Application of the Continuous Rotating Detonation to Gas Turbine

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Abstract. In this paper experimental research on rotating detonation carried out at the Institute of Aviation (IA) in Warsaw are presented. Research was focused on 3-D numerical simulations of detonation propagation in cylindrical chambers and on evaluation of conditions at which rotating detonation is propagating in cylindrical channels for kerosene-hydrogen-air mixtures. Conducted simulations are used for analysis of complex flow – detonation front interaction and for estimating the thermodynamic parameters of the outflow gases. Extensive research on continuously propagating rotating detonation in many different chambers and in different fuel-air mixtures were tested. On bases of conducted calculations, as well as results of experimental study, a few chamber were selected for tests with GTD-350 engine. It was shown that application of the continuously rotating detonation to GTD-350 engine can results with increased efficiency of the engine.

Introduction

Application of the detonation combustion offers significant improvement of efficiency comparing to modern jet propulsion including turbojet and rocket engines. Detonative combustion can be applied for jet propulsion in two different modes, one is Pulsed Detonation Engine (PDE) while other in Rotating Detonation Engine (RDE). Unlike the deflagration, the detonation is a very rapid process. In detonation the reaction front in fuel-air mixture propagates with the velocity of km/s and produces a significant pressure increase. Since the pressure is increased during detonative combustion, efficiency of the engine cycle is increased. In engines, detonation can be organized in different ways, but regardless of the modes, benefit from the detonative combustion application could be very significant as compared to the deflagration combustion. In all detonative cases, the energy release rate and thermodynamic efficiency will be much higher. The principle of the RDE is based on the formation of continuously propagating detonation in a disk-like combustion chamber (toroidal or ring-like shape). The fresh mixture is supplied from one side and combustion products are expanding from the other side of the chamber.

In the Institute of Aviation a propulsion system based on detonative combustion was extensively studied. Research was concerned on application of the rotating detonation to propulsion systems and is focused on mixture formation, initiation and propagation of detonation in cylindrical chambers. Also numerical modeling of such processes is carried out for the optimization of geometry as well as operating parameters. For the last five years extensive testing of the gas-turbine engine, GTD-350, with specially designed detonation chamber in which continuously rotating detonation was propagating, instead of traditional combustion chamber which uses deflagrative combustion, was tested.

In the Rotating Detonation Engine (RDE) a simple configuration and a higher thrust due to the continuous injection could be achieved. Also wider operating conditions, without limitation of injection velocity, could be obtained. Additionally, once initiated, it would continuously operate without a need to reinitiate. Since the engine can operate at lean or rich mixture, low emission of NOx can be expected.

Advantages of application of the continuously rotating detonation (wave) combustion process in all jet engines will results in a very compact combustion chamber, and thus engines will be shorter, simpler and, due to pressure increase in detonative combustion, will execute higher engine performance. Also RDE will have a lower mass and will be less expensive. Such engines will have direct application in many areas, ranging from commercial aircrafts to supersonic transport, as well as

in rocket propulsion. More detailed description of the basic principle and research conducted on application of detonation to the propulsion systems can be found in [1-3].

Numerical simulations

First detailed 2-D calculation of the structure of rotating detonation in cylindrical chamber were performed by Hishida et al. [4]. Later in the Institute of Aviation in-house numerical model REFLOPS was developed especially for study of rotating detonation. The numerical model is based on the classical Euler equations describing the motion of a reacting inviscid gas. The model is capable to simulate detailed chemistry, but to save the computation time, usually simple single or two-step mechanisms are used. The code works on unstructured adaptive grids. This allows a simulation of the detonation in real geometries of the detonation chamber.

Simulations are based on the classical Euler equations describing the motion of a reacting inviscid gas

$$\frac{\partial Q}{\partial t} = -\frac{\partial E}{\partial x} - \frac{\partial F}{\partial y} + S + S_{inj} \,, \tag{1}$$

where

$$Q = \begin{pmatrix} \rho \\ \rho u \\ \rho v \\ e \\ \rho_i \end{pmatrix}, E = \begin{pmatrix} \rho u \\ \rho u^2 + p \\ \rho vu \\ (e+p)u \\ \rho_i u \end{pmatrix}, F = \begin{pmatrix} \rho v \\ \rho uv \\ \rho v^2 + p \\ (e+p)v \\ \rho_i v \end{pmatrix}, S = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ \omega_i \end{pmatrix}, S_{inj} = \begin{pmatrix} \dot{\rho}_{inj} \\ 0 \\ 0 \\ \dot{\rho}_{inj} h_{inj} \\ \dot{\rho}_{inj\,i} \end{pmatrix}. \tag{2}$$

Injection source term S_{inj} is a function of the injection pressure p_{ijn}, temperature T_{ijn}, the ratio of the nozzle area to the wall area f_{nozzle} and height of the channel h_{ch}

$$\dot{\rho}_{inj} = \frac{p_{inj}}{\sqrt{RT_{inj}}} \sqrt{\frac{2\gamma}{\gamma-1}\left[\left(\frac{p}{p_{inj}}\right)^{2/\gamma} - \left(\frac{p}{p_{inj}}\right)^{(\gamma-1)/\gamma}\right]} \frac{f_{nozzle}}{h_{ch}} \;\; : \textit{for subsonic flow}$$

$$\dot{\rho}_{inj} = \frac{p_{inj}}{\sqrt{RT_{inj}}} \sqrt{\gamma\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} \frac{f_{nozzle}}{h_{ch}} \qquad\qquad : \textit{for sonic flow} \tag{3}$$

The source term of the energy equation is a product of the density source term and total enthalpy of the injected gas h_{inj} , while in the species continuity equation the partial densities rates $\rho_{ijn\,i}$ are calculated by multiplying ρ_{ijn} by mass fractions of the components of the injected gas.

