Air breathing rotating detonation engine supplied with liquid fuels

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Abstracts

Application of common fuels in air-breathing engines which will utilize Continuously Rotating Detonation (CRD) is essential for improvement its propulsion efficiency, so research on this subject are carried out at the Łukasiewicz – Institute of Aviation for more than ten years [1-5]. There are some keys to obtain a stable CRD operation: detonation chamber geometry, combustible mixture preparation, initiation and stabilization of the detonation. Two different size models of annular detonation chamber were designed and tested – both have a pre-chamber for the mixture preparation (one of the tested method of the mixture preparation is already patented). Aviation kerosene, propane and extraction gasoline were used as fuels and there were few types of initiator in use – the article presents some methods for detonation mixture preparation and initiation which appeared to be quite effective and practical.

Introduction

The purpose of our investigation was following: to design a CRD chamber with mass flow of about 1 kg/s and possibly small pressure losses (of course it would be great to obtain a pressure gain) which could be applied in a small ramjet engine. Many years ago we started detonation tests with an air-kerosene supplied annular chamber of 226 mm diameter (outer diameter of flow channel) but it was impossible to raise the in-chamber pressure to the right level because of air-supply system inefficiency [5]. Then we improved the air supply system and designed two smaller chambers: of 180 mm and 140 mm diameter respectively. This article presents results obtained for the smaller, 140 mm diameter chamber. Our research was generally centered around a detonation chamber with several distinctive features:

1) the chamber is annular,
2) in front of the chamber there is a preliminary (mixing) chamber,

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3) combustible mixture flows into the chamber through a relatively narrow circumferential slot (this is to prevent the flame from flashing back),
4) behind the slot, there is a rapid expansion of the channel with a vertical wall, being a support for the detonation wave (this support seems to be necessary due to the relatively low average speed of the stream - about 100 m/s),
5) the cylindrical channel of the chamber ends with a circumferential outlet slot (by selecting its size, the pressure in the chamber is changed).

During tests sizes of the slots (inlet and outlet) were varying as well as the chamber height and length. The chambers were successfully tested and most tests were made with the of use of kerosene (Jet-A1) as this fuel was found to be most promising for future ramjet application.

Fuel-air mixture preparation

Continuously Rotating Detonation (CRD) is a very dynamic process - Detonation wave propagates through the combustible mixture with velocities of about 1000 m/s (or higher). The homogeneity of the mixture favors the initiation and stability of such a process. Gaseous propellants makes it easier to achieve such homogeneity, while utilization of liquid fuels makes the mixing process more difficult. Level of fuel droplets atomization must be sufficiently high before detonation front burns such a mixture. The most favorable method is fuel pre-evaporation. For this aim in tested chambers fuel was injected into the hot air stream (the air was previously heated in the supply tank).

Below is presented (Fig. 1) the diagram of such fuel preparation system according to EU patent EP 3 434979 A1 and its (slightly modified) application to 180 mm CRD chamber. Fuel is injected into the primary hot air stream creating highly rich mixture to the level it would not be possible to ignite such a mixture. Further rich mixture enters combustion chamber where it mixes with secondary air stream creating leaner, close to stoichiometric, detonative mixture.

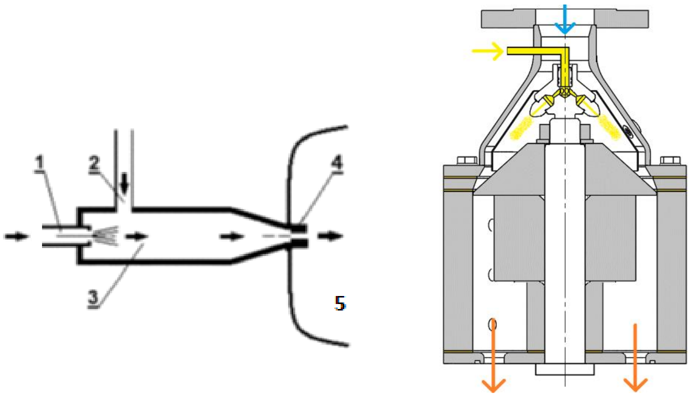

Figure 1: Main configuration of the rich-mixture injector (on left): 1-injection of the liquid fuel, 2-hot air (or other gases), 3-mixing tube, 4-injector of evaporated fuel-gas mixture at concentration above flammability limit, 5 – combustion/detonation chamber. The 180 mm diameter CRD chamber (on right) with modified rich mixture injector (air stream at the chamber's entrance is splitted in two).

