Journal of KONES Powertrain and Transport, Vol. 22, No. 4 2015

ISSN: 1231-4005
e-ISSN: 2354-0133
DOI: 10.5604/12314005.1168420

START-UP AND ACCELERATION CONTROL OF THE TURBINE ENGINE WITH THE DETONATION COMBUSTION CHAMBER

Włodzimierz Balicki

Institute of Aviation
Krakowska Avenue 110/114, 02-256 Warsaw, Poland
Tel.: +48 22 8460011, fax: +48 22 8464432
e-mail: balicki@ilot.edu.pl

Abstract

This article presents the results of tests of helicopter turbine engine, where the classic combustion chamber was replaced with an innovative solution. In this chamber instead of the classic combustion deflagration, was generated a rotating detonation. Theoretical considerations expected to get a higher engine efficiency, because as the thermodynamic Fickett-Jacobs cycle, which can describe the working principle turbine engine detonation chamber, has a higher efficiency than a Brayton cycle, according to which the engines of conventional chamber are working. The appearance of detonation combustion was diagnosed basing on observation of the gas pressure flue in the chamber, using piezoelectric sensors. Before the detonation chamber was used in turbine engine, a series of problems on the various methods of initiation of detonation process and the procedures for controlling the flow rate into the chamber of air and fuel were solved. There was a test stand constructed, which used a helicopter turbine engine GTD-350, wherein the jugs combustion chamber was replaced with detonation chamber. A control system for the flow of fuel in the combustion chamber was developed: aviation kerosene Jet-A1 with addition of hydrogen. With its use obtained unfailing starts of chamber, also the engine running on the idle and on the flight range and accelerations at idle range to flight range. The possibility of the detonation combustion for a long time, especially in transient states - practically limited only by the capacity of fuel tanks – is the achievement of the research team.

Keywords: *turbine engine, combustion chamber, rotating detonation engine (RDE), start-up control*

1. Introduction

Aircraft engines are a kind of "transmitters", in which the chemical energy contained in the fuel is converted into thrust. Among the directions of the development of these engines – in addition to efforts to extend their durability – is a reduction in fuel consumption by the components efficiency increase – in particular the increase in the combustion process efficiency. A chance to achieve this goal is given by a change of fuel combustion in chambers of these engines, particularly the replacement of the classical deflagration combustion, by the continuous detonation combustion.

Although the theory of detonation in gases was formed more than 100 years ago (Chapman 1899, Jouguet 1905), then developed in the forties (Zel'dovich, von Neumann, Döring), that studies concerned mainly the phenomenon of the detonation in pipes filled with mixtures of hydrogen and oxygen or acetylene and oxygen. The concepts of applications were given just recently: for pulse engines (Cooper, Winterberg, Roy 2004) [8], and for turbine and jet engines (Wolański, Fujiwara 2004) [5, 10]. They are still however an innovative studies.

The tests described by scientists were lasting usually less than 1 second due to problems with heat and exhaust gases removal (cooling), and problems with continuous supplying the chamber with a combustible mixture of proper composition.

In the researches at the Institute of Aviation the continuous-flow chamber was used, which – after preliminary tests – has been installed in the turbine engine. There were several hundred attempts made lasting from a few to approx. 60 seconds. The maximum test time was limited only by the durability of materials used to build the chamber and the capacity of fuel tanks.

During these tests not only the rotating detonation was maintained in a steady state for a long time but also the processes of the engine acceleration with the chamber, in which detonation combustion in transient conditions was maintained, was performed.

It was also achieved to detonation combustion of pure aviation kerosene Jet-A1, but only in the "unplugged" chamber with slightly enlarged size. After the suppression of chamber by the engine turbine, pure kerosene has not detonated – the addition of hydrogen was necessary to trigger detonation.

Detonation combustion allowed using very lean mixtures with a coefficient of composition ϕ (the coefficient determining the fuel to air ratio) below the value 0.33. As a result, the average temperature has not exceeded 900°C, which met the restrictions regarding the engine turbine.

2. Test stand and research methods

The tests were performed in a specially rebuilt laboratory of the Institute of Aviation (Fig.2). Each test consisted of several phases: the chamber start-up, maintaining idle range of engine, acceleration and steady state for flight-range.

