

Chapter 2

Development of Gasturbine with Detonation Chamber

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Abstract Extensive and complex studies of the application of continuously rotating detonation (CRD) to gasturbine are presented. Special installation of high pressure preheated air supply system was constructed which allows to supply air at rate of a few kg/s, preheated to more than 100 °C and at initial pressure up to 2.5 bar. Supply system for Jet-A fuel which could be preheated to 170 °C was also constructed. Additionally gaseous hydrogen supply system was added to the installation. Measuring system for control air flow and measurements of detonation parameters were installed and data acquisition and control system implemented. Extensive research of conditions in which CRD could be established and supported in open flow detonation chambers, throttled chambers and finally in detonation chambers attached to the GTD-350 gasturbine engine where conducted. Conditions for which stable detonation was achieved are presented. It was found that for conditions when the GTD-350 engine was supplied by gaseous hydrogen or by dual-fuel, Jet-A and gaseous hydrogen, thermal efficiency of the engine could be improved even by 5–7% as compared to the efficiency of the base engine.

1 Introduction

It is well known that unlike deflagration which results in pressure drops, during detonation pressure is significantly increased, so implementation of detonative combustion into engine may result in improvement of engine efficiency. Such idea was first proposed by Zeldovich (1940), but first possible application of detonation to the propulsion system comes from the University of Michigan where Nicholls et al. built and tested the first pulsed detonation engine (Nicholls et al. 1957). Detonative combustion can be implemented into propulsion systems in many different ways. In engines, detonation can be stationary or nonstationary (pulsating) as

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related to engine frame, stationary or quasi-stationary as related to moving coordinate system. Application of detonation combustion to engine offers not only higher thermodynamic efficiency, but also higher energy release rate and more compact heat release chamber as compared with conventional engines using deflagration. Such engines can be applied to propel subsonic and supersonic airplanes as well as to spaceplanes or rockets. Detailed description of possible application of detonation to propulsion can be found in (Wolański 2011, 2013). During last ten years more research on detonative propulsion was focused on application of quasi-stationary detonation propulsion (stationary as related to the rotating frame of reference). Such engines are the “Rotating Detonation Engine” (RDE), which is alternately called Continuous Wave Detonation Engine (CWDE).

2 Continuously Rotating Detonation

In the early sixties of the last century, at Novosibirsk Institute of Hydromechanics, stabilized spinning detonation was successively achieved by Voitsekhovskii et al. (1960, 1963). The first attempt of practical applications of stabilized spinning detonation was then undertaken at the University of Michigan on development of continuous detonation propulsion system, but unfortunately no successful operation of such system was achieved. In conclusion of the report authors clearly stated: “Nothing has been found that makes the concept not possible but important questions ... remain to be answered. It is believed that much is to be gained from further studies of rotating detonation wave in annular chamber. While successful operation has not been achieved herein, nothing fundamental stands in the way of this accomplishment” (Nicholls et al. 1962). After this, research on application of continuous detonation to propulsion system was interrupted for several years, but at the beginning of this century it was more successfully revitalized in different laboratories (Bykovskii and Vedernikov 2003; Bykovskii et al. 2006; Kindracki et al. 2006; Falempin et al. 2006; Davidenko et al. 2007; Kindracki 2008; Zitoun and Desbordes 2011). Recently experimental and numerical research of CRD are carried out in Russia, Poland, France, USA, Japan, China, Korea and Singapore.

The continuously rotating detonation (CRD) or sometimes called continuous spin detonation, is a basic process for all RDE. It is most often initiated and run in cylindrical chambers, but sometimes also in a disk like chamber or other configurations. Typical configuration of cylindrical detonation chamber is shown in Fig. 2.1 (Wolanski 2010, 2013) and stable CRD pressure record in Fig. 2.2 (Wolanski 2010, 2011, 2013).

The first calculation of rotating detonation structure was performed by Adamson and Olsson (1967), Shen and Adamson (1972). They were examining possibility of using CRD in rocket motor, but even by using very low power computers they were able to recognize basic structure of detonation. The first detailed calculation of the structure in relatively large 2-D cylindrical chamber was performed by Hishida et al. (2009). This was possible for the case when annular cylindrical chamber thickness of channel to radius of the chamber is small. In Fig. 2.3 flow field of the