The model is capable to simulate detailed chemistry and ω_i is calculated as sum of production and destruction of the i-th specie in all reactions

$$\omega_i = \frac{d\rho_i}{dt} = W_i\left[\sum_{k=1}^{m} \pm v_{i,k}\,\alpha\left(k_{k,for}\prod_j C_j^{\upsilon_{jk}} - k_{k,back}\prod_j C_j^{\upsilon_{jk}}\right)\right], \tag{4}$$

Detailed description of the model and solution techniques can be found in [5].

(a)   (b)

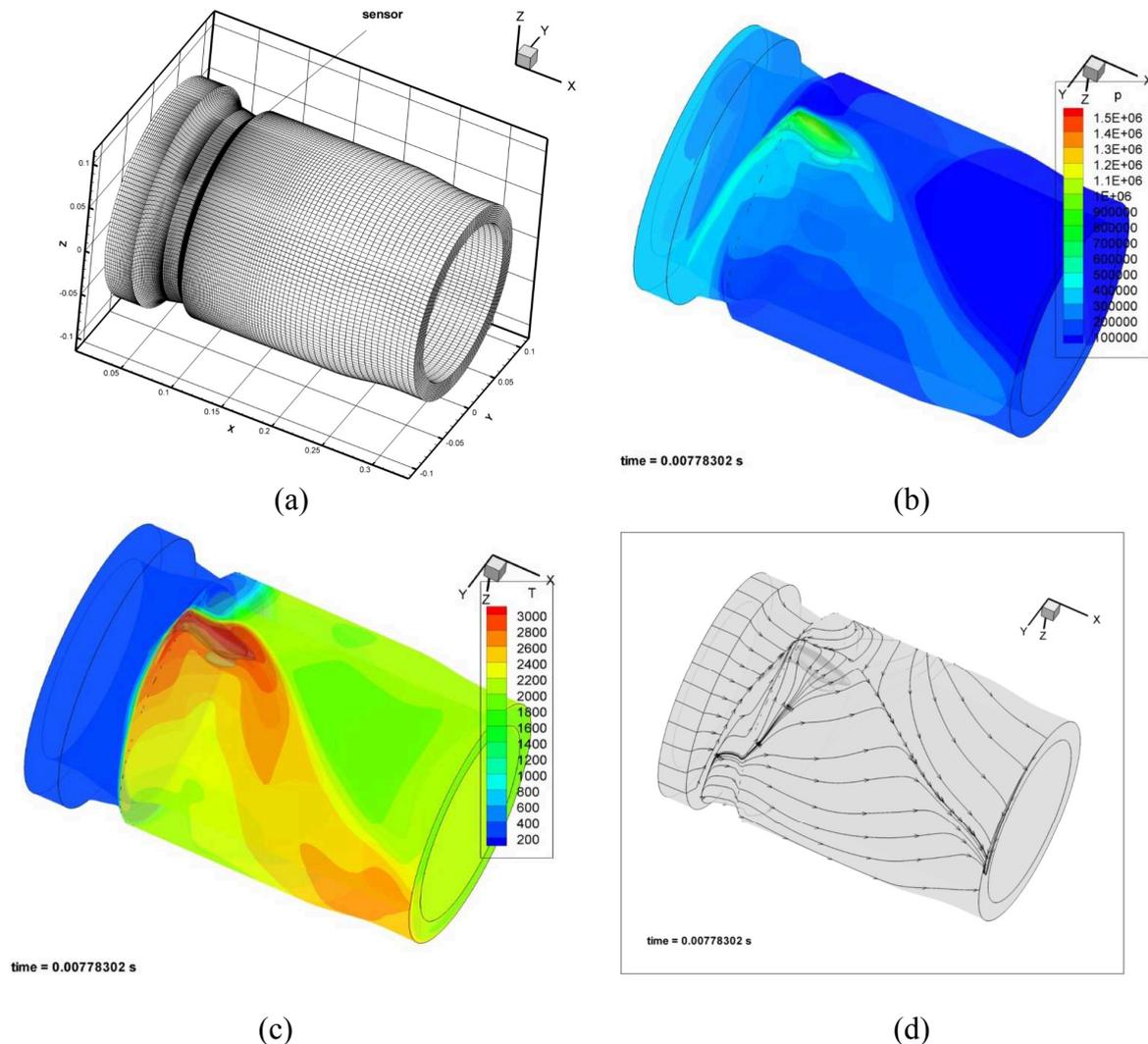(c)   (d)

Fig.1. Typical example of calculation of the structure of rotating detonation wave in hydrogen-air mixture, a- computational grids, b - distribution of the pressure, c - distribution of temperature, d – particles trajectory (flow field).

