ISSN: 1231-4005
e-ISSN: 2354-0133
DOI: 10.5604/12314005.1213590

REPORT ON THE IMPLEMENTATION OF THE POIG PROJECT „TURBINE ENGINE WITH A DETONATION COMBUSTION CHAMBER"

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Abstract

This article contains a description of the work carried out under the UDA-POIG 01.03.01-14-071/09-10 project titled "A turbine engine with a detonation chamber". The work carried out during the project involved 14 construction, research and calculation tasks. Various research stands designed to analyse the process of mixture formation, initiation of detonation and research of rotating detonation in combustion chambers were constructed. Test stand for examining a turboshaft engine with detonation combustion chamber was built. Those test stands allowed powering the combustion chambers and the engine with both liquid and gaseous fuels, simultaneously or separately. At the same time, REFLOPS software, which could calculate the propagation of a detonation wave was created, and used in the design of further versions of combustion chambers. Data from the experiments was used to verify the calculations and models created in the mentioned software. GTD-350 engine was used as the base; the structure of which (combustion chamber situated outside the turbine-compressor unit) facilitated modifying the shape of the detonation combustion chamber. During the research, great emphasis was placed on the safety of researchers. Working with hydrogen in high temperatures and JET-A1 fuel, which was additionally heated, and the usage of the oxy-acetylene detonators forced extreme caution, and full compliance with developed procedures. The project was divided into 14 tasks that were often conducted simultaneously in a 20-person team implementing the project. The work was completed by performing comparative studies between conventional engine with deflagration combustion chamber, and modified engine with a detonation combustion chamber. During the completion of the project, it was the first working demonstrator engine with detonation combustion chamber in the world.

Keywords: *combustion, rotating detonation, turbine engine*

1. Introduction

UDA-POIG 01.03.01-14-071/09-10 project called "Turbine engine with a detonation combustion chamber" was carried out in the Institute of Aviation in the period from 01.01.2010 to 31.03.2015 [1].

The aim of the project was to develop a new, unique solution of a turbine engine fitted with a detonation combustion chamber. The use of detonation combustion chamber in the engine allowed to increase the engine efficiency, simplify its design, reduce the engine weight, and to reduce the production costs. The increase in efficiency is estimated at 5-6%.

In addition, due to the increase of efficiency, fuel consumption will be lower, which will lead to lesser greenhouse gases emissions, such as CO_2. Additionally, the use of detonation combustion in the engine allows usage of methane or hydrogen as engine fuel, which will result in an even larger reduction of CO_2 emissions when using methane, and complete elimination of greenhouse gases emissions when using hydrogen as a fuel. Studies have shown that the use of hydrogen as a fuel in this process gives very good results.

2. Description of the R&D work carried out

The project involved the implementation of 14 research and development tasks.

2.1. Task No. 1. Modelling the preparation of combustible mixture

A software for numerical modelling of the process of creating the combustible mixture was developed. Fuel evaporators, mixture in the gas phase, direct injection into the pre-chamber and direct injection into the detonation chamber were modelled. The model of using detonations to generate shock waves to break up the droplets, and intensify evaporation and mixing was also prepared.

2.2. Task No. 2. Construction of test stand for studying the process of mixture preparation

During the task, the test stand for testing the process of combustible mixture formed by injecting kerosene into the air stream was constructed. The stand is equipped with visualization test chamber to allow photographing and filming the process of injecting and spraying the fuel. Visualization chamber is supplied with air from a compressed air tank, which can be preheated to a temperature of approx. 150°C. The fuel (Jet-A1 kerosene) is injected into the chamber using the pressure supply system, wherein the present injection pressure is achieved by using compressed nitrogen.

The visualization test chamber allows changing the velocity of the air stream flowing through it, using an adjustable outlet (changing the outlet cross section area).

2.3. Task No. 3. Research of the mixture preparation process

Research of injection and spraying of the fuel was carried out for different shapes of the flow route, different types of injectors (stream, swirl), different fuel injection pressures, and different airflow rate in the chamber. Research was also carried for different positioning of the fuel injectors, and for using additional elements (such as rollers and wedges) to improve the breakdown of the fuel stream. Effects of changing temperature of air supplied to the visualization chamber were also examined. Fuel-air mixture was photographed, and in chosen experiments, it was filmed using a high-speed camera. Videos were subjected to stop-motion analysis, using software that can determine the size and distribution of fuel droplets. Results of simulations performed by the software created in task 1 were used for the experiment designing.

