EXPERIMENTAL STUDIES OF A LIQUID PROPANE–AIR PULSE DETONATION ENGINE

S. M. Frolov[1,2,3], **V. S. Aksenov**[1,2,3], **V. S. Ivanov**[1,2], **and I. O. Shamshin**[1,2,3]

[1]Center for Pulse-Detonation Combustion
Moscow, Russia
[2]N. N. Semenov Institute of Chemical Physics
Russian Academy of Sciences
Moscow, Russia
e-mail: smfrol@chph.ras.ru
[3]National Research Nuclear University
"Moscow Engineering Physics Institute" (NRNU MEPhI)
Moscow, Russia

Ramjet engines operating on a thermodynamic Brayton cycle (pressure $P = const$) are currently widely used in flying vehicles. For many decades, such engines were continuously improved in terms of better design and materials and their further improvement requires large investments. Alternative solution is to improve the thermodynamic efficiency of the thermodynamic cycle used in ramjets by applying innovative pressure gain combustors. Increase in the total pressure in the combustion chamber can be achieved by an increase in the rate of unsteady combustion of fuel–oxidizer mixture and/or by changing the combustion mode. The most attractive combustion mode in terms of its thermodynamic efficiency is detonation [1]. The thermodynamic cycle with a controlled detonation combustion is referred to as Zel'dovich cycle in honor of Academician Zel'dovich who developed theoretical grounds for the application of detonation to propulsion. In a detonation wave, the maximum release rate of chemical energy stored in the fuel is achieved (energy is released in a very thin layer of shock-compressed mixture), and the entropy increment in the detonation products is less than in the products of constant-pressure combustion. In view of it, two basic schemes of detonation combustion are currently considered, one with intermittent detonation waves traveling along the combustion chamber (pulse detonation engines, PDEs), and another with detonation waves continuously circulating in a tangential direction across the combustion chamber (continuous detonation engine, CDE). Both schemes are considered promising for advanced ramjets [2].

The objective of this work is to design, fabricate and test a PDE operating on a liquid propane–air mixture and to measure its thrust performance at the laboratory test stand.

1 Experimental Setup

Figure 1 shows the schematic of the experimental setup with air and fuel supply systems, thrust table, PDE, control module, and data acquisition system.

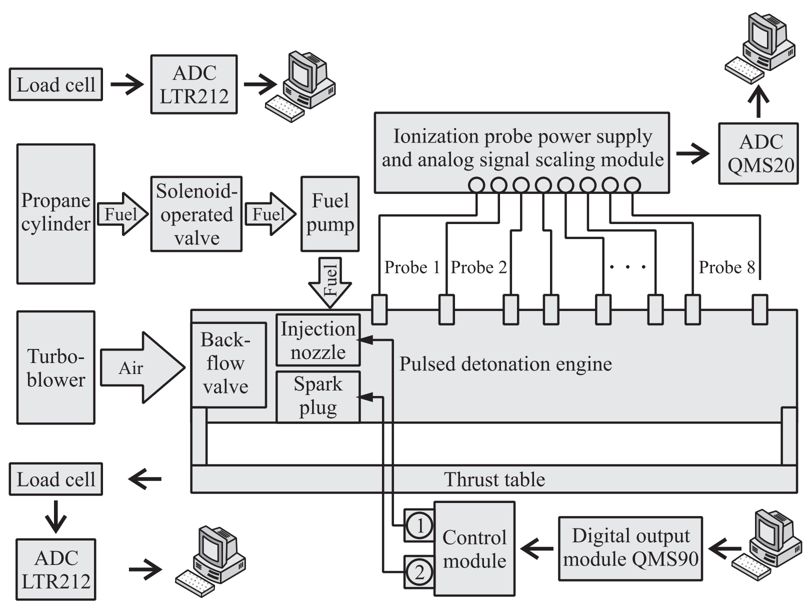


Figure 1 Schematic of the experimental setup with the PDE

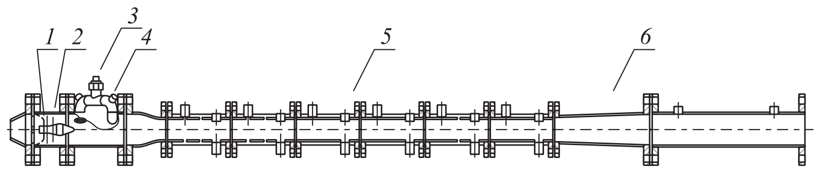


Figure 2 Schematic of the PDE: *1* — backflow valve; *2* — fuel injectors; *3* — mixing chamber; *4* — ignition system; *5* — water cooled detonation tube with turbulizing obstacles; and *6* — nozzle extension