This numerical cod was used for extensive numerical simulations of continousely rotating detonation in a different chamber geometry and different mixture compositions. Using this code the optimization of geometry of tested chambers including mixing and evaluations of the chamber performance were performed. Typical results obtained by the developed model are shown on Fig.1. Since that time many numerical codes were developed to calculate detonation preparty and detonation structure. Some examples of such calculationcan br fond eswere [6-8]. As a example of this is the new original high order numerical scheme with positivity- preserving method and complex boundary treatment, which effectively preserves the positivity of the density and pressure and high order accuracy at the complex boundary without violating the conservation [6,7]. It provides a remarkable numerical strategy to investigate rotating detonation engine.

Experimental research

The experimantal investigation of the continousely rotating detonation at the Institute of Aviation in Warsaw were carried out on the specially designed rig, which consisted from the high pressure supply line and the speciall designed air heater. The constructed high pressure supply system could deliver the air preheated up to 150 ^{o}C with initial pressure up to 4 bars at the rate up to 4 kg/s. At the end of the high pressure supply line the experimatal detonation chamber was attached. Schematic diagram of such chember is presented on the Fig. 2.
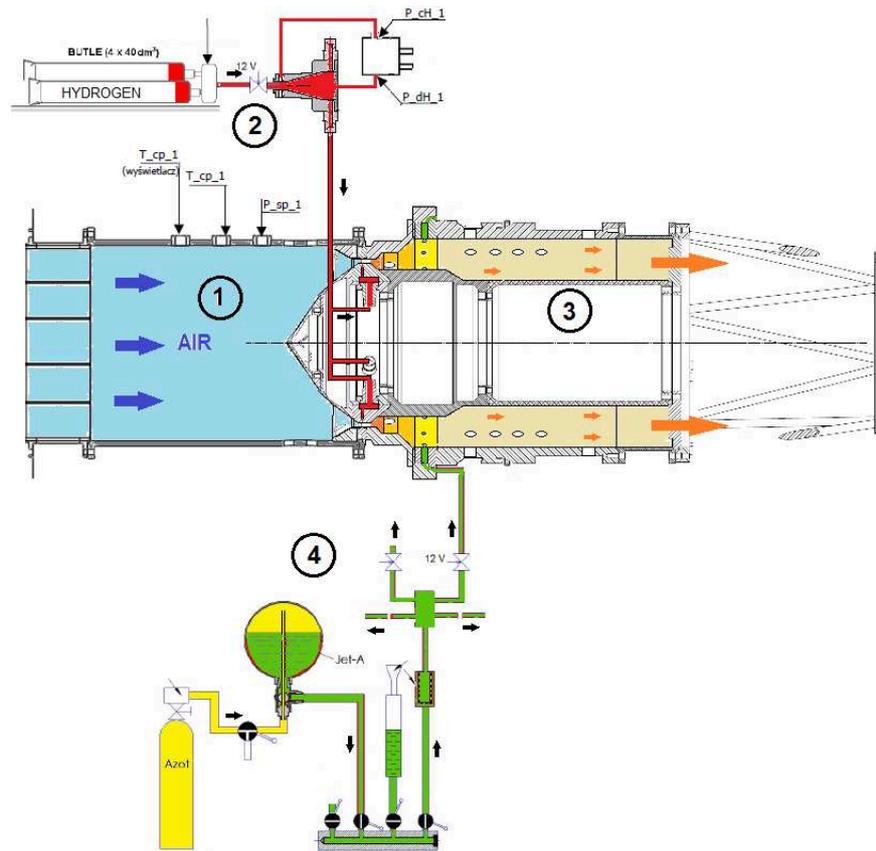
Fig.2 Schematic diagram of the test stand at the Institute of Aviation: 1.Air inlet; 2. Hydrogen supply system; 3. Combustion chamber; 4. Jet-A supply system

   The chamber was equipped with a duel fuel supply system. The gaseous hydrogen was supplied from the high pressure bottles utilizing specially adopted pressure reduction system. Jet A fuel was supplied from specially designed high pressure tank using pressure fed nitrogen system. Jet A fuel could be also preheated to temperature up to 170°C. Liquid fuel was injected into detonation chamber by specially designed injectors located at the entry to the chamber. Specially designed ignitor (initiator of detonation) was also located in the detonation chamber. Chamber is usually equipped with numerous gauges, such as pressure transducers, thermocouples as well as pitot tubes for velocity profile measurements. Schematic diagram of the detonation chamber is show on Fig.3.
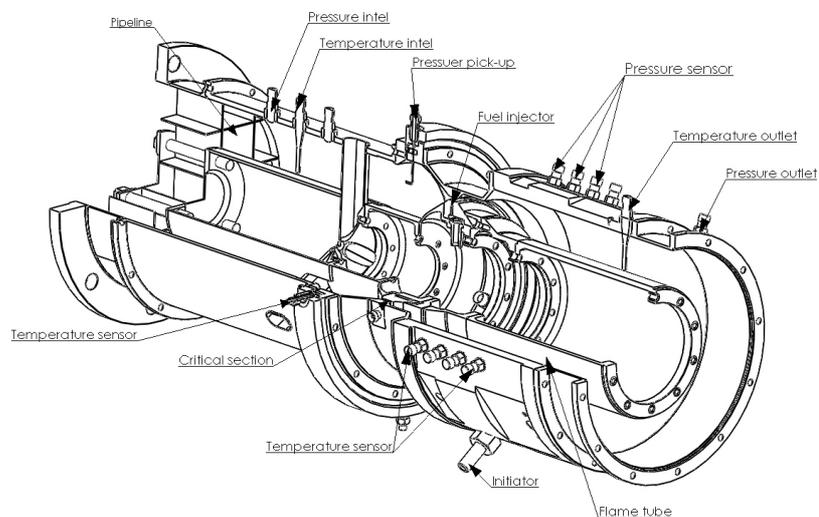