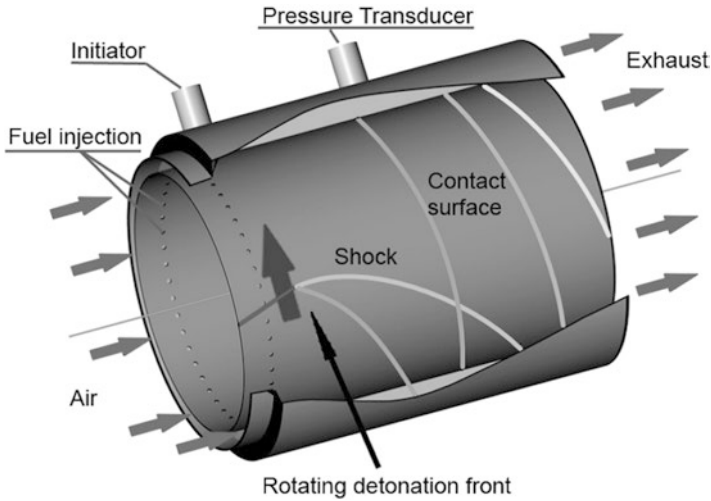


Fig. 2.1 Schematic diagram of detonation chamber for basic research of CRD

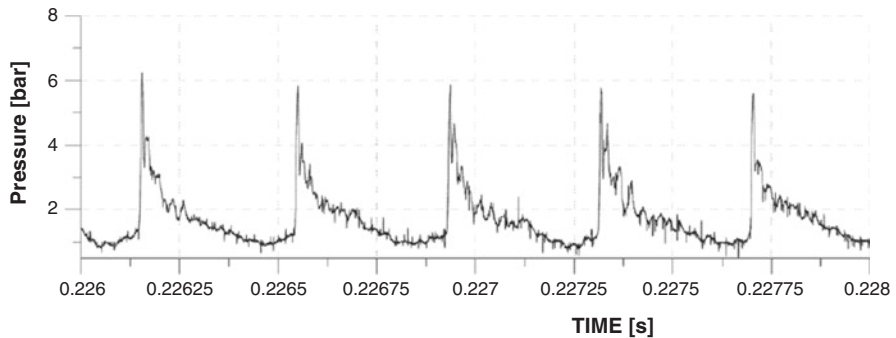
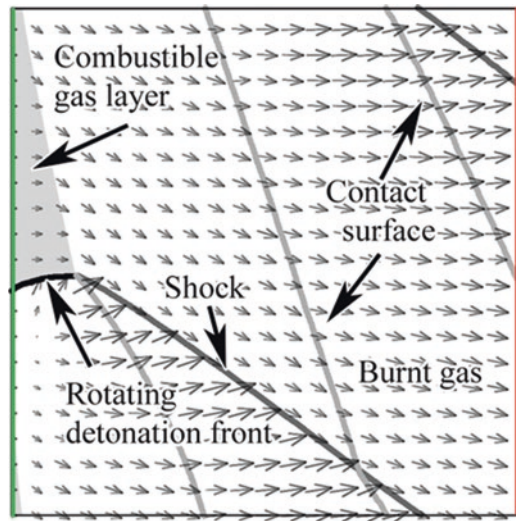


Fig. 2.2 Typical pressure variation for stable CRD in research chamber

CRD is shown in laboratory coordinate system. From this calculation a very important conclusion could be drawn, that even detonation wave rotate along circumference of the detonation chamber, flow of the products from chamber is basically axial, so in RDE there will be very little losses of energy for rotational component of the flow. A detailed description of 2-D structure of CRD can be found in (Hishida et al. 2009). When a chamber depth is larger, the 3-D calculation of CRD performed is necessary. Detailed calculations of 3-D CRD structure are now being performed in many research centers in Poland, France, USA, Russia, Japan, Korea, Singapore and other countries (Kindracki et al. 2011; Folsiak et al. 2011; Schwer and Kailasanath 2010; Shao and Jian-Ping 2010; Kailasanath et al. 2011; Davidenko et al. 2011; Yamada et al. 2010).

Fig. 2.3 Computational results of 2-D CRD structure showing velocity vector in laboratory coordinate system (Hishida et al. 2009)



3 Experimental facility

Research of application of CRD to gasturbine were carried out at the Institute of Aviation for nearly 5 years (2010–2015). For the research GTD-350 engine, which is used to power Mi-2 helicopter (NATO reporting name “Hoplite”) was chosen. The reason for this choice was the location of the combustion chamber, which basically is located outside the rotating part of the engine, compressor and turbines, and made engine combustion chamber modification relatively easy.

RD-350 Gasturbine Engine

GTD-350 engine consist of the seven-stage axial flow compressor plus single-stage centrifugal compressor. Maximum compression ratio is between 4.5–6 (depending on version) and maximum air flow rate about 2 kg/s. The engine has a single reverse flow combustion chamber and two turbines: single-stage compressor turbine and two-stage power turbine. A schematic diagram of the GTD-350 is presented in the Fig. 2.4.

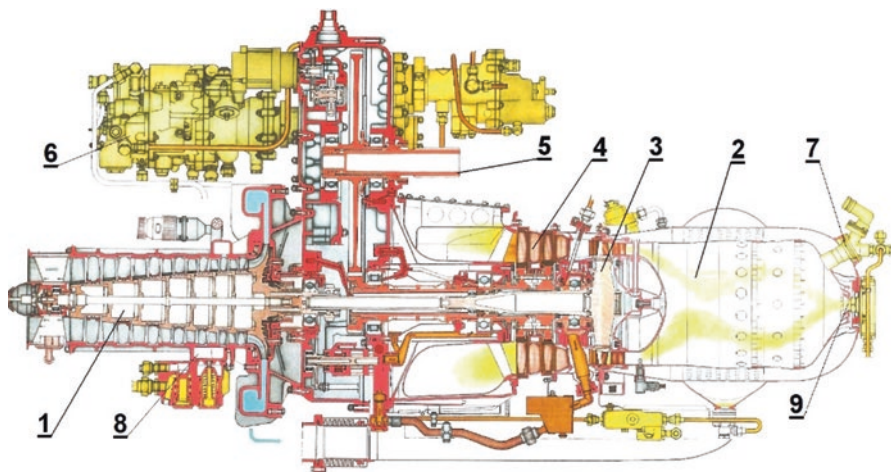


Fig. 2.4 Schematic diagram of the GTD-350 gas turbine engine. 1 compressor, 2 combustion chamber, 3 compressor turbine, 4 power turbine, 5 power shaft, 6 pump-regulator, 7 ignition device, 8 air bleeding valve, 9 main injector