The atmospheric air is supplied to the PDE from a 22-kilowatt *FPZ* turboblower SCL K11-TS (airflow rate 1200–1765 m^3/h) via a flexible air manifold. Fuel (liquid propane) is supplied to the PDE from a standard cylinder suspended on a fixed *Tedea-Huntleigh* load cell (model 1022, grade C3) with the maximum load of 20 kg via a safety solenoid valve and fuel pump. The fuel pump provides continuous circulation of fuel in the fuel supply line with four fuel injectors and raises the pressure in the line to the level of 12–16 bar.

The PDE is installed on the thrust table. The thrust table is designed to allow small displacements of the PDE along its axis. The thrust produced by the PDE is measured with a *Tedea-Huntleigh* load cell (model 1022, grade C3) with the maximum load of 200 N.

The PDE (Fig. 2) comprises the backflow valve *1*, fuel injectors *2*, mixing chamber *3*, ignition system *4*, 50-millimeter diameter detonation tube with turbulizing obstacles *5*, nozzle extension *6*, and water cooling jacket. Fuel injector nozzles are located in the PDE mixing chamber where sprayed fuel is mixed with air and the formed two-phase mixture moves further downstream to fill the detonation tube. The fuel–air mixture is ignited by two automotive spark plugs mounted in a special bypass channel designed according to patent [3]. Turbulizing obstacles have variable shape, spacing, and blockage of tube cross section to provide fast deflagration-to-detonation transition (DDT) [4] and are designed according to patent [5].

The control module controls fuel supply and ignition based on TTL (transistor–transistor logic) signals from the *R-Technology QMBox QMS90* digital unit linked to a personal computer (PC). The input pa-

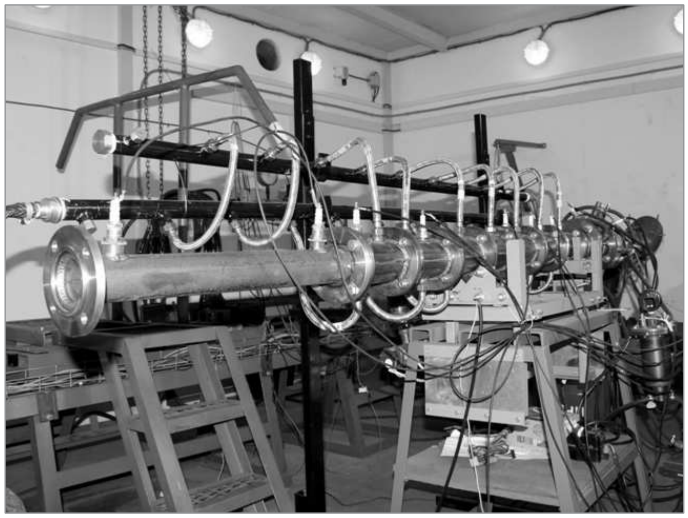


Figure 3 Photograph of the experimental setup with the PDE

rameters are the PDE operation frequency, fuel supply duration, time delay of ignition triggering, and ignition signal duration.

The data acquisition system includes 8 ionization probes (modified automotive spark plugs) mounted along the detonation tube and *R-Technology QMBox QMS20* analog-to-digital converter (ADC) connected to a PC. Signals from load cells are transferred to the PC via the *L-card LTR212* ADC. In short-duration experiments, 8 high-frequency piezoelectric PCB 113B24 pressure transducers are installed along the detonation tube in the same cross sections with the ionization probes.

Figure 3 shows the photograph of the experimental setup with the PDE.