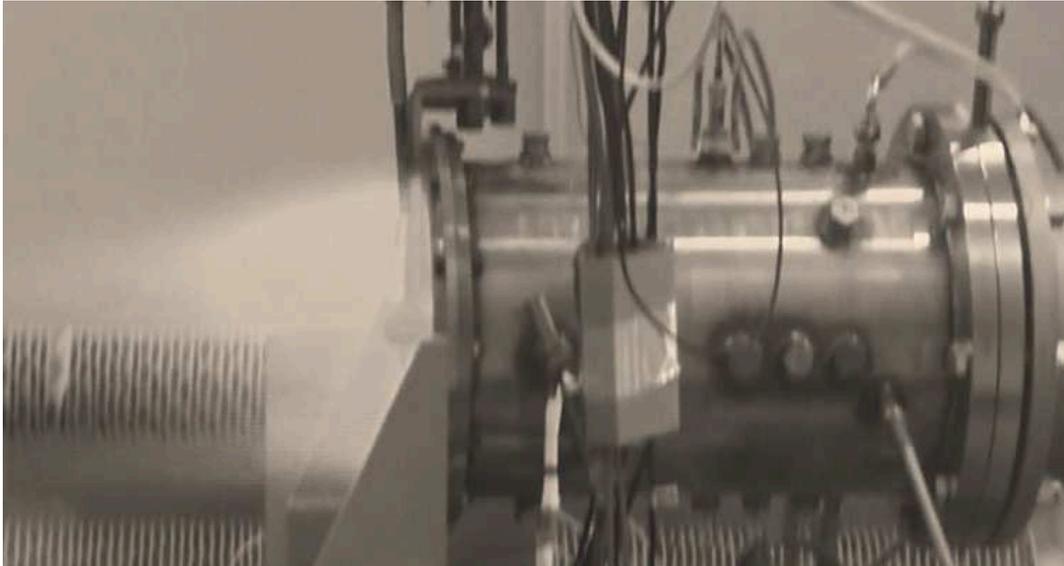Fig. 3. Schematic diagram of detonation chamber.

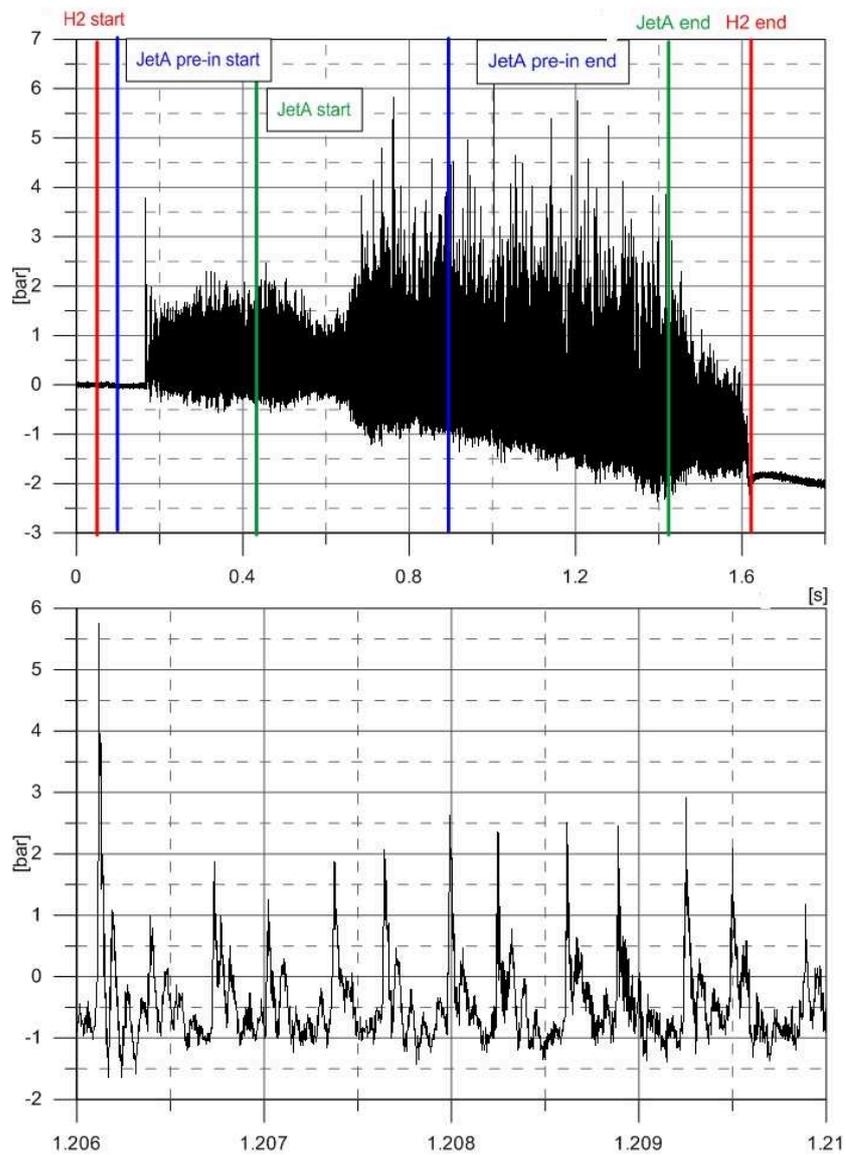Fig. 4. Picture of outflow of the detonation products from the chamber.