Experimental results proved efficiency of this method. In the next step the research on fuel injection before combustion chamber without splitting hot (150-200 °C) air stream into primary and secondary streams was carried out (on the 140 mm diameter CRD chamber).

Initiation of CRD

There were 3 types of initiators used: detonation tube H_2-O_2 or C_2H_2-O_2 (3000-5000 J), strong spark plug (10-20 J) and a black powder "pistol" (500-1000 J). Best results were achieved for the black powder initiator – it worked quite reliably in the widest range of mass flow and O/F ratios (despite the fact that the detonation tube initiator theoretically had much more energy). The black powder charge was electrically fired (with the use of a percussion cap).

CRD chamber geometries

The basic D = 140 mm diameter CRD chamber scheme is presented in Fig. 2. During test sizes of cross sections A3.1, A3.2 and A8 as well as the chamber length L were changed. There were measured following parameters: in-chamber fast pressure changes (in the main channel close to 3.1 section), in-chamber static pressure (P3.2_stat), T2 temperature, fuel mass flow, thrust generated by the chamber. The air mass flow was calculated based on measuring orifice of own design. The geometrical parameters of the cross-section were marked with reference to research conducted by, among others, Keaming et al. [6], Bach et al. [7], Brophy et al.[8,9].

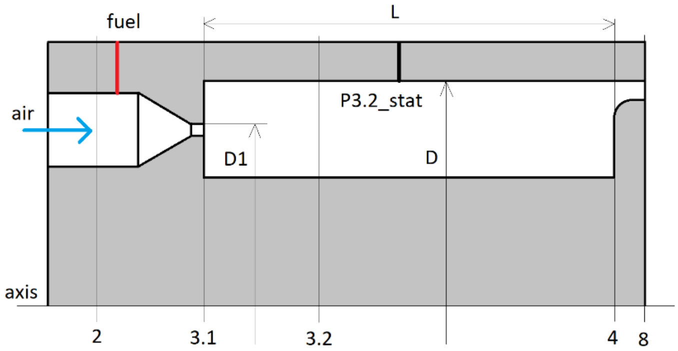

Figure 3: Scheme of the basic, 140 mm CRD chamber with indicative fuel injectors and statical pressure measurement point (P3.2_stat) location.

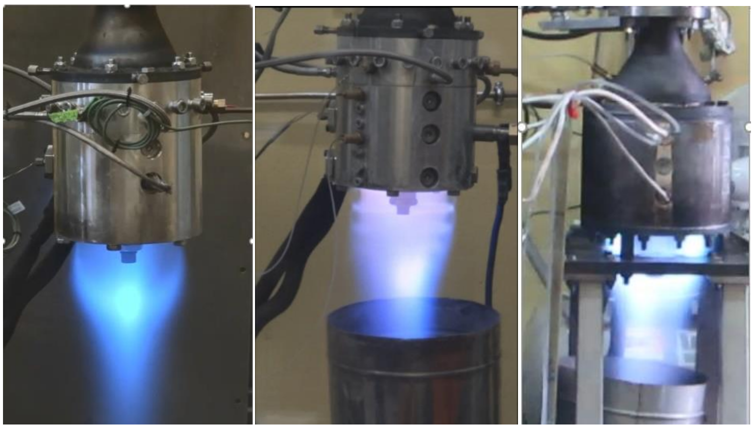

Figure 2: Combustion chamber fed with Jet-A working on the test stand : 140 mm chamber (on left and in the middle) and 180 mm (on right).

Some chosen test results obtained for D = 140 mm and L = 125 mm chamber (see Fig.2), are presented in the table below (Table.1). No. 13 shows results for deflagration mode – for comparison.

Table 1: Some results for basic chamber (D = 140 mm, L = 125 mm): 1-12 detonation, 13 - deflagration.