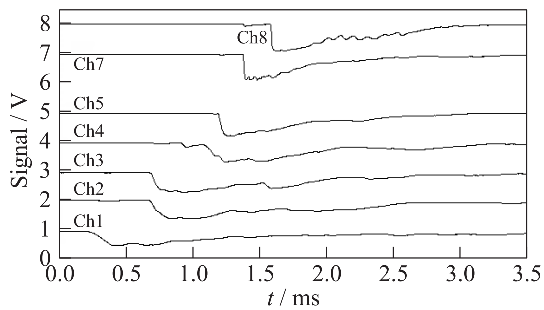
2 Results and Discussion

Described below are the results of two experimental series. In the first series, the PDE tube had no nozzle extension. In the second series, the PDE tube had a conical nozzle extension.

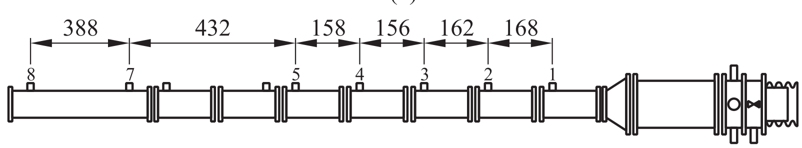
2.1 Pulsed detonation engine without nozzle extension

In the first experimental series, a 2.1-meter long 50-millimeter diameter PDE tube without nozzle extension was used.

Figure 4 shows the example of ionization probe records for one randomly selected shot of the PDE operating at a frequency f of 2 Hz. The table in Fig. 4b presents the reaction front velocity D calculated based on the known lengths of the measuring segments L and times of front arrival taken from these records. The estimated error of determining the D value is 3%. At the end of the detonation tube, the reaction front



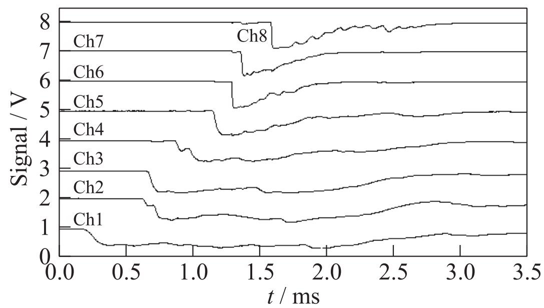
(a)



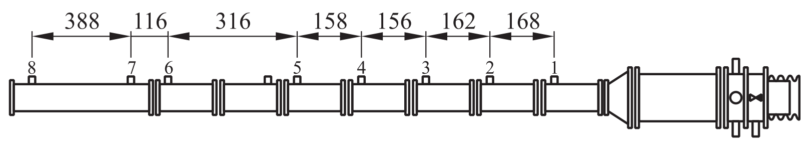
Measuring segment	L, mm	D, m/s
1–2	168	230
2–3	162	—
3–4	156	490
4–5	158	880
5–7	432	2350
7–8	388	1840

(b)

Figure 4 Example of ionization probe records for one randomly selected shot of the PDE operating at a frequency of 2 Hz (a) and calculated reaction front velocities at different measuring segments (b); Ch stands for channel



(a)



Measuring segment	L, mm	D, m/s
1–2	168	400
2–3	162	3060
3–4	156	810
4–5	158	570
5–6	316	2700
6–7	116	1680
7–8	388	1770

(b)

Figure 5 Example of ionization probe records for one randomly selected shot of the PDE operating at a frequency of 20 Hz (a) and calculated reaction front velocities at different measuring segments (b)

velocity is seen to be close to the thermodynamic value of the detonation velocity in the stoichiometric propane–air mixture ($\sim$ 1800 m/s). When the PDE operation frequency $f = 20$ Hz, the qualitative picture remains similar (Fig. 5).