Fig.5. Pressure record for dual fuel test.

There were more than twenty different configurations of the chamber tested and more than thousand experiments were conducted. Exemplary picture of chamber operating on continuously rotating detonation is presented on the Fig. 4. Most of the experiments lasted less than one second, since steadily operating conditions were usually achieved after dozen of milliseconds. In some experiments during a single test a few different conditions were tested. On Fig. 5 pressure measurements from such experiments are shown. In this case chamber operated initially on hydrogen-air mixture, then on hydrogen-JetA-air mixture and at the end of 1,5s test on hydrogen-air mixture again.

Results of experiments conducted for JetA –air mixture at the different rate of air supply and the different rate of liquid fuel injection into the chamber are depicted on Fig.6. During this experiments air flow rate was changed from 1.4 to 4 kg/s and the coefficient λ , indicating excess air, was change from 0.7 to 1.6. For this domain tests with stable detonation (red dots) as well as no detonation (blue dots) are indicated. It can be seen that there are regions of operation under which stable detonation is obtained as well as the regions in which no stable detonation can be obtained. There are also regions were both modes can exists, indicating uncertain condition for stable detonation.
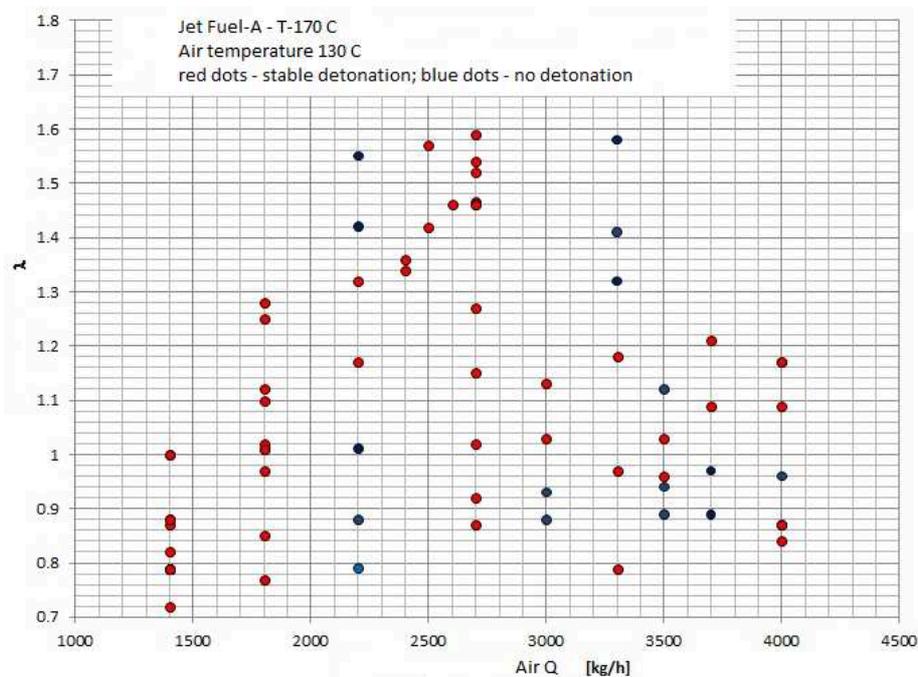

Fig.6. Dependence of detonation stability as a function of air flow rate and air excess rate λ.