2.4. Task No. 4. Development of specialized software for calculating the propagation of a detonation wave in the detonation combustion chamber

Specific software for modelling detonation processes in 3D was developed. The program models the propagation of detonation, completed with flow patterns, and breakdown and vaporization of fuel drops. It also models mixing gas streams and boundary layer in flows with detonations and shockwaves. Kinematic models of chemical reactions were used.

It was assumed in the task, that the starting point would be to develop an improved version of the REFLOPS 1 software. REFLOPS 1 is a software that allows solving the inviscid flow equations with chemical reactions on structural grids. Due to its relative simplicity and solving speed, it was used in the initial stages of the project and in implementation of these models, which require mesh structure (higher-order models) or a large amount of memory (flows with droplets). This program is used to perform calculations with simple geometries and to test used software solutions, such as calculations with GPUs. Some mathematical models were implemented in the software, such as the model of impact of the fuel droplets on the flow. This version of the software is called REFLOPS D. REFLOPS 1 has also become the basis for implementing high-order solvers, for example the WENO 5-th order solver.

The second step in the development of the software was creation of a new software, REFLOPS 2, which allows calculation of inviscid flows with chemical reactions on non-structural grids. Solvers working on non-structural grids are essential elements of this software. These are the second order solvers. Another important element of the REFLOPS 2 software is a non-structural grid interpreter that reads mesh files saved in Gambit format.

The third step of creating a specialized software was to complement the REFLOPS 2 software with elements that enable modelling of turbulent dissipation. The version of the software with the turbulent mixing models was called REFLOPS 2.1.

2.5. Task No. 5. Creation of simulation of detonation combustion process and numerical optimization of the combustion chamber

The task consisted of modelling activities of the detonation chamber, from the initiation process, through the propagation detonation, and up to defining the phenomena affecting the stability of propagation. Chamber operation during states of emergency and during transient operating conditions was simulated. Simulations were performed on several variants of combustion chambers that were scheduled to be tested on the test stand. Data from simulations were used for initial selection of the combustion chambers geometries. Test results from the test stand were used to select appropriate coefficients applied to the software created in task 4. Parallel implementation of research tests and modification of the software made it possible to simulate the behaviour of the detonation chamber under conditions, which cannot be reproduced on the test stand, or the occurrence of which would involve the danger of damaging the chamber.

2.5. Task No. 6. Construction of the test stand for studying rotating detonation for air-kerosene mixture

Technical project and executive documentation of the test stand dedicated to research of rotating detonation phenomenon in the tube of incandescent combustion chamber were made, and the facilities of the piston engine test stand located in building “K” of the Institute of Aviation were modernized. For this purpose, in two test chambers electrical installation was modernized and exhaust fans were installed, the control room was soundproofed, a pipeline connecting the main bus of compressed air with the test stands was constructed. The section between compressor hall and compressed air consumption point and the section of 250 kW electrical installation of 40 meters length used to power up the heating elements installed on the pipeline, were thermally insulated. Band heaters with an output of 200 kW, and the compressed air flow rate control and measurement system were installed on the pipeline. Modification of the compressed air system made it possible to deliver to both test stands compressed air with following parameters: air flow rate up to 2.5 kg/s, pressure up to 0.7 MPa and temperatures up to 130°C. The test stand consists of a bed, fuel-supply system, ignition system, measuring system, air intake system, and exhaust gases outlet system. The fuel-supply system consists of liquid Jet A1 fuel installation and gas fuel – hydrogen – installation. In the kerosene installation, pressure of up to 50 bar is maintained. The fuel is heated up to the temperature of 180°C. Hydrogen fuel installation consists of a tank, in which pressure up to 30 bar is maintained, the regulator, mass flow rate measurement system, and controlled flow rate regulator. Ignition system allows the ignition of the combustible mixture inside of the tested tube of incandescent combustion chamber, by propagation of the shock wave in the gas igniter chamber, or by thermal explosion at the spark plug of K15 jet engine. Gas igniter is powered by oxy-acetylene fuel, and detonated by the spark plug. The air intake system consists of a compensator, stream straightener, and the gas parameters measurement segment. The measurement and data acquisition system has been implemented on the control computer, on National Instrument NI-PCI-625 measuring card, equipped with a high-speed analogue-digital converter, designed for the acquisition of electrical signals and two-way communication with the environment, using LabView software from National Instruments. Software “Hamownia SCXI (12)” was developed.