In the engine, the existing combustion chamber (pitchers) was replaced by the research chamber (Fig. 3). To allow the engine start-up and facilitate the control of the combustion chamber, it was supplied with air from a stationary compressor. The fuel system has been removed from the engine. The exhausts from the compressor were throttled, so the pressure after the compressor depending of the rotating speed of its rotor was corresponding to the pressure existing on the same engine in the normal configuration.

To control the tests process the computer was used, which also recorded measurement results. Among the several dozen measured values, there were rotation speeds of the rotors of gas generator and power turbine, the flow rate of kerosene, hydrogen and air, temperatures and pressures of air and exhaust gases, as well as the resistive torque of eddy current brake.

The optimal sequence of switching on and off the fuel flow into the combustion chamber was selected because of the numerous tests. It was executed by switching discrete valves and hydrogen and kerosene flow control valves by signals from the control computer. Mixture ignition in the combustion chamber was trigged by discharge at the semiconductor spark. In order to achieve a certain ignition two independent ignition systems were used. Fig. 1 shows an example of changing the control signals during the test.

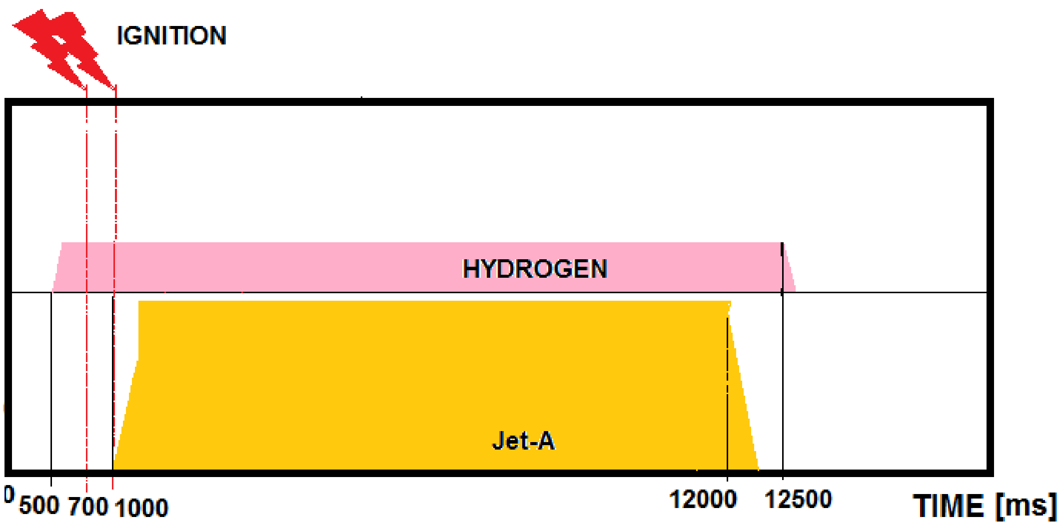

Fig.1. The controlling sequences of the opening and closing of fuel flow into the combustion chamber (hydrogen and kerosene Jet-A) and starting the ignition systems (basic and reserve)