After selection of the few best configurations of chambers, detonation chamber were integrated with the GTD-350 helicopter engine and tested. Schematic diagram of detonation chamber integrated with the engine is show on the Fig.7.
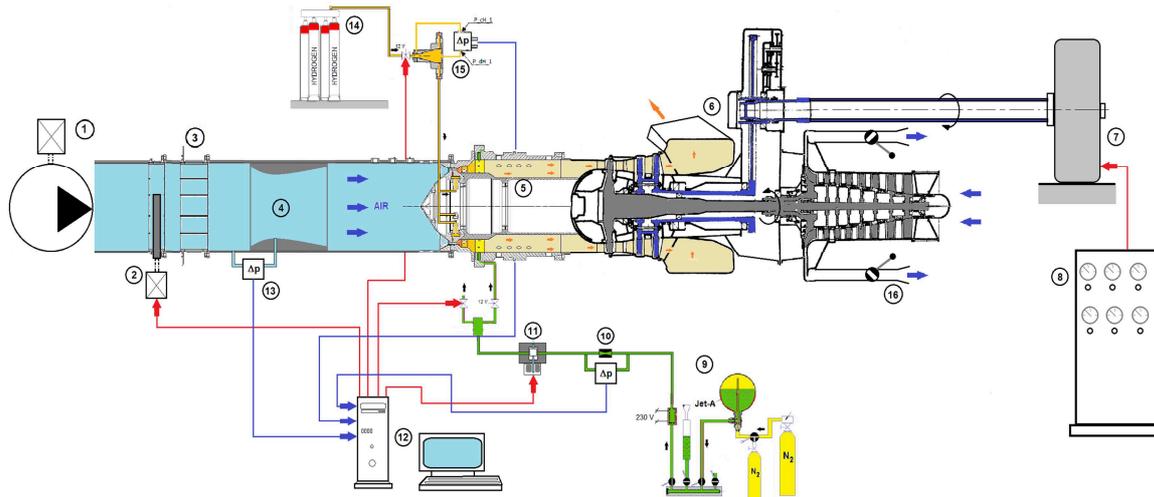
Fig. 7. Shematic diagram of GTD-350 engine integrated with detonation chamber and supply of air flow.
1 – air supply; 2 –control of air supply rate; 3 – air flow equalizer; 4 –measurement of air flow rate; 5 – deetonation chamber; 6 – main segment of the GTD-350 engine; 7 – torqu measurement; 8 – control system; 9 –Jet-A supply system10 –Jet-A flow rate measuring system ; 11 – electro-hydraulic actuator WLP-4; 12 – control computer and data acqusition system; 13 – gage for air flow measurement; 14 – hydrogen supply system; 15 – hydrogen flow rate measurement sydstem; 16 – trotle of air flowin out from engine compresor.

