Airbreathing Kerosene-Fueled Detonation Combustion Chamber-Comparison of Different Combustion Modes

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1 Abstract

This paper presents research on a jet engine with a detonation combustion chamber for liquid kerosene. In the present study, the operation of an annular chamber and a hollow chamber was tested. During the course of the work, various combustion mods were obtained from deflagration and acoustic combustion, through unstable detonation and combustion at high-frequency instabilities to detonation combustion, where the wave spin velocity exceeded 95% of the CJ velocity. For similar combustion chamber and nozzle geometries, the achieved performance of such an engine operating in different modes was compared. The study compared process stability, specific thrust in relation to the mass flow of air and fuel, as well as parameters of throttling the flow through the chamber - pressure gain. The article is a continuation of the research on the stability of the rotating detonation process [1].

2 Introduction

The development of engines with rotating detonation is taking place in several directions. Rocket engines have been tested in many research centers worldwide [2-6]. Thanks to the application of rotating detonation, rocket engines achieve smaller dimensions and weight [7], which is important for the further development of space technology. Much hope is being pinned on the application of the rotating detonation phenomenon to ramjets and turbine engines. Significant work is being carried out in turbine engines for hydrogen gas fuel for future energy applications [8-12]. The application of a detonation combustion chamber to ramjet engines demonstrates very clearly the advantages of rotating detonation technology over existing solutions [13-15]. The use of such combustion makes it possible to significantly shorten the combustion chamber, which for currently operating ramjet systems sometimes exceeds several meters.

Work to adapt the phenomenon of rotating detonation to the Rotating Detonation Ramjet Engine is underway at the Lukasiewicz -Institute of Aviation. A new method has been developed, and a stable rotating detonation process has been achieved for liquid fuels such as aviation kerosene, propane, and gasoline. Since kerosene is the most widely used fuel in aviation, the development of RDE focused on this fuel. The study uses common kerosene (JET-A) without any admixtures.

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3 Tests and results

The test stand (Fig.1) was equipped with a system for measuring supply pressure, chamber pressures, kerosene and airflow, and thrust. Compressed and heated to about 150°C, air was fed to simulate the chamber's operation in flight at speeds of Ma from 1.7 through 2.1.

The combustion chamber has a diameter (*D*) of 141 mm, in the annular version, the channel heights (*h*) tested in the presented research were 21 mm and 53 mm. The chamber is equipped with a convergent-divergent nozzle. The length of the combustion chamber (cylindrical part) was *L* = 125 mm.

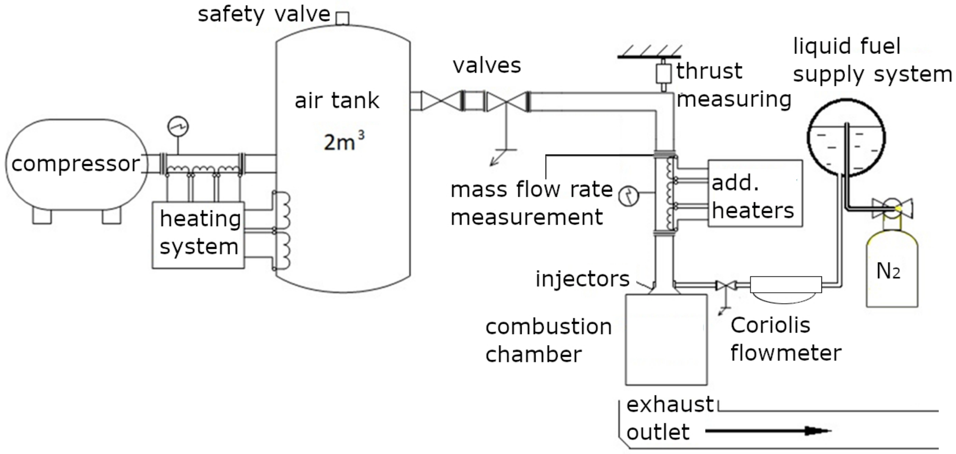

Figure 1: Scheme of rotating detonation combustion chamber stand test.