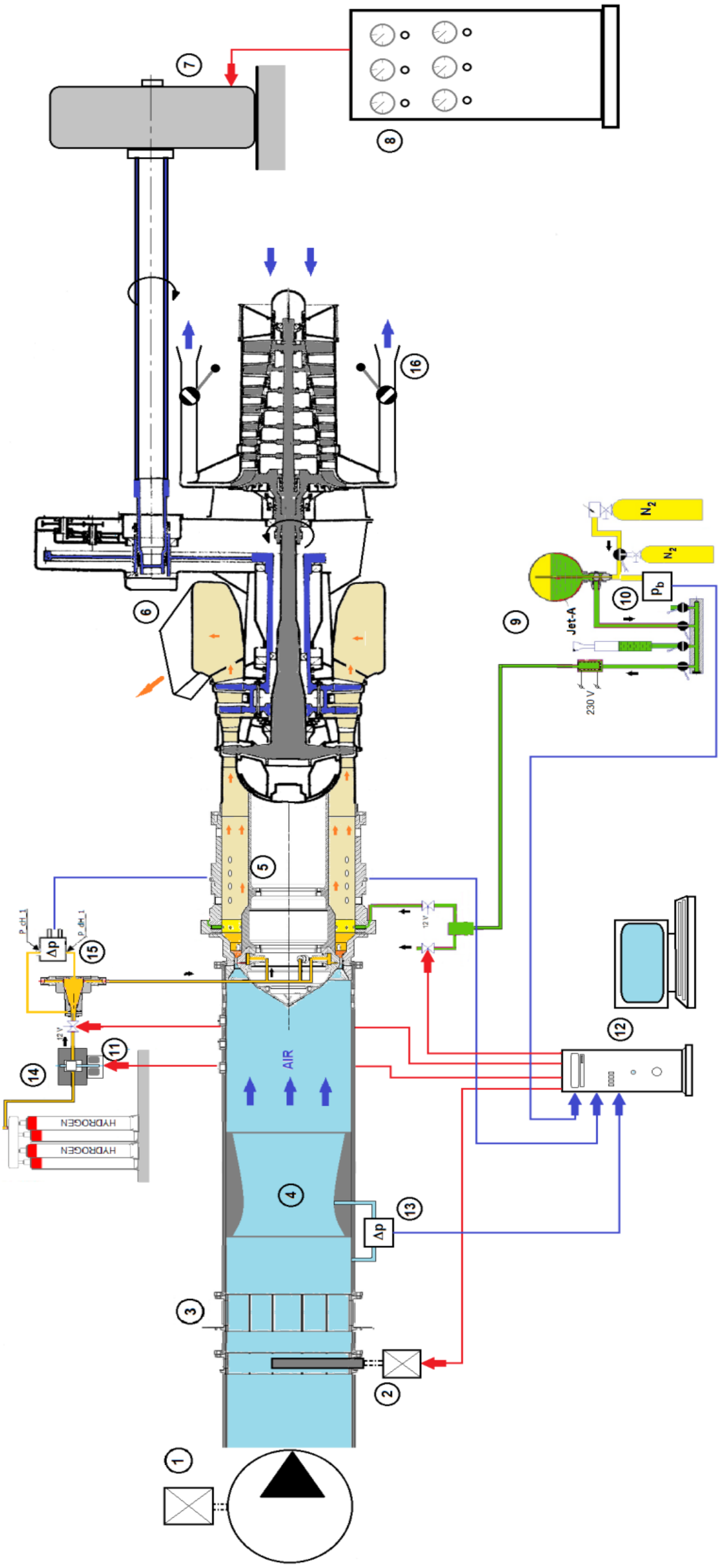

Fig. 2. Control system of the turboshaft engine with detonation combustion chamber (For chamber research during engine run): 1 – air compressors unit; 2 – air flow controller; 3 – igv; 4 – Venturi air mass flow measurement; 5 – detonation combustion chamber; 6 – turboshaft engine GTD-RD; 7 – brake; 8 – brake controller; 9 – Jet-A injection system (pressurized by nitrogen) 10 – Jet-A flow meter; 11 – electro hydraulic booster; 12 – management computer; 13 air flow differential pressure; 14 – hydrogen supply system; 15 – hydrogen flow differential sensor ; 16 – air exhaust with suppression valve;

The rotating detonation was detected on basis of the exhaust gas pressure in the chamber, which was measured by piezoelectric sensors. The sensors were cooled by flowing water. The sampling frequency of this signal was 1 200 000 samples per second. This allowed determining the time between the wave transitions. On this basis, its velocity was determined. These calculations are complicated by the fact that in lean mixtures there are often two or three waves running behind.

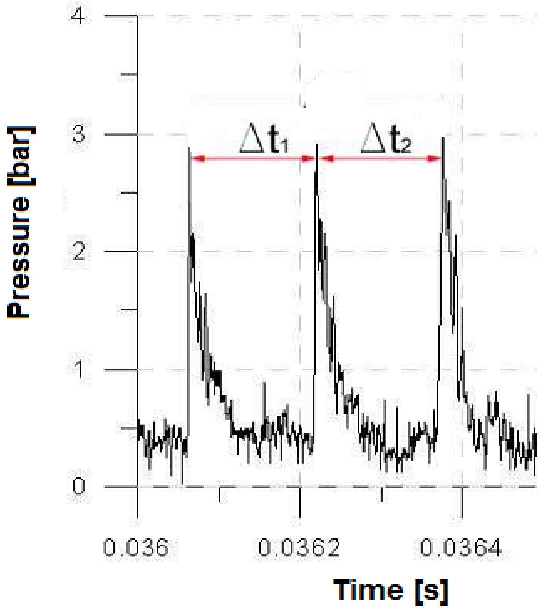

Fig. 3. Exhaust gas pressure pulsation measured by a piezoelectric sensor

The measurement data were processed mainly using Excel and Grapher. These programs allowed processing of large data files (from a several seconds lasting test, a few hundred MB volume file has been obtained).

