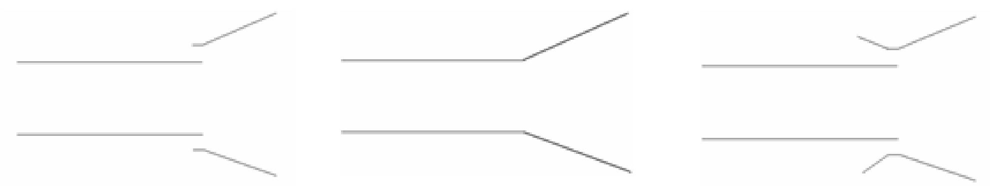


Figure 8: Dependence of ambient air consumption (α) on gap between the detonation combustion chamber and ejector (ΔD)



1 **2** **3**

Figure 9: Conical ejector (1), conical nozzle (2), ejector as Laval nozzle construction (3)

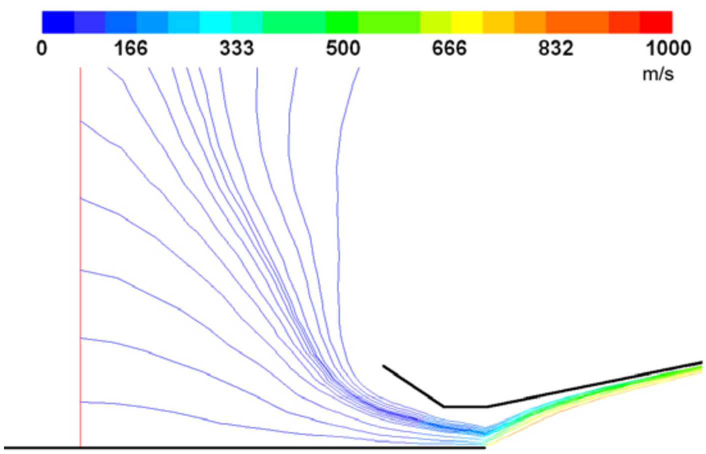


Figure 10: Flow structure through ejector

Conclusions

The influence of nozzle configuration on the thrust was studied experimentally in present work in a periodic regime. It was shown that dependence of specific impulse on diameter of the nozzle has extreme. Optimal diameter was found to be equal 1.8 tube diameters.
The influence of the form of ejector on the thrust at single pulse operation was studied numerically in the work. The optimal construction of the ejector was estimated at which the specific impulse is maximum. Optimal gap between ejector and combustion chamber was found equaled to 8% of tube diameter.
Data obtained can be typical for pulse detonation engines.

Acknowledgments

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