Figure 6 compares the images of the PDE plume in detonation mode (Fig. 6a) and in deflagration mode (Fig. 6b). In the detonation mode, the registered reaction front velocities inside the detonation tube vary from 1600 to 2000 m/s, whereas in the deflagration mode they

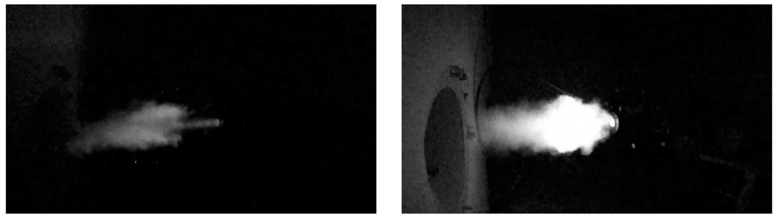


Figure 6 Images of the PDE plume in detonation mode (a) and in deflagration mode (b) at operation frequency 20 Hz

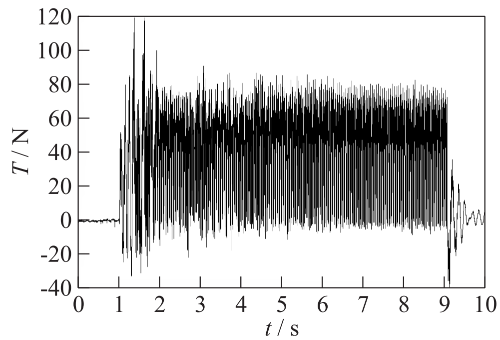


Figure 7 Typical time history of the PDE thrust measured by the load cell at PDE operation with 20 Hz. The mean thrust is ~ 45 N

vary from 800 to 1000 m/s. The deflagration mode is attained when the fuel–air mixture in the PDE tube is excessively fuel rich or fuel lean as compared to the mixture composition required for the detonation mode.

Figure 7 shows a typical time history of the PDE thrust $T(t)$ measured by the load cell at PDE operation with $f = 20$ Hz for 8 s. Clearly, the PDE thrust is oscillatory but positive with the mean value $\overline{T}$ of approximately 45 N. The mean value of thrust is taken as an integral

$$\overline{T} = \frac{1}{\tau} \int\limits_{t}^{t+\tau} T(t)\, dt$$

Table 1 Thrust performances of the PDE vs. operation frequency at a fixed cycle fuel-fill time $t_f = 25$ ms

f, Hz	$\overline{T}$, N	I_{sp}, s	$\dot{m}_f$, g/s
2	7.0	1075	0.66
4	12.5	1015	1.26
8	21.0	940	2.28
10	28.6	990	2.95
15	39.5	990	4.07
20	44.6	800	5.69

where the time interval τ is $\tau = t_e - t_i$ with t_e and t_i taken equal to 8.5 and 2 s, respectively, i. e., beyond the transient initial and final phases of PDE operation in Fig. 7.

Table 1 presents a set of experimental data for the mean PDE thrust ($\overline{T}$) depending on the operation frequency f at a fixed cycle fuel-fill time t_f of 25 ms. In addition, Table 1 lists the following quantities:

– mean fuel mass flow rate

$$\dot{m}_f = \frac{m_f}{\tau}$$

where $m_f = W(t) - W(t+\tau)$ and $W(t)$ is the mass of fuel cylinder at time t; and

– mean fuel-based specific impulse

$$I_{\mathrm{sp}} = \frac{\overline{T}}{\dot{m}_f g}$$

where g is the acceleration of gravity.

It follows from Table 1 that with the variation of the operation frequency, the fuel mass flow rate $\dot{m}_f$ in the experiments increases starting from 0.66 g/s at 2 Hz and attaining 5.69 g/s at 20 Hz. It is seen that the mean thrust increases with the operation frequency while the specific impulse is about 1000 s at f = 2–15 Hz and drops to 800 s at f = 20 Hz. The latter is possibly caused by deterioration of fuel–air mixing at higher frequencies and incomplete combustion of fuel. With decreasing the cycle fuel-fill time t_f below 25 ms, the operation process in the detonation mode is not observed due to the failure of DDT (the minimum fuel-fill distance should be equal or exceed the DDT run-up distance in the detonation tube). Note that the minimum value of t_f depends on the level of air velocity in the detonation tube. In the experiments discussed herein, the typical air velocity in the tube measured by an anemometer is about 50 m/s. With increasing the cycle fuel-fill time t_f above 25 ms, the specific impulse gradually decreases. For example, at 2-hertz operation frequency, the specific impulse attains 1075 s at $t_f = 25$ ms and only 500 s at $t_f = 100$ ms.