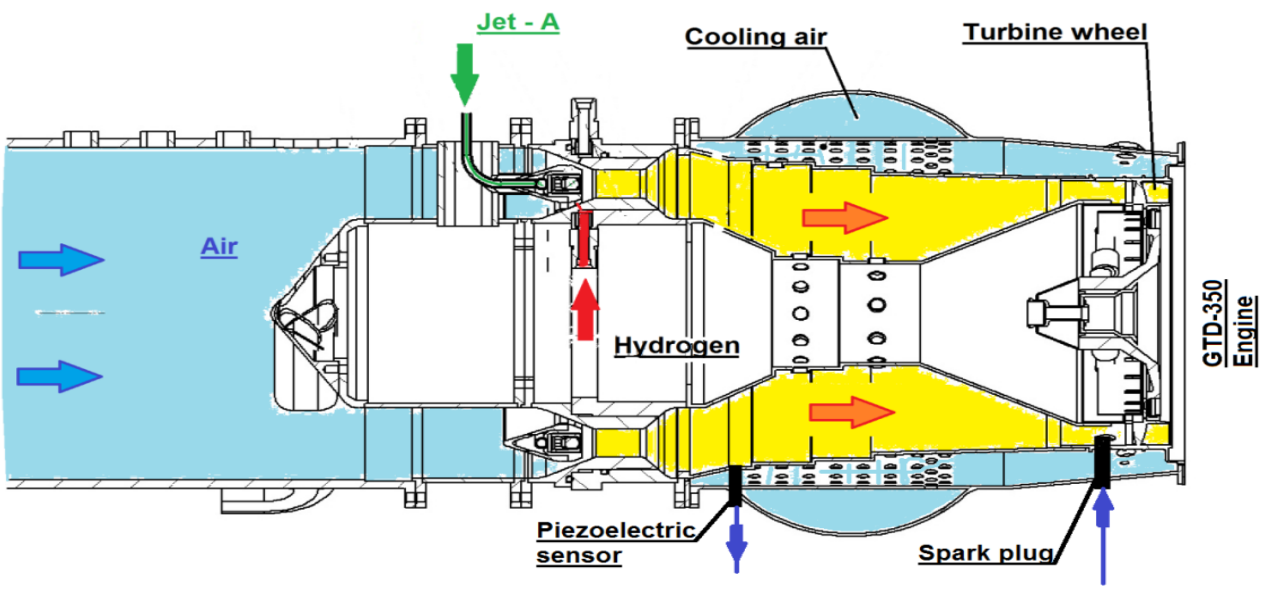

Fig. 4. The cross-section of one version of the test chamber that was installed on the engine GTD 350 with the hydrogen and kerosene Jet-A injectors (co-current injectors placed before the inlet to the throat of combustion chamber)

The combustion chamber of a rotating detonation is the source of the noise with an intensity range up to 120 dB._For this reason, the service test bench was equipped with a hearing protector, and the engine was placed in a chamber that uses a special isolation.

Fuel was placed in a separate room – beyond the engine "box".

3. The results of tests

During the project, dozen or so tests of acceleration of the engine with detonation chamber from the idle-range to the flight-range (n_{TS} ≈50% do n_{TS} ≈84%) were made. In these tests the time of raising the fuel flow to the chamber has been changed (from the intensity corresponding to idling-range to intensity corresponding to flight-range). The range of these time changes was from 15 seconds to 5 seconds. There were also attempts to minimize the contribution of hydrogen. It has been found out that in cases where its initial participation corresponded the coefficient storage $\phi < 0.2$ detonation did not exist - regardless of the flow of kerosene.

In Fig. 5 and 6 there are presented results of the acceleration test, in which the rise time of flow of kerosene Jet-A was about 5 seconds. The analysis of the exhaust gas pressure measured by a piezoelectric sensor shows (Fig. 5), that there are 3 detonation waves which travel at a speed of approx. 1440 m/s.