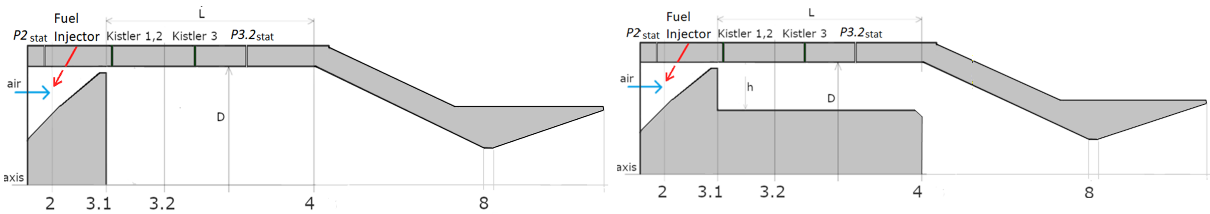

Figure 2: Schematic diagram of the tested combustion chambers. Hollow chamber (left) and annular chamber (right). The heights h of the annular chamber tested in these studies were 21 mm and 53 mm.

Pressure in the chamber was measured using ceramic pressure sensors, as well as piezo-quartz sensors (Kistler 603CAB), with a high sampling rate (up to 1 MHz), the recording of which allowed determination of the combustion mode. At least two sensors placed in the transverse plane were used. The sensors were offset by an angular value of 120 degrees (in some tests, a third sensor was installed in the longitudinal plane). On the basis of analysis of the pressure record recorded by such sensors, the existence of waves, their number, direction, and speed were determined. Based on these observations, the combustion mode in the chamber was determined. FFT or STFT analysis was also carried out.

In the tests, various combustion modes were obtained, starting with deflagration, where usually the flame “did not fit” in the chamber, and the engine thrust was only slightly greater than the engine thrust before fuel was applied. Often, the deflagration process was accompanied by low-frequency instability (LFI). In many experiments, high-frequency instabilities (HFI) were achieved - which included combustion accompanied by shock waves, but their propagation was often very chaotic. Unsteady and steady detonation was also achieved. For this mode of combustion it was possible to determine the number of waves, their speed.

LFI (Low-frequency instabilities)

Frequency and pressure amplitudes suggest the appearance of the interaction of the combustion process with pressure pulsations (thermoacoustic instabilities). Pressure excites with frequencies of about 400 - 600 Hz inside the chamber. Such combustion is accompanied by sound at the same frequencies.

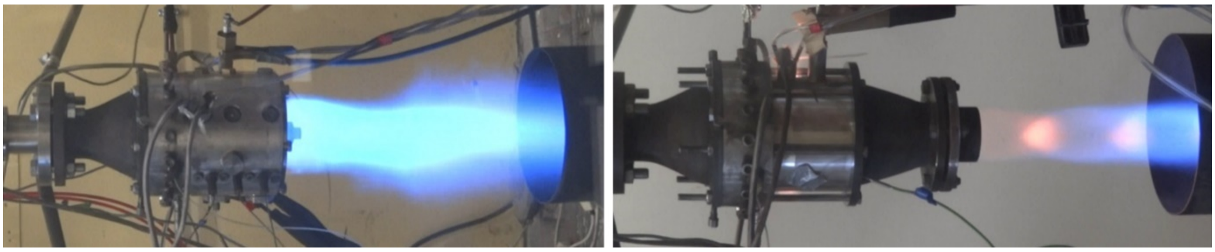

Figure 3: The flame in deflagration accompanied by LFI (left picture), and the flame during detonation (right picture) - the same is true of the flame during HFI or unstable detonation operation.

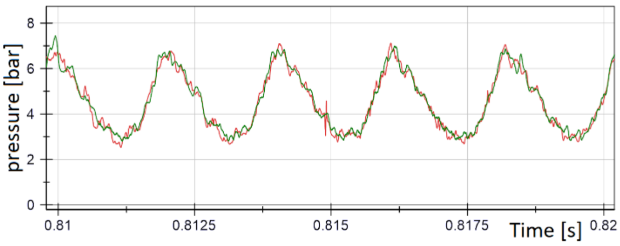

Figure 4: An example of Low-Frequency Instabilities of the pressure inside the combustion chamber.

HFI (High-Frequency Instabilities)

In HFI mode, the pressure recordings made it possible to see that there are waves in the chamber, but it is difficult to discern the number, direction, and speed of the waves. Pressure amplitudes are at the level of several bars. Such instabilities sometimes appear at the beginning of the experiment, sometimes as transient effects during an unstable detonation, in several trials such an effect was achieved throughout the entire test period.