2.7. Task No. 7. Performing research of process initiation of spin detonation of a mixture of kerosene-air, the choice of methods of initiation of the process

The process of initiation of detonation is reduced to creating a strong shock wave, which will compress the gas mixture so that its temperature will allow the chemical reactions to occur just behind the shock wave. The amount of the energy needed to initiate a detonation process depends on many external factors and on the “sensitivity” of the mixture. To initiate deflagration combustion process the concept of “minimum ignition energy” is used. For gaseous mixtures energy less than 1 mJ is sufficient. If the fuel is in liquid form, this energy is approx. 10-100 mJ. In comparison to these values, the energy required directly to initiate a detonation process the mixture is greater by several orders of magnitude and reaches up to thousands of J. The energy needed to initiate also depends on the type of detonation: a flat, cylindrical or spherical. The least energy is required to initiate flat detonation and most of it is needed for spherical detonation. In the present study, detonation of a mixture of kerosene and air had to be initiated. For this purpose, three types of initiators are selected:

- Powder initiator (as initiating charge black powder was used),
- MW initiator (as initiating charge lead azide and pentaerythritol tetranitrate were used),
- Gas initiator (as initiating charge a stoichiometric mixture of acetylene and oxygen was used).

In the further work, following were tested as the initiator:

- The ignition system of the turbine engine,
- The system using stun pistol cartridges,
- Plasma ignition system,
- Spark ignition system,

As a method of initiation for the engine GTD-350 detonation combustion chamber spark ignition system generating a single high voltage pulse was selected.

2.8. Task No. 8. Performance of experimental studies of spin detonation process, determining the temperature field as a function of pressure, temperature and composition of the mixture

1100-samples tests in which 24 design variants of combustion chambers were conducted. The influence of the injection pressure of fuel (flow rates), the composition of the combustible mixture, the temperature of the initial air and fuel to the detonation combustion process was investigated. Composition of the combustible mixture was changed in the range of $\lambda = 0.8 \dots 1.4$ – for mixtures of air / kerosene Jet-A and in the range of $\lambda = 0.9 \dots 4.5$ for mixtures of air / hydrogen (up to the border of the flame). The air injected into the chamber was heated in order to obtain temperature in the range from + 20 ° C to + 130 ° C. The chambers were tested over the range of possible flow rates of refrigerant – from 1200 kg / h up to 7200 kg / h. The study was conducted for a number of variants of the geometry of the chambers, injectors and initiators of detonation placement and for different throttling of the outlet of combustion chamber (the pressure in the chambers) by using a shutter system designed for this purpose.

Parameters of detonation were determined by measurements with fast piezoelectric sensors of pressure courses inside the chamber (sampling at frequency between 600 000 and 1 200 000 samples per second). With this method, speed of the wave and pressure amplitude was determined. The measurements also allowed distinguishing knock and deflagration.

In the outlet section of “”the chamber 16 thermocouples were placed. Signals obtained from them allowed determining flue gas temperature distribution at the outlet of combustion chamber.

Aim of this work was to control a process of knock and to obtain dynamic gas parameters of flue gases corresponding with engine work parameters.

GTD-350 in the idling range and in range “Through II”. By this method, the chamber was prepared for test of working together with the engine, which was performer in task no. 12.

2.9. Task no. 9. Cooling system research

A technical project with executive documentation, components of research stands no. 2 as well as body of research combustion chamber was done. Piston engine dynamometer room located in building “K” of Institute of Aviation was built over. It consists of (ŁOŻE), regulated system of bleed air from inlet channel into coating cooling the pipe, fuel installation, electrical ignition installation, installation for measurement of investigated object, power systems and flow rates.

Orifices for measurements of air mass flow in channels of primary and secondary air were designed, created and calibrated.

Functional tests of flue gas cooling system in incandescent tube have been made. On the basis of 8 maps of the field of pressure and temperature in incandescent tube for mixture combustion in the range (L = 0.8 – 1.4- for fuel JETA and (L = 1.0 – 3.6 for gas H2) The distribution and size of the openings of air supply cooling, both the structure and the exhaust stream and regulating circumferential and radial temperature field in the cross section of the inlet to the compressor stator were optimized.

The construction of incandescent tube was modified (diameter of the outer cylinder φ 229).

Combustion chamber was made (outer body and the incandescent tube – diameter of the outer cylinder φ 254)

2.10. Task No. 10. Development of a mathematical model and theoretical characteristics of the engine

A mathematical model of helicopter turbine engine GTD-350 consisting of various structural components: inlet, compressor, turbine and combustion chambers of two types: classic combustion chamber with deflagration and chamber with detonation was developed. In addition, a model describing environmental parameters (atmosphere), and the power receiver model (brake) was built.