Detonation Chambers

The initial part of the research was to evaluate conditions at which CDW could be established in a chamber of the diameter suitable for connecting the turbine to the engine. To find the optimum configuration of the chamber many different detonation chambers were tested. Since it was found that for pure Jet-A fuel continuous detonation is difficult to establish, and is basically not very stable, two other configurations were tested. Beside the chamber which used only Jet-A fuel, a chamber that was supplied only by gaseous hydrogen as a fuel and dual fuel detonation chambers in which Jet-A and gaseous hydrogen are used simultaneously were tested. In the case of dual fuel supply, the gaseous hydrogen consists usually of less than 25%, as related to energy contribution during combustion, but some time hydrogen concentration can even exceed 50%. Schematic diagrams of such chambers are presented in Fig. 2.5. In all cases chambers were supplied by high pressure preheated air. The initial pressure of air used in experiments was ranging from 1 bar to 2.5 bar and the initial air temperature was in the range of 80–130 °C, at the inlet to the chamber. The flow rate of air could also be changed from 0.4 kg/s up to 2.5 kg/s. All dual fuel chambers were tested in three different modes: supplied only by Jet-A fuel, supplied only by gaseous hydrogen and supplied by both fuels simultaneously. In the case of Jet-A fuel, also two different modes were tested: fuel supplied at ambient temperature and fuel preheated to 170 °C. A schematic diagram of the fuel supply system is shown in Fig. 2.6.