2.2 Pulsed detonation engine with nozzle extension

In the second experimental series, a 2.1-meter long 50-millimeter diameter PDE detonation tube with long (500-millimeter) conical nozzle extension was used. The half-angle of nozzle cone extensions was 1.7°. An additional section of cylindrical tube 80 mm in diameter and 520 mm long was attached to the nozzle exit. The photograph of the PDE–nozzle extension assembly is shown in Fig. 8. The reaction front velocity in the nozzle extension is measured by ionization probes installed upstream and downstream the conical section as shown in Fig. 8.

Figure 9 shows the example of ionization probe records for one randomly selected shot of the PDE operating at a frequency $f = 2$ Hz with the cycle fuel-fill time $t_f = 100$ ms. As before, the table in Fig. 9*b* presents the reaction front velocity D calculated based on the known

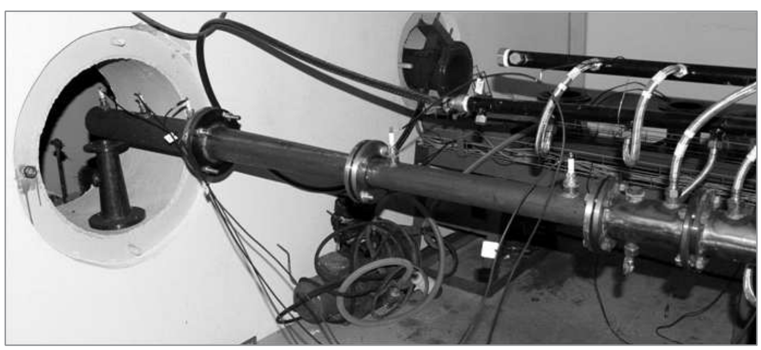
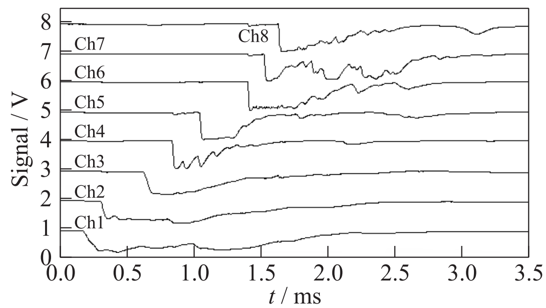
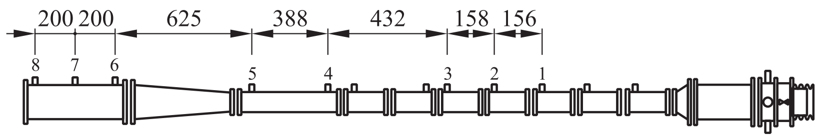


Figure 8 Photograph of the PDE with nozzle extension



(*a*)



Measuring segment	L, mm	D, m/s
1–2	156	1540
2–3	158	500
3–4	432	2025
4–5	388	1865
5–6	625	1775
6–7	200	1630
7–8	200	1870

(*b*)

Figure 9 Example of ionization probe records for one randomly selected shot of the PDE with nozzle extension operating at a frequency of 2 Hz (*a*) and calculated reaction front velocities at different measuring segments (*b*)

lengths of the measuring segments L and times of front arrival taken from these records. At the end of the 80-millimeter cylindrical tube, the reaction front velocity is seen to be about 1800–1900 m/s indicating that a detonation wave is successfully transitioned through the conical nozzle. Figure 10 shows the measured time history of PDE thrust measured by the load cell in the same run as taken for Fig. 9.