For easier initiation of the engine work the air supply to detonation chamber was used from external sourse, however, this air supply rate was cerefully controlled, at the nominal operating condition, to be the same as from air compressor attached to the driving turbine. Detonation products from attached to the engine detonation chamber was flow first trough single stage turbine attached to air compressor. Then the products were driving two stage turbine which ussualy transfer the power to helicopter gear box and finally to the rotor. Rate of rotation of both turbines were measured as well as the torq from the second turbine. This allows to calculate the power obtained on the second two stage turbine, or so called "free turbine". Additionally taking into consideration measured flows of both fuels (JetA and hydrogen) fuel consumed was calculated. Hydrogen usually consist less than quarter of energy delivered to the engine by both fuels, however, for some configurations addition of hydrogen was necessary to obtain stable detonation in the chamber. Test were usually lasted about 20s, however there were no restriction to run engine for the longer time. With the addition of hydrogen engine could be run for very lean mixture, so there were no necessity to add cooling air to detonation products. For such conditions typical temperature profile at the detonation chamber exit are shown on the Fig.8. For this test calculated lambda (λ) for both hydrogen (contribution og the hydrogen to the whole mixture) and overall lambda, for both fuels used in the experiment is shown on the Fig.9. So one can see that in this case detonation was obtained for relatively very lean mixture, which means that future turbine engines which will use detonative combustion chamber and lean mixture will not require additional cooling air for products directed into turbine stage. Dependence of the power on the drive shaft (so called „free turbine") as a function of time is shown on the Fig.10.
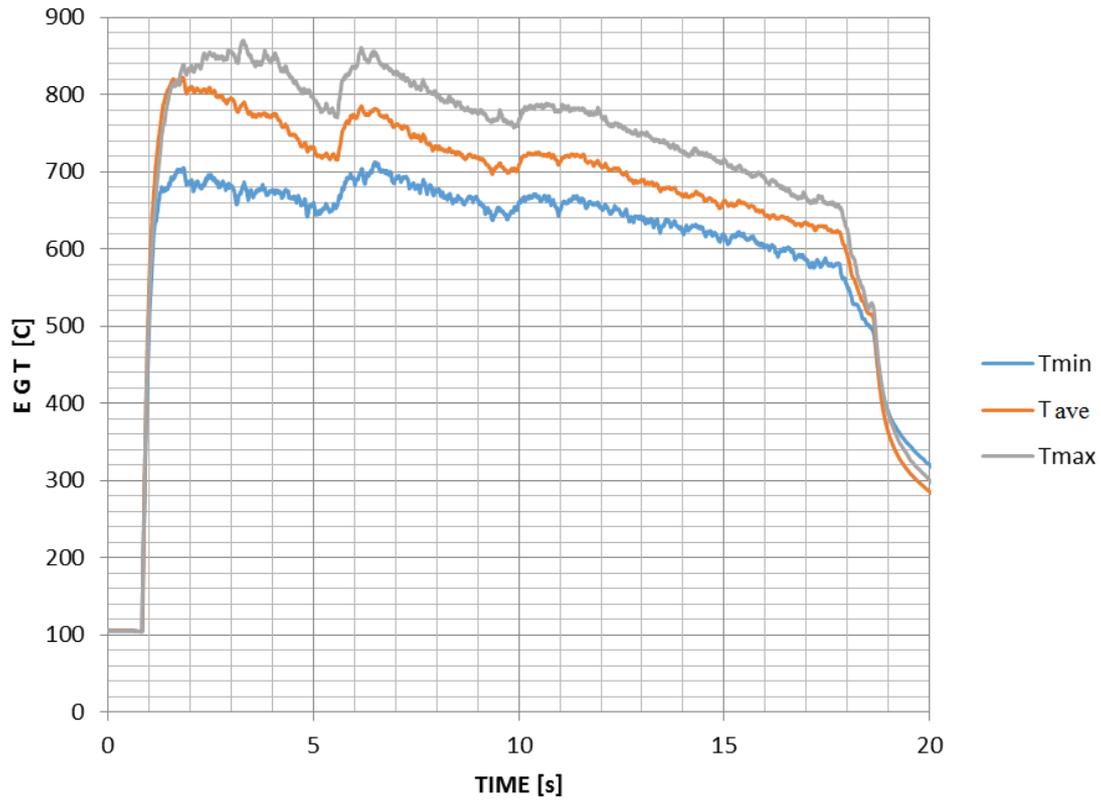
Fig.8. Temperatures at the exit of detonation chamber (before first turbine) for 20s run experiment. Blue line shows minimum temperature, gray line-maximum measured temperature and red mean temperature at the exit.
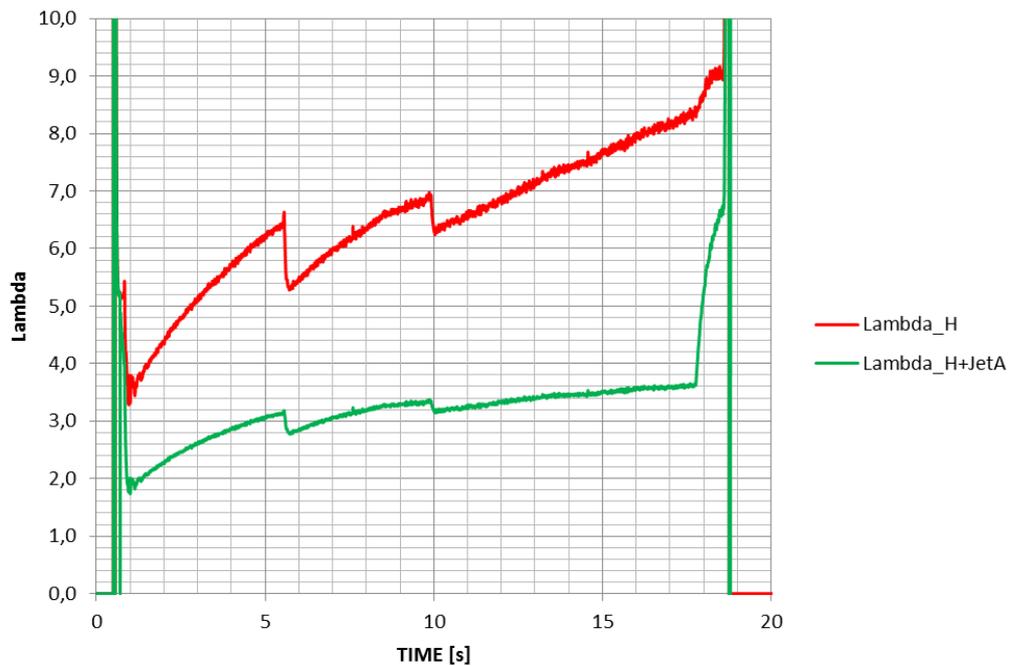

Fig.9. Variation of the λ with time for hydrogen and for both fuels used in the test.
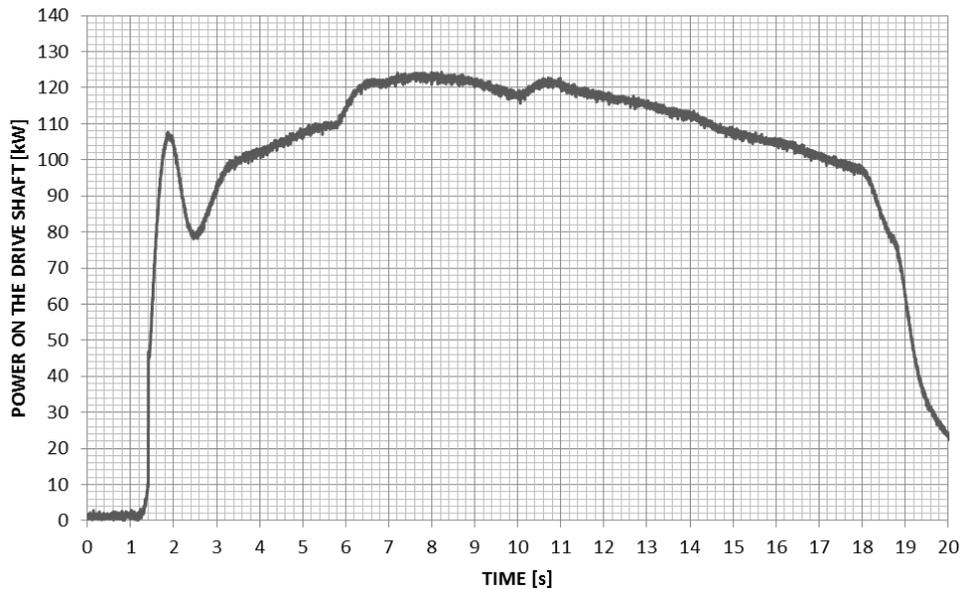
Fig.10. Dependence of the power on the drive shaft (so called „free turbine") as a function of time.