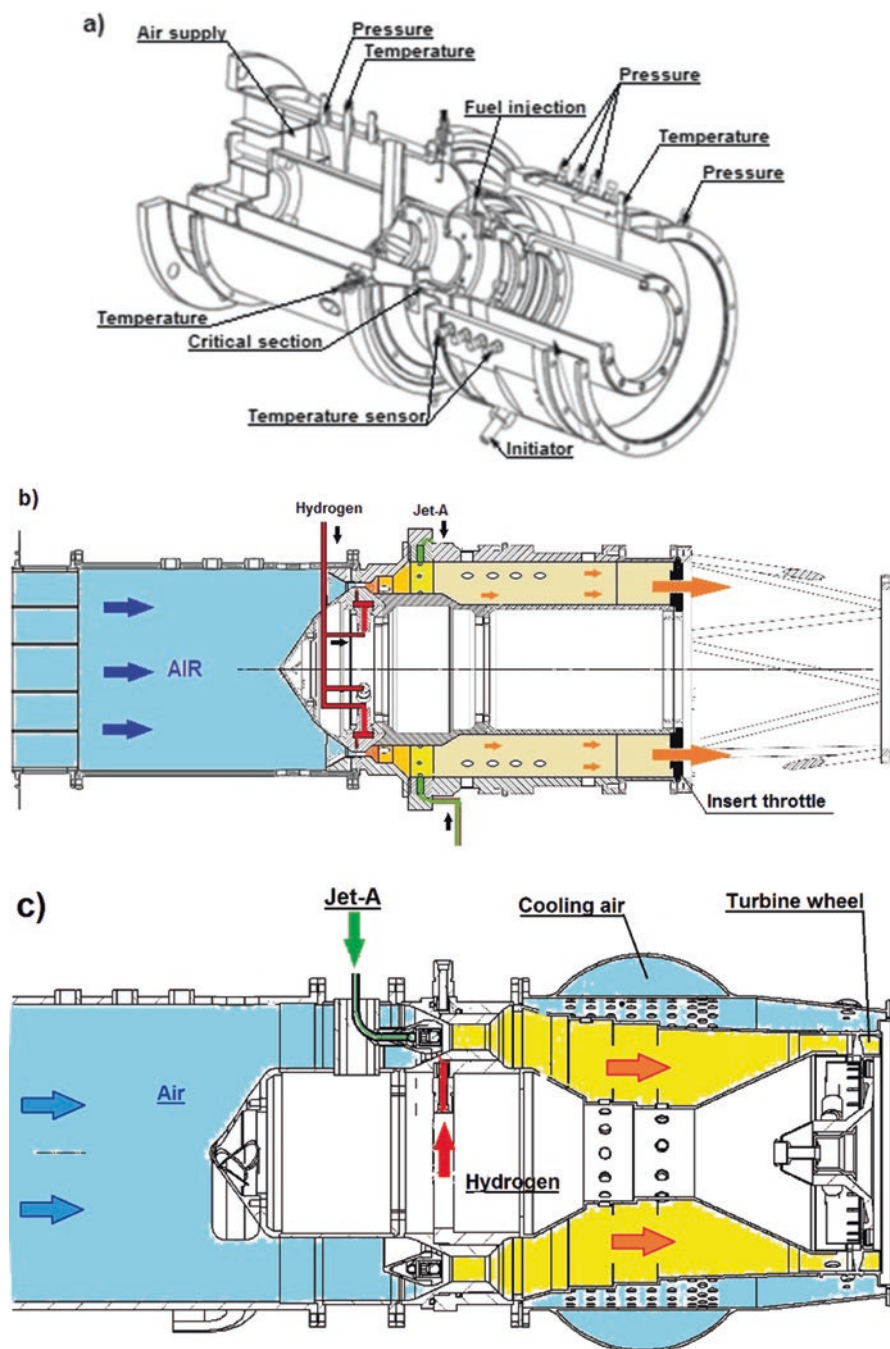


Fig. 2.5 Different configurations of tested chambers: (a) schematic diagram of cross-cutting view of detonation chamber with indication of typically used measuring points, (b) diagram of dual fuel detonation chamber, (c) diagram of dual fuel detonation chamber with supply of cooling air

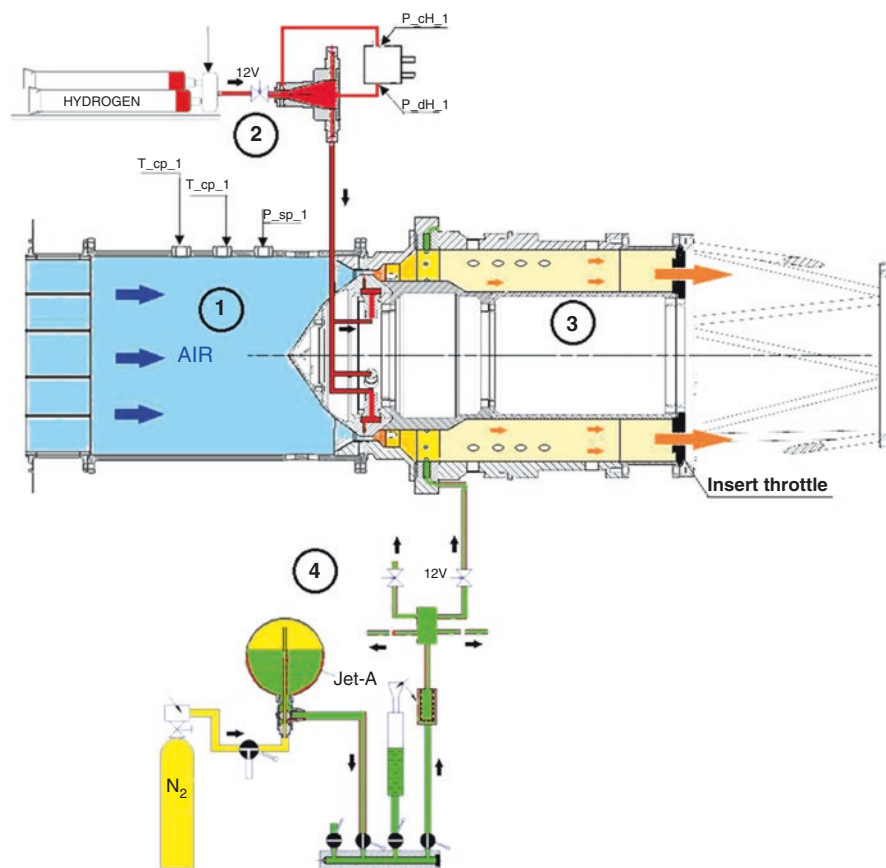


Fig. 2.6 Schematic diagram of the research chamber with dual fuel supply system. 1 air flow, 2 hydrogen supply system, 3 chamber “hot part”, 4 kerosene Jet-A supply system

GDT-350 Gasturbine with Detonation Chamber

Final research were carried out at the test stand in which detonation chamber was directly connected to the GTD-350 gasturbine engine. Schematic diagram of the test stand is shown in Fig. 2.7. GTD-350 gasturbine engine is working in this case in the open cycle.

In this case high pressure preheated air from compressor and preheater is supplied to the detonation chamber, which is directly connected to the inlets of the turbines of the GTD-350 engine. Detonation products enter vanes of the turbine stage, which is directly connected to compressor. Then products flow through free turbine which is connected to the brake, which measure the torque, so the power can be calculated. Compressed air in multistage compressor is throttled to the desire pressure, so the power delivered from the turbine to compressor is calculated and