A simple theory of oblique detonation wave was developed for the model the combustion chamber with rotating detonation, which was subsequently adopted as the basis for the calculation of detonation parameters of spinning detonation.

Calculations were performed for theoretical cycle engine with parameters corresponding to the engine GTD-350. The results only serve as a verification of the applicability of the theory. Assuming constant compressor and turbine efficiency, a very large increase in the efficiency is obtained for knock. However, making calculations for the actual characteristics of the compressor and turbine creates problems with convergence model, although this model works well for burning deflagration. This indicates the possibility of a problem with the stable operation of the engine. Work done in this task will be further developed in the tans for a motor control (task 14).

Mathematical model described above has been implemented in the program "THE performance" written in C++, using the Eclipse development environment. It consists of two layers. Parent layer calculations, such as the "Main" contains the main loop that iterates through three independent variables: airspeed M expressed in Mach number, altitude H and the expense of fuel mf. It calls the function responsible for the initiation of calculations, determination of start conditions, main calculation, convergence control and recording of the results.

Model takes into account the effect of detonation combustion chamber in the whole engine. It allows estimating the parameters of the engine in various flight conditions.

2.11. Task No. 11. Integration of the detonation chamber with the engine

The task was to develop a technical design of parts and assemblies that would enable build over selected combustion chambers (tested in the task of No. 8) on the engine GTD-350, to make changes the engine design and to adapt the measurement system stands for the control and registration of parameters of air and exhaust gas in duct of the engine.

The following was done:

1. Measurement and control installation for the stand 2 with a modified engine GTD-350 with additional measurement channels for acquisition of measured parameters by the system.
2. For the purpose of testing the engine GTD-350 with research combustion chamber modifications were done:

- Compressor rotor load system with outlet section throttling system was designed and manufactured,
- Engine exhaust pipes were modified,
- Transmission elements for drive the turbine wheel on the electro-whirl brake were made,
- Water-cooling system for eddy brake and installation control system was done.

3. "Windmilling" attempts for generator engine GTD (without measuring chamber) on the bench were made.
4. Two test chambers of different design suitable for mounting on the engine GTD were made including:

- Heat resistant tungsten alloy tubes 1.4828 and fasteners 1.4878 / 32H.

5. Power system of chambers of both liquid fuel JET A and H_2 gas was modified by system controlling the size of the expense of fuel. Additionally:

- Kerosene supply installations air were modified,
- An integral kerosene heating system was made,
- Kerosene concurrent injector system was modified,
- Counter current injector was made.

2.12. Task No. 12. Experimental research of engine demonstrator

After the integration of the engine with detonation combustion chamber tests of starting, idling, and work at different speeds and loads were carried out. Actual motor parameters were measured: power, fuel consumption and gas-dynamic parameters of the medium. The study was conducted for two versions of the geometry of combustion chambers: one with the throat (critical section) and a second with a valve blocking the propagation of pressure waves in the opposite direction to the flow of the medium (which is the subject of the patent filed). We tested the combustion chamber with two types of incandescent tube: outer diameter φ of 254 and φ 229 mm. The study was conducted on a modified test stand equipped with eddy current brake allowing change of the engine load, speed measurement and torque developed by the turbine drive motor. This required construction of the cooling system for the brake containing an external tank and demineralized water pump. Engine acceleration tests from idle to the scope of the range II for different mixture composition regulation programs were carried out. Motor control – through an appropriate flow of fuel into the combustion chamber took place automatically, by using the system developed in the task 14.

2.13. Task No. 13 Comparison of the performance of turbine engine with a simple combustion chamber and turbine engine with gas chamber that uses rotating detonation

Tests of four **after TBO** (Time between Overhaul) engines GTD-350 were performed on propeller stand. Their characteristics for the purposes of comparison with a factory new engine GTD-350 were determined. Two of them were later rebuilt into demonstrators GTD-RD with detonation (a spinning detonation) combustion chamber. Comparative tests of demonstrators GTD-RD (with detonation chamber) were performed in conditions that simulated GTD-350 engine operating conditions. Tests were carried out with hydrogen fuel (hydrogen gas) and were combined fuel (hydrogen + kerosene in all proportions). The resulting characteristics were compared with the characteristics of the factory new engine GTD-350 in order to estimate the impact of the application of the combustion chamber with a rotating detonation on engine performance.