No	Fuel	A3.1 [mm^2]	$\frac{A3.1}{A3.2}$	$\frac{A8}{A3.1}$	P2_stat [bar]	T2 [°C]	P3.2_stat [bar]	dm/dt [kg/s]	λ	Thrust [N]	I* [m/s]	PG [%]
1	propane	587	0.073	2.00	8.02	154	6.63	0.6	0.85	704	1173	-17.3
2	kerosene	587	0.073	2.00	8.13	153	6.66	0.62	0.77	734	1185	-18.1
3	gasoline	587	0.073	2.00	8.13	150	6.76	0.58	0.72	724	1248	-16.9
4	propane	875	0.108	1.34	7.4	187	6.1	0.79	0.70	1010	1278	-17.6
5	kerosene	875	0.108	1.73	7.6	155	6.53	0.71	0.74	884	1245	-14.1
6	kerosene	875	0.108	1.97	7.3	155	6	0.75	0.86	946	1262	-17.8
7	kerosene	875	0.082	1.97	7.66	180	6.3	0.8	0.80	991	1239	-17.8
9	kerosene	1159	0.079	2.02	7.38	200	6.11	1.06	0.86	1404	1325	-17.2
10	kerosene	1159	0.079	2.02	8.18	192	6.75	1.1	1.00	1446	1315	-17.5
11	kerosene	1159	0.079	2.02	7.76	194	6.32	1	0.95	1370	1370	-18.6
12	kerosene	1159	0.079	2.02	7.69	176	6.37	1	0.85	1309	1309	-17.2
13	kerosene	1159	0.079	1.30	7.87	190	7.13	1	0.97	918	918	-9.4

Pressures P2_stat and P3.2_stat are static, absolute pressures.

dm/dt is total mass flow (air + fuel).

λ is air–fuel equivalence ratio during the combustion process (during initiation this parameter was about 30% higher – the change is caused by air stream chocking).

Thrust generated by the tested chamber was measured directly.

Parameter I* is defined as following: I* = Thrust/(dm/dt). This parameter is not a real impulse, because the measured thrust is affected by unknown pressures acting on the area of exit section of the chamber (A8), but it is still quite convenient for comparisons (e.g. point no. 13 I n Tab.1).

PG is estimated pressure gain and it is defined as follows (all pressures are absolute):

$$PG = \frac{P3.2_{total} - P2_{total}}{P2_{total}}$$

Although measured pressures were static their values are very close to the total pressures, because of relatively small flow velocity (difference is in order of 1-2%), so in this case you can state:

$$PG \approx \frac{P3.2_{stat} - P2_{stat}}{P2_{stat}}$$

Similarly, assuming that the total pressure of the stream at the exit (A8) is close to the total pressure inside the chamber (A3.2) you can find: $P8_{total} \approx P3.2_{total} \approx P3.2_{stat}$, and accordingly:

$$PG \approx \frac{P8_{total} - P2_{total}}{P2_{total}} = \frac{P8_{total}}{P2_{total}} - 1$$

Below you can see fast pressure courses registered for different fuels (test: 1-3 in Tab.1) – it is also the CRD mode confirmation.

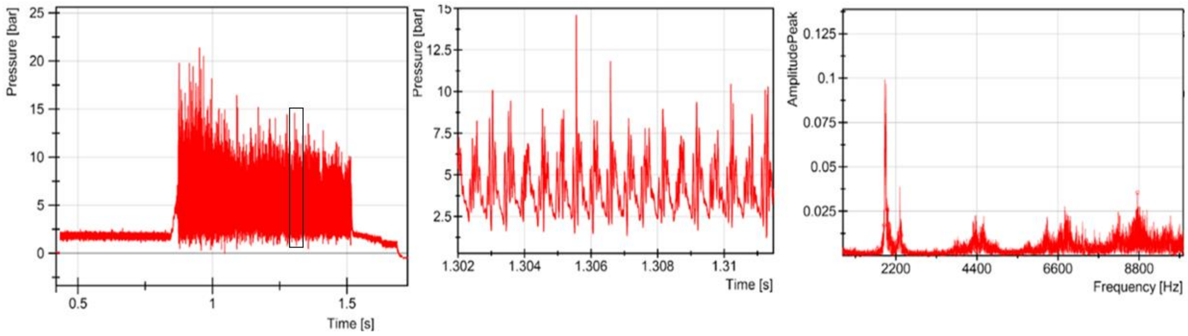

Figure 4: High frequency pressure course and Fourier transform for propane-air mixture (no. 1 in Tab.1).