The dependence of the power on the drive shaft as the function of total fuel consumption is shown on the Fig.11. In this graph, for the case when hydrogen and JetA was used, the energy released by hydrogen was calculated to equivalent mass of JetA fuel, so performance of the tested configuration of the engine can be compared to nominal parameters of GTD-350 engine. On this picture linearized dependence of nominal relation between the power on drive shaft and fuel consumption was shown for three cases, for test chamber 4 and 5 as well, as for comparison, for nominal engine performance. The engine with test chamber 4 have higher specific fuel consumption than original engine with deflagrative (classical) combustion chamber, while chamber 5 shows smaller fuel consumption than original engine. It was calculated that for this case efficiency of the engine was increased by 5-7%. This was due to introduction into the chamber of specially designed gas-dynamic valve, which unlike small entry slot in classical detonation chamber does not create significant pressure losses.
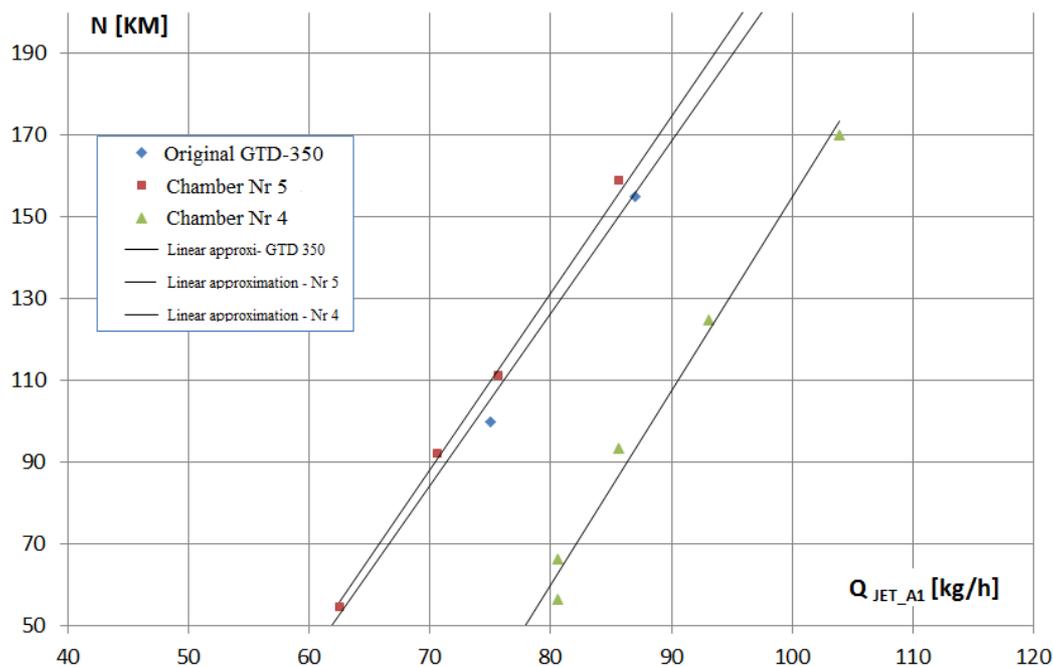
Fig.11. Dependence of power on the drive shaft as the function of overall fuel consumption. For the case of dual fuel use the energy released from hydrogen was calculated to the equivalent mass of JetA.

Summary

Extensive theoretical and experimental work on development of continuous rotating detonation engine was carried out for nearly 5 years in the Institute of Aviation in Warsaw. During the duration of the project new numerical code for 3-D simulation of performance of rotating detonation was developed and it was used to better understanding the nature of rotating detonation and to optimization of the detonation chamber configuration.

More than twenty different configurations of the detonation chambers were tested experimentally for detonation stability and range of conditions under which continuously stable rotating detonation was achieved was documented. Most of the research were carried out for dual fuel, Jet A with small addition of gaseous hydrogen, Many tests were also carried out for the Jet A only.
Best configurations of the chambers were finally attached to gas turbine, GTD-350 helicopter engine and tested for performance. During tests engine was accelerated to nominal operating conditions while power and specific fuel consumption were measured. It was found that at this condition engine can be operated at lean mixtures and that the specific fuel consumption was lower than nominal, so the estimated improvements to the nominal engine operating conditions were estimated to be between 5% to 7% better than for original engine.

Since the results of the research is so positive we like to continue research on the application of continuously rotating detonation to the integrated rocket-ramjet engine. For such configuration benefits from the application of the continuously rotating detonation might be even larger.

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