2.14. Task No. 14. Development of a dynamic model of the engine and the engine control system

Full dynamic model of the turbine engine GTD-350 with detonation combustion chamber consisting of component models was developed. The model is implemented in Matlab-Simulink. The verification of the model was conducted comparing the results obtained in the simulation with the results of measurements performed on a real engine. On the basis of this model the system structure and the motor control algorithms were developed. Later they were checked in action on the motor, using the LabVIEW software package and electrohydraulic valve actuators. The engine was controlled automatically to keep steady state in different operating ranges of the engine, and to control the processes of acceleration of the engine from idling range to the range through II.

3. Description of the results

Project’s primary objective, which was to present the structure more efficient and more environmentally friendly turbine engine than previously used, was completed. At the workshop organized “International Workshop 2014 on Detonation for Propulsion” we presented the world's first working turbine engine with detonation chamber. “Operating parameters of the engine are better by 5-6% compared to the same engine fitted with classical combustion chamber. As a result, two test stands were created: one for testing fuel mixing and the other to study the combustion chamber, designed for testing rotating detonation and enabling simultaneous supply of liquid and gaseous fuels. A team of designers and researchers with unique qualifications was formed in the project. Expanded team of young workers who already have extensive experience in design and research. The results of the work have been presented at a number of national and international conferences.

Acknowledgement

Research conducted during 2010-2015 under the project UDA-POIG.01.03.01-14-071, “Gas turbine with detonative combustion chamber” supported by EU and Ministry of Regional Development, Poland.

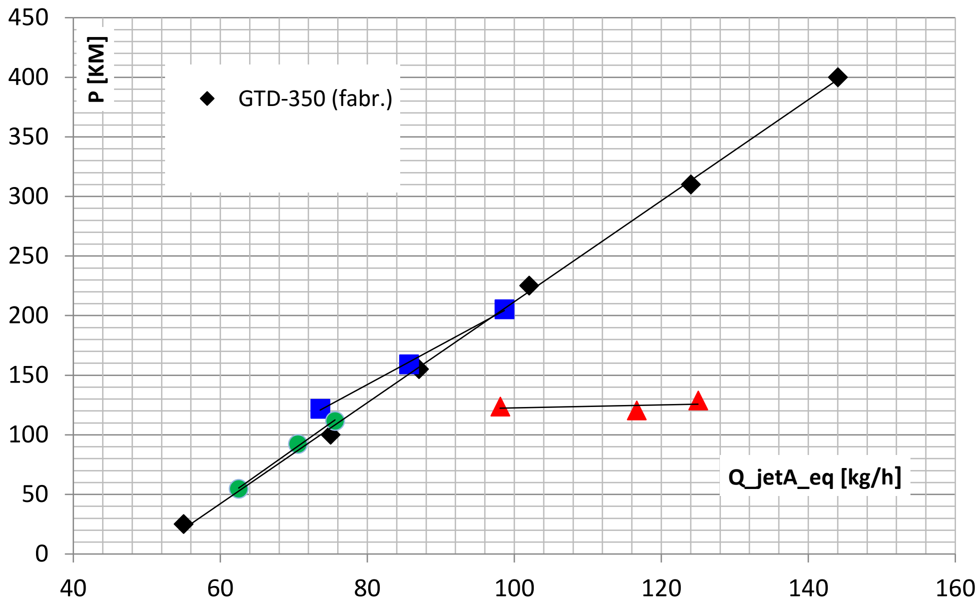

Fig. 1. Comparison of the adjusted fuel consumption for unit GTD-RD2 and "deflagration" engine GTD-350 (K15, K17 type of combustion chamber)

References

[1] Kalina, P., *Turbine Engine With Detonation Combustion Chamber in Institute of Aviation*, Journal of KONES, Vol. 21, No. 1, pp. 119-125, 2014.

[2] Kawalec, M., Perkowski, W., *Initiation of Rotating Detonation in Experimental Combustion Chamber*, Journal of KONES, Vol. 20, No. 4, pp. 163-169, 2013.

[3] Perkowski, W., *Study on Kerosene Atomization Process Under a High Speed Air Stream*, Journal of KONES, Vol. 18, No. 4, pp. 341-349, 2011.

[4] Wolański, P., *Research on the Application of Continuous Rotating Detonation to Gas Turbine*, Polish American Conference on Science and Technology, Journal of Polish-American Science and Technology, Vol. 9, pp. 15-48, Columbus, Ohio 2015.

[5] Wolanski, P., *Development of the continuous rotating detonation engines, in Progress in Pulsed and Continuous Detonations*, edited by G. D. Roy and S. M. Frolov, Torus Press, pp. 395-406, Moscow 2010.