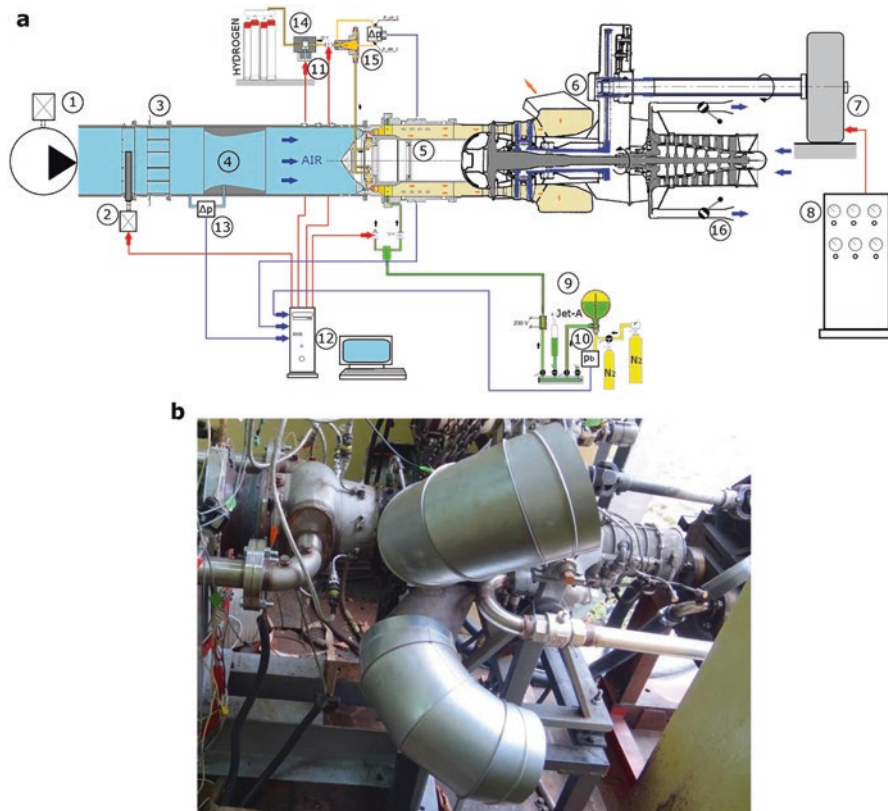


Fig. 2.7 Gas turbine research facility. (a) control system of the turboshaft engine with detonation combustion chamber: 1 air compressors unit, 2 air flow controller, 3 inlet flow equalizer grid, 4 venturi air mass flow measurement, 5 detonation combustion chamber, 6 turboshaft engine GTD-350, 7 brake, 8 brake controller, 9 Jet-A injection system (pressurized by nitrogen), 10 Jet-A flow meter, 11 electro hydraulic valve, 12 management computer, 13 air flow differential pressure, 14 hydrogen supply system, 15 hydrogen flow differential sensor, 16 air exhaust with suppression valve. (b) picture of test stand

performance of the engine can be obtained. Supply of both fuels (hydrogen and Jet-A) is controlled by computer and the data acquisition system collects and records parameters of the engine test.

4 Experimental Research

Extensive research were carried out at the Institute of Aviation for nearly 5 years. Initial works were directed into preparation of special installation of compressed and preheated air supply system, fuel atomization and mixture formation, selection

of the detonation initiator system, design and construction of control and data recording system. Over ten different detonation chambers were tested, initially with an open end and then with a throttle placed at the end of the chamber to simulate turbine inlet as well as pressure drop at the turbines. In the open chamber tests it was possible to evaluate most favorable conditions which support continuously rotating detonation (CRD) in the chamber. Besides pressure measurement which was made for each run, also visual observation of flame, direct photography as well as noise level and frequency, were usually used to identified mode of combustion in the chamber. If CRD was initiated the very short flame was observed accompanied by high frequency noise. For deflagrative combustion long flame emerging from the chamber was easily visible with a low frequency noise. Typical pictures of flame emerging from the chamber for non-detonation (deflagration) and detonation case are shown in Fig. 2.8.

Even for open chambers detonation was much easier to initiate if the Jet-A fuel was preheated to about 170 °C (better atomization and mixture formation). A typical pressure record for detonative combustion of Jet-A fuel mixed with air is presented in Fig. 2.9.

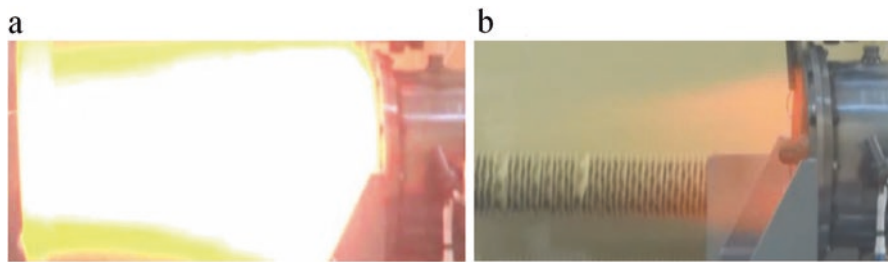


Fig. 2.8 Direct picture of flame emerging from the combustion chamber for (a) deflagrative combustion, (b) for detonation

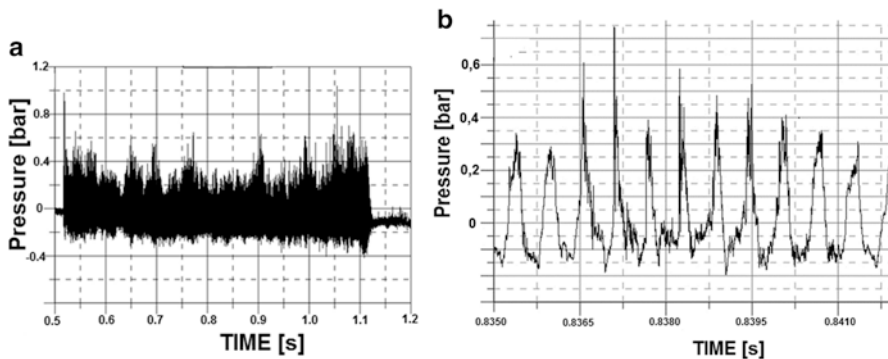


Fig. 2.9 Typical pressure records of rotating detonation in cylindrical chamber for liquid kerosene, air supply rate – 0.7 kg/s (100 °C), Jet-A – 0.032 kg/s (170 °C), (a) the whole test record, (b) the enlargement of selected interval