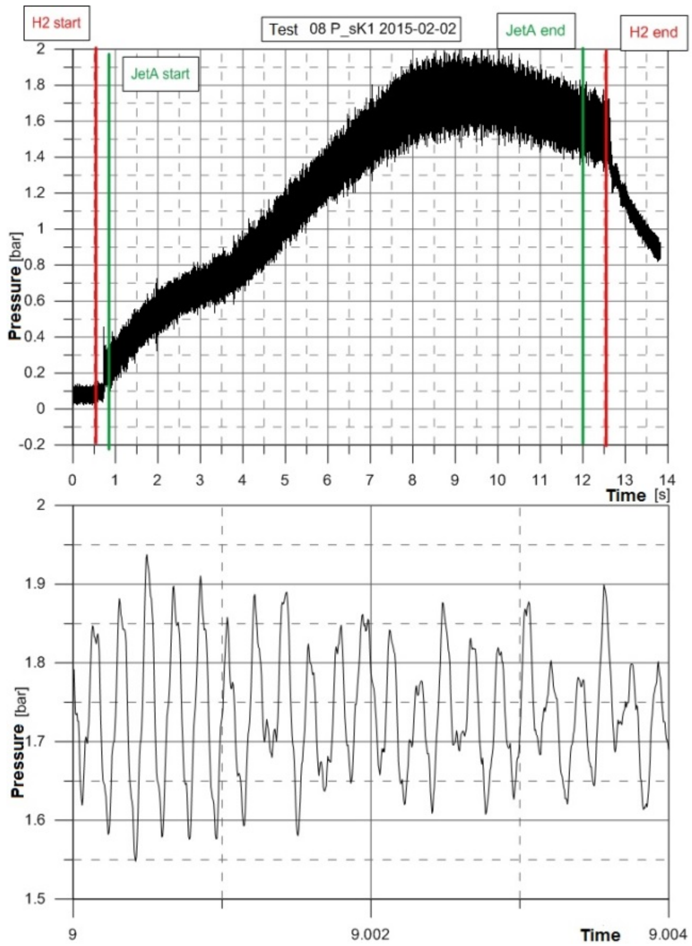

Fig. 5. The process of the exhaust gas pressure in the combustion chamber during the engine acceleration. The pressure measured by a piezoelectric sensor. The flow of fuel and ignition controlled as in Fig. 1

Engine reached the flight-range after about 7 seconds from start-up of the combustion chamber (compare the course of „*Compressor rotor speed*" on Fig. 6). It is quite a short time but cannot be compared with the "classical" start-up of such engine. In this case, the rotor "windmilling", i.e., has already had an initial rotational speed caused by the flow of the air stream. It is a phenomenon occurring when starting the helicopter engine during flight.

Stepwise changes of hydrogen flow shown in Fig. 6 are caused by executive valve in a flow control system (this valve had a control window adjustable in steps).