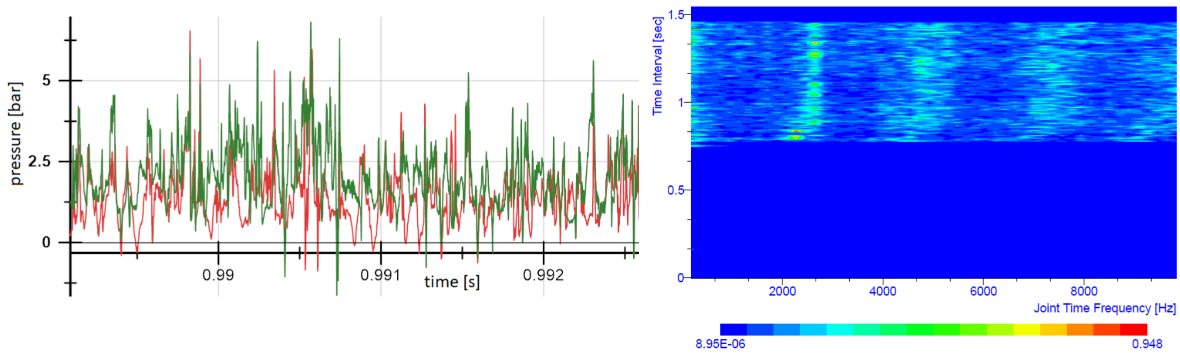

Figure 5: An example of combustion recording in HFI mode.

Unstable detonation

Unsteady detonation allows the observation of rotating waves and estimates their number and speed. The values of the pressure peaks are highly variable; the speed does not usually exceed 65% of the Chapman-Jouget speed [16]. Moreover, the effects of longitudinal HFI, tangential HFI [3], galloping detonation, etc. can be observed.

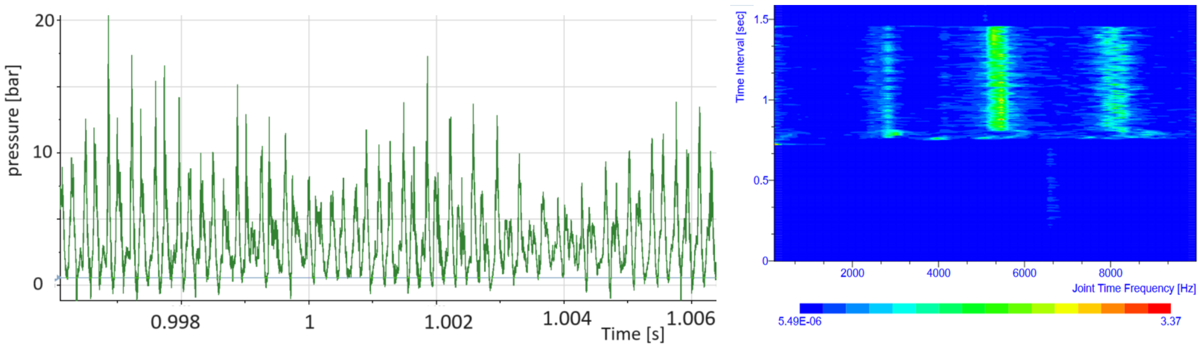

Figure 6: Pressure records of unstable detonation. Time between peaks 1.85e-4 s, dominant frequencies throughout the test, at 5.7 kHz.

Stable detonation

With certain geometric and power supply parameters of the chamber, stable spinning detonation can be achieved. In the present study, single waves were observed and rotated at 1750 m/s, which corresponds to 97% CJ speed of Chapman-Jouget velocity.

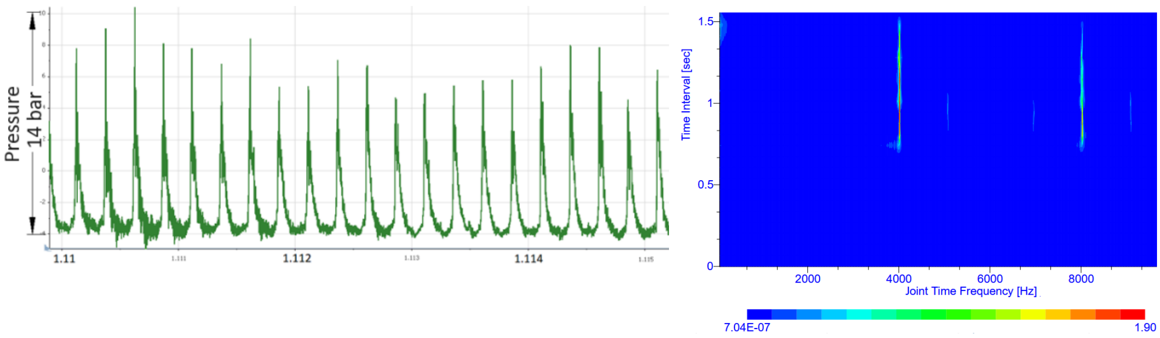

Figure 7: An example of a stable pressure recording of a spinning detonation process. Time between peaks 2.5e-4 s, dominant frequencies stable throughout the test, at 4 kHz.