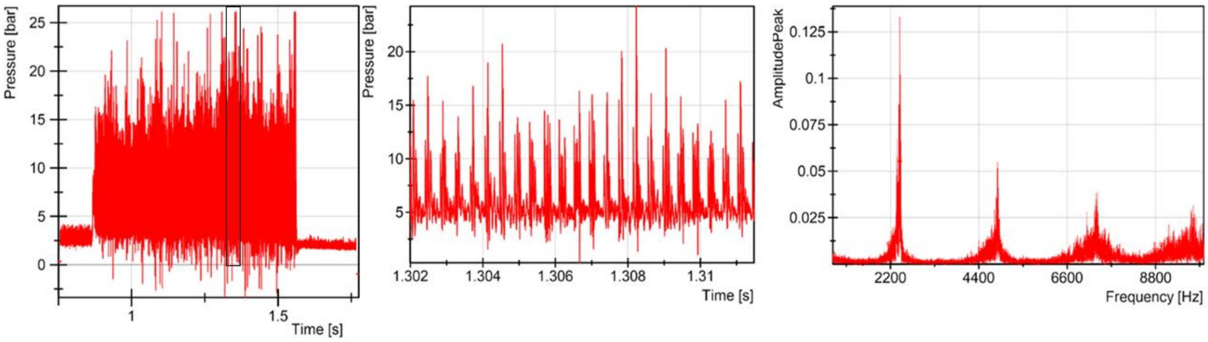

Figure 5: High frequency pressure course and Fourier transform for kerosene-air mixture (no. 2 in Tab.1).

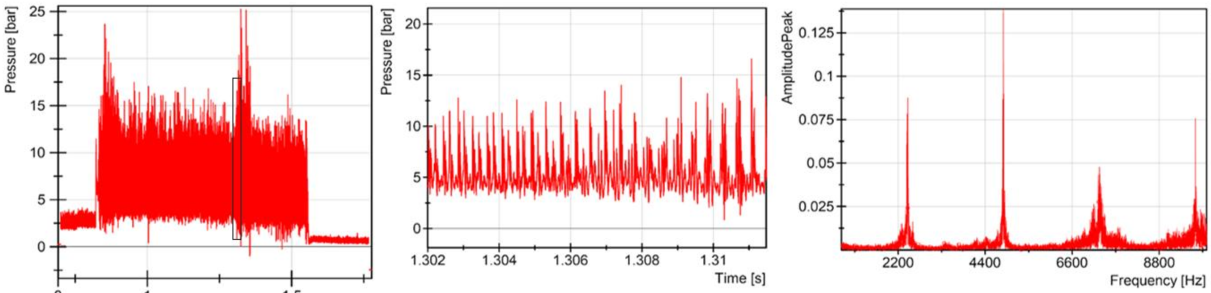

Figure 6: High frequency pressure course and Fourier transform for gasoline-air mixture (no. 3 in Tab.1).

Conclusions

1) The paper presents some results of experimental investigation on CRD made on annular 140 mm diameter chamber, supplied with hot air and 3 different liquid fuels.
2) The results for kerosene and gasoline were similar while for propane the detonation was less stable and "clear".
3) For the moment a positive pressure gain was not observed – contrary – pressure losses are quite big (14-18%). It is because the flow channel shape is very "unsmooth" (the channel

cross section changes rapidly). It may be also caused by relatively short combustion chamber (L dimension), so the next tests will be done on extended chamber (L = 250 mm).

4) The successful initiations of detonation were obtained only for rich and close to stoichiometric mixture (during CRD mode) – it was because applied initiatiators was not able to initiate very lean mixture (only after initiation air stream was decreasing rapidly for about 30 % while fuel stream was remaining approximately the same).

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