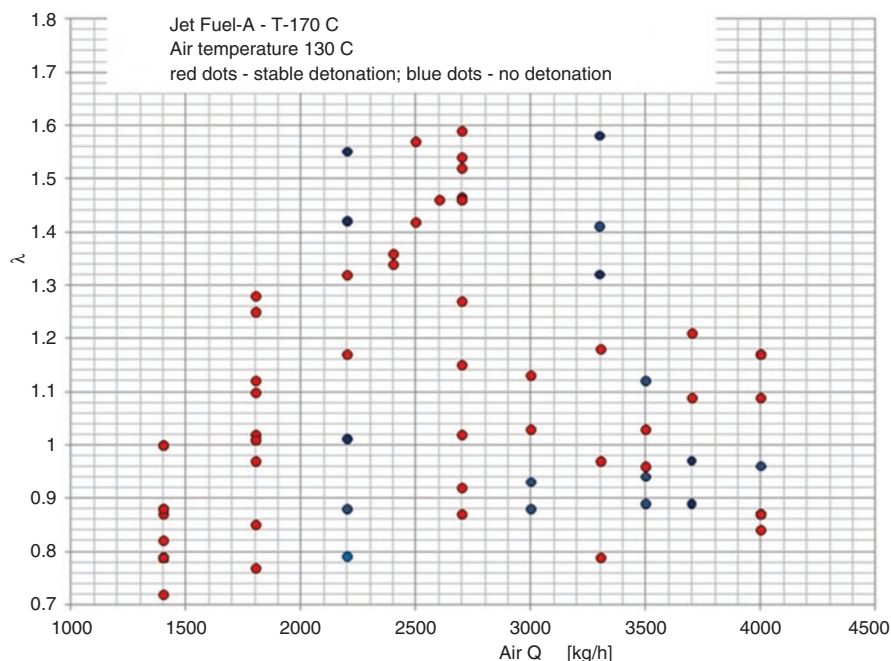


Fig. 2.10 The results of stable detonation and no detonation for Jet-A fuel –air mixture. Fuel was preheated to 170 °C and air to 130 °C

However, stability and repeatability of detonation for those tests were rather poor. It is clearly visible in Fig. 2.10, which present collection of many test results for such a mixture, at different air supply rate as well as different fuel supplies λ (λ – ratio of air supply rate to the theoretical stoichiometric air supply rate). For low rates of air supply, which results in lower velocity at the inlet and probably better mixture formation was obtained and detonation was stable, but for higher rate of air flow appearance of stable detonation is not certain and rather stochastic. To improve stability of detonation of Jet-A fuel, detonation chambers were modified to allow dual-fuel supply.

Gaseous hydrogen was added as the sensitizer for the jet fuel. This drastically improved stability of initiated detonation in the chamber. Typical pressure record for dual-fuel supply system is presented in Fig. 2.11. It is clearly seen that addition of hydrogen to the mixture improved stability and intensity of the detonation process. It is also clearly seen that when jet fuel is cut off and hydrogen is still being supplied, detonation combustion is continued, but intensity of such a process is much weaker. The best results are, however, obtained for hydrogen-air mixtures. As it is seen in Fig. 2.12, pressure picks are very even and very stable. 3-D numerical calculations were also carried out to verify the structure and stability of such detonation. Contours of pressure, temperature and mass fraction of hydrogen as well as particles streamlines are depicted in Fig. 2.13.