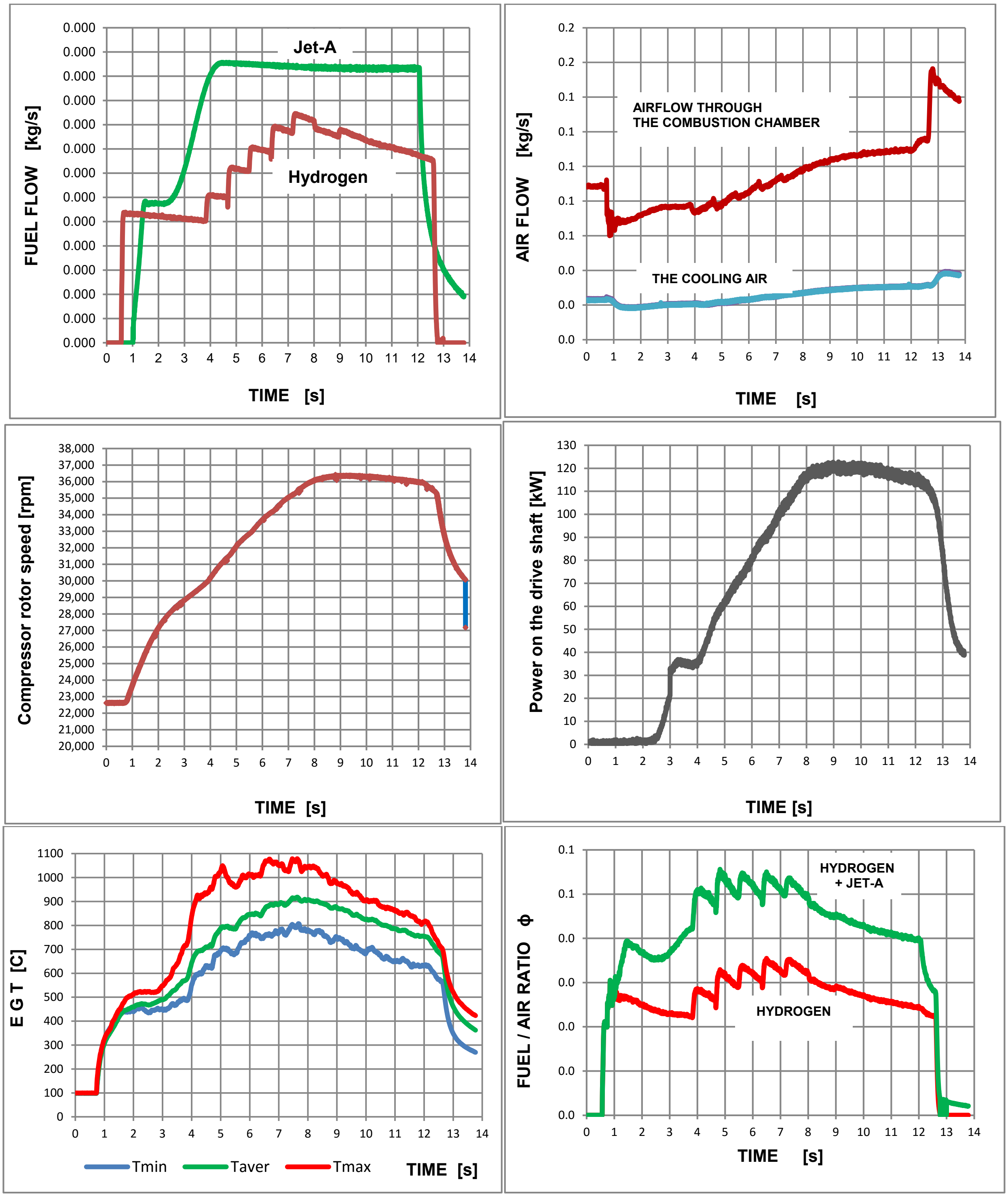

Fig. 6. The graph of selected operation parameters the engine GTD-350 with detonation combustion chamber during acceleration from idling-range to the flight-range.

The exhaust gas temperature (EGT) measured with a set of 16 thermocouples that were placed in front of the engine turbines. Fig. 6 shows the graph of signals from the two thermocouples: the one that shows the highest value of flue gas temperature T_{max} and the other showing the lowest values of gas temperature T_{min}. There is also included the "average" temperature values T_{aver}, which was calculated on the basis of signals from thermocouples. Large differences in temperature between the maximum and minimum testify to the unequal exhaust gas temperature before turbine. It seems that this is due to the flow of cooling air stream applied "transversely" to the exhaust gas stream (Fig. 4). The same (deprecated) construction of the combustion chamber was here used, as in the engine GTD-350.

The detonation the even more lean mixtures would allow to change the structure of the chamber in order to eliminate the need to apply additional cooling-air. This should improve temperature uniformity of the exhaust behind chamber.

4. Summary

The tests have proved that it is possible to operate the turbine engine combustion chamber with a rotating detonation. This applies to steady operation states and transient states.

Because of pulsing nature of the combustion phenomenon (pressure pulses with high frequency, exceeding 1500 Hz) it would be expedient to use the combustion chamber for example to jet engine (without turbine). It is hard yet to determine the durability of the turbine propelled by the exhaust gases from such chamber. In order to do it, long-term tests would be necessary.

In the presented tests, the chamber was supplied with heated air kerosene Jet-A1 and additionally hydrogen. The additive was necessary to maintain detonation combustion. The detonation of pure kerosene could probably be possible, if it was led to a gaseous state by heating, or improve its mixing with the air e.g. using aeration injectors. Unsuitable spraying of kerosene is the cause of the partial droplets subsidence on the walls of the chamber and the formation of slag there. In these tests, we used "commercial" vortex injector Danfoss designed for oil-burned furnaces.

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