Finally, Table 2 compares the thrust performances of the PDE without and with nozzle extension at two values of the operation frequency

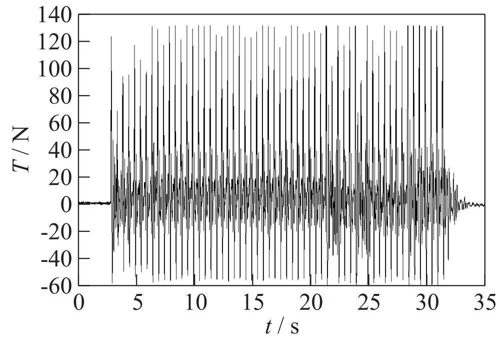


Figure 10 Typical time history of the PDE thrust measured by the load cell at PDE operation with 2 Hz. The mean thrust is 11 N

Table 2 Thrust performances of the PDE without/with nozzle extension for two operation frequencies (8 and 10 Hz) at a fixed cycle fuel-fill time $t_f = 25$ ms

f, Hz	$\overline{T}$, N	I_{sp}, s	$\dot{m}_f$, g/s
8	21.0/24.3	940/1100	2.28/2.25
10	28.6/29.7	990/1075	2.95/2.82

(8 and 10 Hz) and at a fixed value of the cycle fuel-fill time (25 ms). Here, the PDE without nozzle extension is the 210-centimeter long 50-millimeter diameter detonation tube discussed in section 1, whereas the PDE with nozzle extension is the same detonation tube with long conical nozzle extension and additional cylindrical tube section 80 mm in diameter with the total length of 345 cm. It is seen that both the mean thrust and the mean specific impulse are higher for the PDE with nozzle extension. These results confirm a well-known fact that partial fuel fill makes the PDE more efficient (see, e. g., [2]).

3 Concluding Remarks

The PDE operating on liquid propane–air mixture in the mode of repetitive DDT has been designed, fabricated, and tested on the laboratory test stand allowing for measurements of thrust and fuel mass flow rate.

The test campaign included two experimental series. In the first series, the PDE tube had no nozzle extension. In the second series, the PDE tube had a conical nozzle extension. In the tests, two parameters were varied, namely, the cycle fuel-fill time (from 25 to 100 ms) and the operation frequency (from 2 to 20 Hz). It has been shown in the experiments of the first series that there exists the minimum value of the cycle fuel-fill time (25 ms at given experiment settings) required for the DDT which is explained by the existence of the minimum run-up distance for the detonation to arise. The increase in the cycle fuel-fill time from 25 to 100 ms at 2-hertz operation, other conditions being equal, results in the gradual decrease of the specific impulse from 1075 to 500 s. The increase of the operation frequency from 2 to 20 Hz at the cycle fuel-fill time of 25 ms, other conditions being equal, results in the growth of PDE thrust from 7 to 44.6 N, while the specific impulse is about 1000 s at 2–15 Hz and decreases to 800 s at 20 Hz. The latter is most probably caused by deterioration of fuel–air mixing at higher frequencies and incomplete combustion of fuel. The use of nozzle extension in the second experimental series resulted in the increase of PDE thrust performances. Thus, at a fixed cycle fuel-fill time (25 ms) and the operation frequency (10 Hz), the PDE with nozzle extension exhibits both a higher thrust (29.7 against 28.6 N) and a higher specific impulse (1075 against 990 s) indicating that partial fuel fill makes the PDE more efficient.

Further work will be focused on increasing the operation frequency and replacing liquid propane with aviation kerosene.

Acknowledgments

This work was supported by the Russian Science Foundation (grant 14-13-00082).

References

1. Zel'dovich, Ya. B. 1940. To the question of energy use of detonation combustion. *Zh. Tekhn. Fiz.* 10(17):1453–1461. [In Russian.]
2. Roy, G. D., S. M. Frolov, A. A. Borisov, and D. W. Netzer. 2004. Pulse detonation propulsion: Challenges, current status, and future perspective. *Prog. Energ. Combust. Sci.* 30(6):545–672.

3. Frolov, S. M., and V. S. Aksenov. 2012. Device for the pulsed ignition of the combustible mixture. PCT patent application No. 2012111224 from 26.03.2012.
4. Frolov, S. M. 2008. Fast deflagration-to-detonation transition. *Russ. J. Phys. Chem. B* 2(3):442–455.
5. Frolov, S. M., V. S. Aksenov, and A. A. Berlin. 2011. Method of initiation of detonation in a tube with a combustible mixture and device for its implementation. Patent of the Russian Federation for the invention No. 2427756 from 27.08.2011. Priority of 04.03.2010.