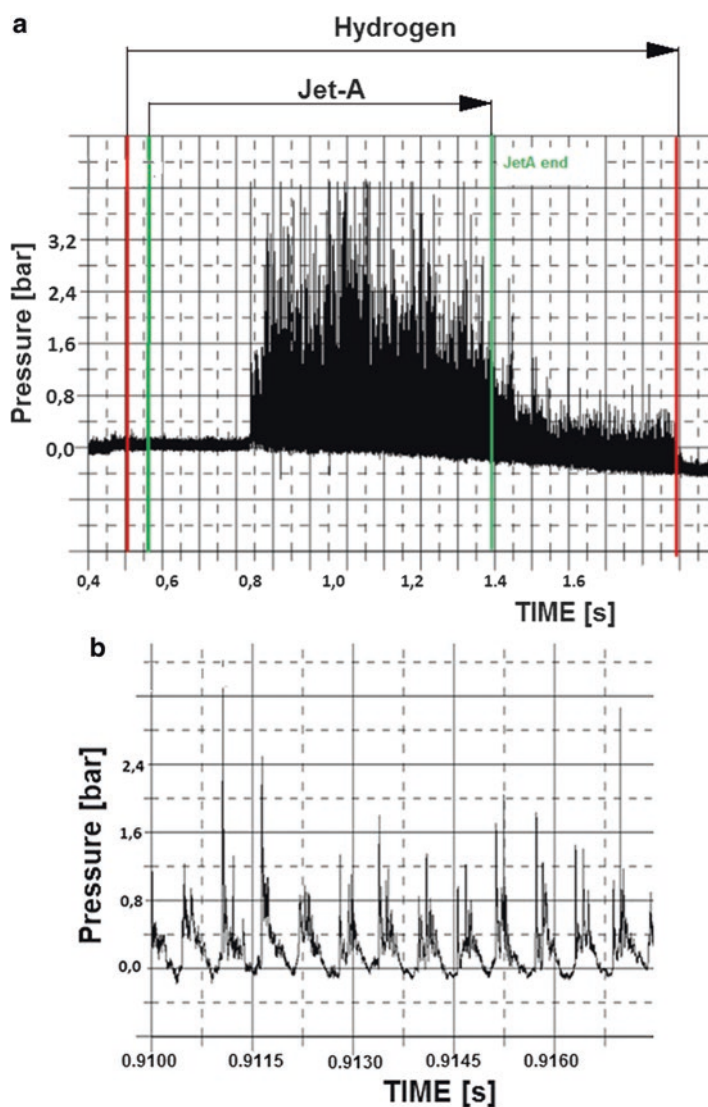


Fig. 2.11 Typical pressure record for dual fuel (hydrogen and kerosene), air supply rate – 2 kg/s, H_2 –0.022 kg/s, Jet-A – 0.021 kg/s.(a) the whole test record, (b) the enlargement of selected interval

Such calculations are very helpful in understanding the details of flow field in chamber at given condition, and as a result, help to modify geometry of the detonation chamber. In tested chambers detonation in hydrogen-air mixture was usually very stable as compared to dual-fuel mixtures.

It is very well seen in Fig. 2.14, where variation of rotating detonation velocity with time is clearly visible.

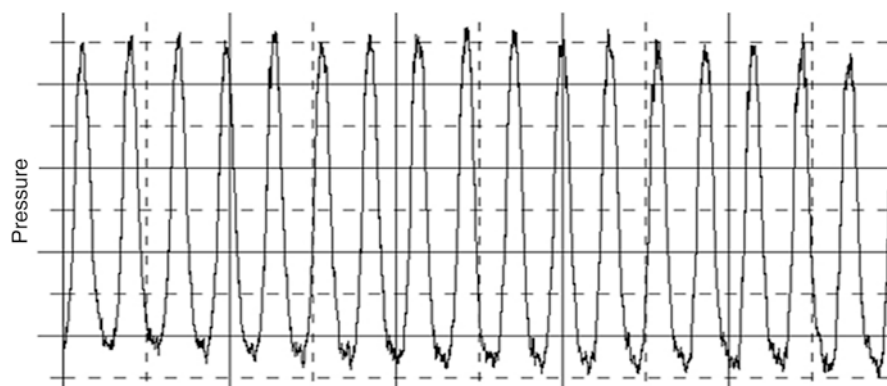


Fig. 2.12 Typical pressure records for hydrogen-air mixture, the enlargement of selected interval, air supply rate – 1 kg/s, H_2 –0.017 kg/s

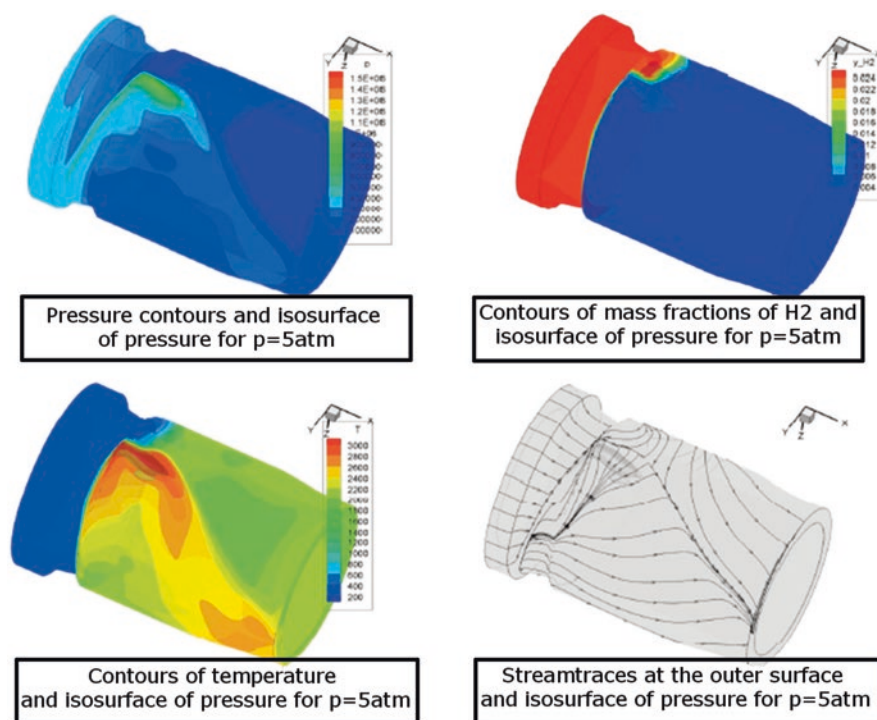


Fig. 2.13 Numerical calculations of CRD structure in 3-D complex geometry for hydrogen-air mixture (Folusiak et al. 2011)