Different combustion modes were achieved in the conducted trials.

For each test, the specific thrust (1) and pressure gain (2) were estimated, and the type of combustion achieved was determined.

$$F_s = \frac{\text{Thrust}}{\dot{m}_{\text{air+fuel}}} \qquad (1),$$

$$\text{PG} = \frac{P\,8_{\text{total}} - P2_{\text{total}}}{P2_{\text{total}}} \qquad (2),$$

The parameters of the combustion chamber operating in different modes were then compared (Fig. 8)

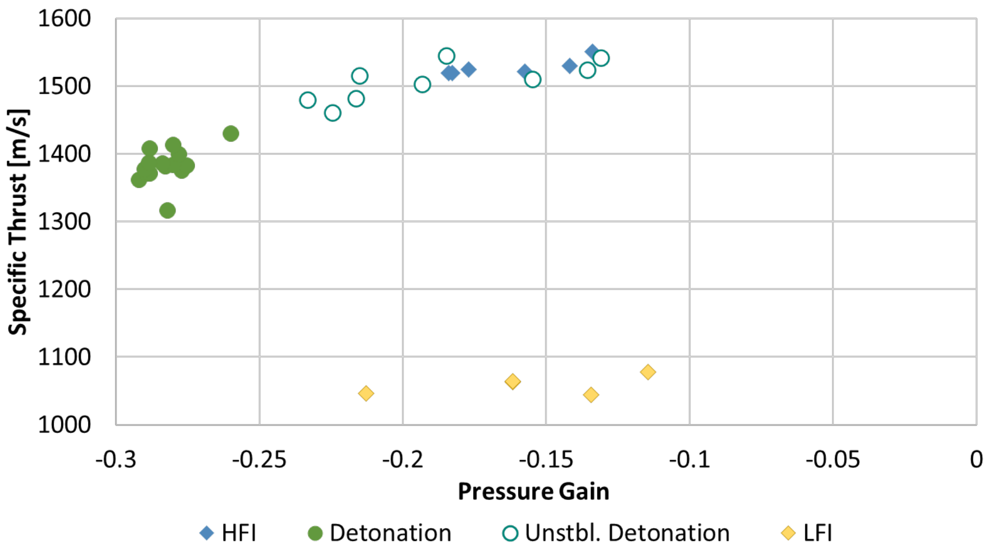

Figure 8: Comparison of the operation of the combustion chamber operating in different modes.

4 Discussion and Conclusion

Different combustion modes were obtained by modifying the A8/A3.1 cross-sectional ratio parameter (Fig. 2). For small values of this parameter, i.e., about 1.5, when the outlet area from the chamber is 1.5 times larger than the inlet area, LFI was most often obtained. For A8/A3.1 values of the order of 1.8 - 1.9, the rotating detonation mode was obtained. The most stable process of rotating detonation was observed for A8/A3.1 = 1.9 while using an annular chamber with a high channel of h = 53mm (Fig. 2), as well as for a hollow-type chamber.

As the experiments show, obtaining a very stable process of spinning detonation was not at all the most favorable from the point of view of the performance of the combustion chamber. The reason for this is mainly due to two aspects:

1) Very stable detonation is obtained with a fairly large chamber inlet throttling: A8/A3.1 of the order of 1.8 - 1.9. Inlet throttling helps stabilize the process but is not optimal in terms of flow and obtaining high pressure in the combustion chamber. This reflects on the specific thrust and pressure gain.
2) Stable detonation is accompanied by strong shock waves, propagating right at the inlet of air and fuel into the combustion chamber. In a stable detonation, these waves are very fast (more than 95% CJ speed) and are therefore accompanied by high-pressure peaks. Local high pressure located just outside the combustion chamber inlet partially blocks the flow into the combustion chamber, which also reflects on chamber pressure, thrust, and flow parameters.

The best performance of the combustion chamber was obtained for unstable detonation modes and for HFI. It is likely that HFI is detonation with very high instability. What is worth noting is that the Specific Thrust values obtained in the experiments at 1550 m/s are close to the theoretical values that can be obtained for such a mixture and such a pressure (theoretical values are about 1600 m/s).

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