Experimental Research of Performance of Combined Cycle Rotating Detonation Rocket-Ramjet Engine

Piotr Wolański, Michał Kawalec Institute of Aviation Warsaw, Poland

1 Introduction

Detonation propulsion offers significant improvement of engine efficiency, and due to these advantages, there is a growing interest in development of such propulsion systems. This is because in detonation pressure is increasing significantly and the energy release rate is much higher than in deflagration. Engines utilizing detonation are also easier to scale as compared to conventional engines which use deflagrative combustion. Basically, there are three types of jet engines which can utilize detonation for energy release in engine combustion chamber, these are: Pulse Detonation Engine (PDE), Standing Detonation Engine and Rotating Detonation Engine (RDE). Recently main attention in development of detonation propulsion systems is focused on engines based on continuously rotating detonation, or RDE, since in such engines detonation continuously propagates, as long as the fuel and oxygen are supplied into the chamber, so the thrust is produced continuously, unlike as in PDE were thrust is produced as a successively repeating pulses. Another advantage of the RDE over PDE is, that once initiated engine operate continuously, as long, as fuel and oxidizer is suppled to detonation chamber. Continuously rotating detonation is most often produced in cylindrical chambers and such chambers can be utilized in different kinds of propulsion systems, such as gas turbines, turbojet engines or rocket engines. The aim of this work is to test experimentally operation of the combined cycle rocket-ramjet engine utilizing continuously rotating detonation. Basic idea of such engine was already discussed many years ago and first configurations of the engine can be found in [1-4], while some results related to experimental and theoretical analyses can be found in [4-6], and schematic diagram of such engine is presented below on Fig.1.



Fig.1 Schematic diagram of combined cycle rocket-ramjet engine.

Correspondence to: Piotr.Wolanski@ilot.edu.pl

2. Experimental research

The experimental research was carried out at test facilities of the Institute of Aviation in Warsaw. As a base for research model of rocket engine utilizing continuously rotating detonation created in the cylindrical chamber of diameter of 130 mm and channel length of 50 mm and channel high of 3.5 mm was utilized. The mixtures of gaseous methane and oxygen were used in all experiments. Schematic diagram of the research facility for model rocket engine is presented on Fig.2a. Before each of the experiments both gaseous methane and gaseous oxygen were transferred from big bottles to the small reservoirs at given initial pressure of 9 bar for methane and 13 bar for oxygen. Such procedure allows to supply both mixture component at nearly constant pressure for the duration of 0.6s. For both supply lines calibration was performed to know rate of fuel and oxidizer flow to detonation chamber, so it was possible to control both, rate of supply of components as well as equivalence ratio of produced mixture. All tests were controlled by PC computer connected to control board which send signal to open/close fuel and oxygen valves, send signal to spark, which ignited mixture. The measurements of pressure variation in cylindrical detonation chamber and thrust were collected by the data acquisition system. Initially calibration tests were carried out to determine performance of the model rocket engine itself. Since the rate of supply of both fuel and oxidizer to the detonation chamber were measured as well as produced thrust, specific impulse was calculated for a giving range of the equivalence ratio. After calibration, the rocket segment was incorporated into subsonic diffusor, external combustion chamber and convergent nozzle. Then the integrated rocket-ramjet engine was attached to the outlet of the nozzle from the air supply channel. Schematic diagram of such system is presented on Fig. 2b.



Fig.2. Schematic diagram of the research facilities: a) basic rocket engine with supply and measurements system, b) rocket-ramjet placed at the exit of subsonic flow from air supply system.

For engine operation in rocket mode both pressure variation in cylindrical detonation chamber and thrust were measured. Typical pressure variations in cylindrical detonation chamber at rocket mode operation are presented on Fig.3a, while typical thrust variation records are shown on Fig. 3b. Series of experiments were



Fig. 3, Variation of the pressure in cylindrical detonation chamber for rocket mode operation (a) and typical variation of measured thrust (b).

conducted for different equivalence ratio of gaseous methane-oxygen mixture, ranging from 0.58 to 0.81. For these operating conditions, range stable detonation in cylindrical chamber of the engine was only recorded for mixture equivalence ratio ranging from 0.66 to 0.81, while for lower equivalence ration no detonation was recorded.

After those experiments the engine was modified and subsonic diffusor, external combustion chamber and convergent nozzle was attached. Special struts was used to center outer structure of the ramjet section of the engine with core of rocket module. Also the inner con of diffuser was attached to the front of the rocket module. The whole engine was fixed to specially designed arm and connected to force sensor for thrust measurements. The rocket-ramjet engine was then placed at the front of the line which provided high rate of air flow to the engine. The spacing between air supply line and entry to the engine was about 20 mm and the velocity measured at exit of the air supply line was 200 m/s, with small variation of about 5 m/s. Before each of the experiments containers with gaseous methane and gaseous oxygen were filed to desirable

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pressure, ignition system was charged and then flow of air was initiated. When air flow reached steady state conditions, automatic sequencer was triggered by computer and experiments were conducted. In each experiment the trust was measured and then specific impulse, related to gaseous propellant supply to rocket core of the engine, was calculated. Also a special camera recorded whole process, so the stability of engine operation could be monitored. Experiments were conducted for the mixture equivalence ratio related to rocket mode of the engine ranging from 0.66 to 0.8. From measured thrust of combined cycle rocket-ramjet engine and measured rate of mixture supply to rocket mode, the specific impulse of the whole system was calculated. The view of the cut of the engine interior is presented on the Fig.4a, while the picture if operating engine is presented on the Fig. 4b. It is clearly seen that the combustion products flowing out of the engine are leaving convergent nozzle at pressure equal to atmospheric pressure and flow is subsonic, no Mach discs are observed. Typical measured thrust variation is presented on Fig.5, and variation of the calculated specific impulse as the function of equivalence ratio of rocket mixture is presented on Fig.6. On this figure results of calculated specific impulse for both rocket mode and combined cycle rocket-ramjet mode of operation are presented. It can be clearly seen that for combined cycle operation specific impulse is always higher than for rocket mode operation only and in optimum conditions, for conducted experiments, the value of specific impulse can be even higher than 40%.





b)

Figure 4. Internal view of the rocket-ramjet subsonic engine configuration (a) and picture of working engine (b).



Figure 5. Typical variation of thrust for rocket-ramjet mode of engine operation.



Fig.6. Variation of the specific impulse as a function of equivalence ration for both rocket mode and rocket-ramjet mode of engine operation.

4. Discussion and conclusions

Experimental tests of combined cycle rocket-ramjet engine utilizing continuously rotating detonation under simulated subsonic flight conditions were successfully conducted. Initial results show that using such configuration in rocket-ramjet engine during atmospheric flight offers significant advantages as compared to simple rocket engine configuration. In such configuration rocket engine works only as a generator of hot partially burned gases, which can react very quickly in the ramjet combustion chamber and generate the thrust. Experiments conducted at the institute of Aviation in Warsaw for subsonic operating condition show specific impulse/thrust improvement, in normal operating conditions, of up to 40% over the conventional rocket engine mode. Further research of rocket-ramjet operating at the different operating conditions can provide necessary data for optimization of such engine. It will also be desirable to conduct such research for supersonic flow conditions.

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