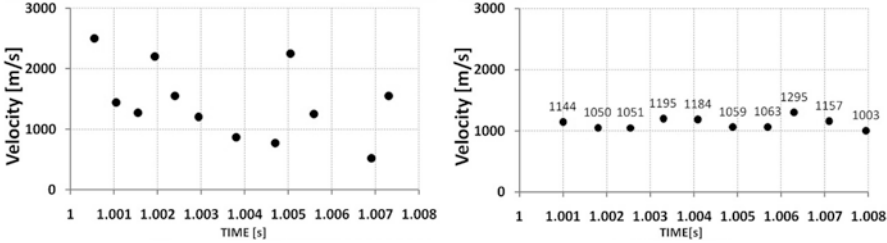


Fig. 2.14 Stability of the CRD, (a) Hydrogen and Jet Fuel and Air mixture, (b) Hydrogen and Air mixture

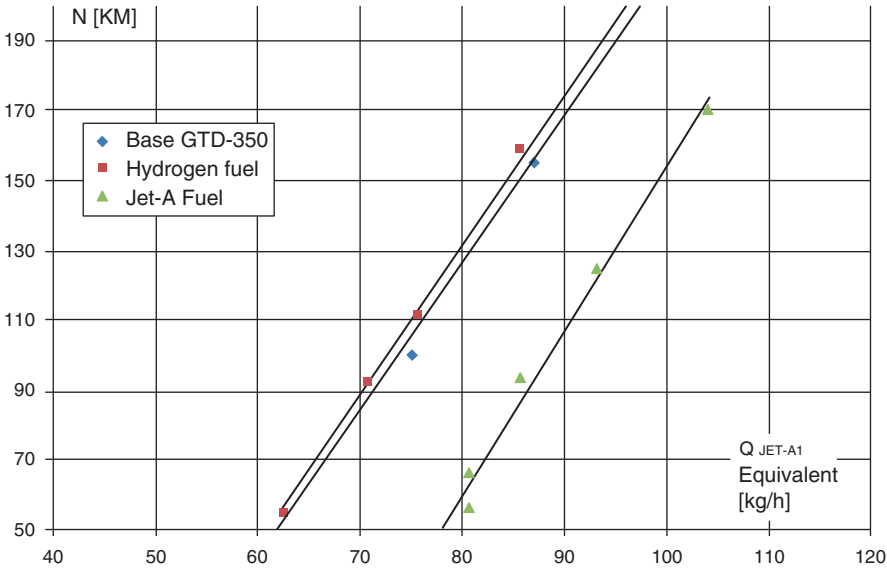


Fig. 2.15 Engine shaft power as a function of fuel consumption (for Hydrogen and Jet-A in equivalent of total heat)

Mixtures of hydrogen with jet fuel exhibit rather big instability, while for hydrogen-air mixture continuously rotating detonation is very stable. Finally, many experiments were conducted with GTD-350 engine attached to detonation chamber. At those tests not only stability of detonation was monitored but also performance of the engine calculated. Experiments were conducted for lean mixture conditions at which maximum temperature of the products, at chamber exit, were below temperature allowed for the first stage of high pressure turbine. It was found that on Jet-A fuel supply system engine can operate, but the performance of such engine is even below base GTD-350 characteristic. Best performance of the engine was obtained for hydrogen-air mixture. Due to limitation of hydrogen supply test were carried out for the duration less than one minute, but this was sufficient for the engine to operate at the steady state conditions. At such case engine operates steadily

and shows higher efficiency by 5–7%. Slightly less performance was recorded for dual fuel supply system (gaseous hydrogen and liquid preheated Jet-A fuel). Results from the experiments are presented in Fig. 2.15.

5 Summary and Conclusions

Complex research on application of continuously rotating detonation to gasturbine engine were performed at the Institute of Aviation in Warsaw. Special experimental facility was built and equipped with control and measurement systems. Initially research was focused on the mixture formations well as on the process of initiation of detonation in chamber. The conducted research shows that preheating of the liquid fuel is very helpful for better mixture formation, but it does not guarantee successful initiation of detonation as well as stability of detonation process. A much better performance was obtained for dual fuel supply. An addition of gaseous hydrogen to the liquid fuel improves the initiation and stability of the CRD. The best results, however, were obtained for the mixtures of air with gaseous hydrogen.

It was found that performance of GDT-350 with detonation chamber can improve efficiency of the engine even by 5–7%, when engine is supplied with gaseous hydrogen, but also some improvements were recorded for dual fuel mixtures. Unfortunately, when engine was supplied only by Jet-A fuel improvement of engine performance was not possible. However, paraphrasing the statement of Michigan group from sixties of the last century, that nothing has been found that makes the concept not possible but higher pressure and larger diameter of the chamber will be required to stabilize rotating detonation in Jet-A fuel-air mixture. As it is known that detonation stability is related to the cell size, and cell size is decreasing with increase of the pressure, so one can expect that for conditions under which modern jet engines are operating – stable continuously rotating can be achieved for jet fuel air mixtures. However, more research in higher initial pressure and in larger dimensions of the detonation chamber are necessary to implement continuously rotating detonation to gasturbines and jet combustors, which will result in higher engine efficiency and higher engine performance.

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Detonation Control for Propulsion

Pulse Detonation and Rotating Detonation Engines

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