DETONATION ENGINES

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Abstract

In this paper survey of jet engines based on detonation combustion is provided. After short historical view, basic schemes of engines utilizing detonation are described. Possible improvement of propulsion efficiency due to detonative combustion which results in pressure increase is presented and comparison of deflagrative and detonative combustion is discussed. Detailed description of Pulsed Detonation Engines (PDE) as well as Rotating Detonation Engines (RDE) is given. Also basic principle of engine utilizing Standing Detonation is provided. Special attention is given to RDE, since rotating detonation can be applied to all kind of jet engines including, turbine, ramjet and rocket engines. Basic research of rotating detonation in cylindrical chambers for hydrogen-air mixtures is presented. A typical pressure record for experiments carried out in laboratory conditions is given. Schematic diagrams of turbofan engines are compared to classical ones and advantages and disadvantages of application of rotating detonation to these engines is discussed. For ramjet engines, schematic diagram of engine operation is depictured. Special attention is given to the rocket engines utilizing rotating detonation. Experimental research of small models of rockets engines with aerospike nozzle is presented. Test of such engines were carried out for gaseous fuels, such as: hydrogen, methane, ethane and propane with gaseous oxygen. Measurements of pressure and thrust are presented. Finally, possible configuration and applications of combine cycle rocket-ramjet engine utilizing rotating detonation is discussed.

Keywords: *detonation engines, detonation, PDE, RDE*

1. Introduction

Detonation process was described first by Berthelot, Vieille, Mallard and Le Chatelier in 1881 and nearly twenty years later the zero dimensional theory of detonation was independently presented by Chapman and Jouguet [1, 2]. First attempt of application of pulse detonation to jet propulsion was made at the University of Michigan by J.A. Nicholls in fifties of the last century [3] and first demonstration of establishment of the continuously rotating detonation was demonstrated fifty years ago by Vojciechovski, Metrofanov and Topchiyan at the Institute of Hydrodynamics of Siberian Branch of Soviet Academy of Sciences in Novosibirsk [2]. About twenty years ago intensive research was reinitiated on Pulsed Detonation Engine (PDE) and nearly ten years ago on Rotating Detonation Engines (RDE). Many papers on this subject can be found in publications [4-14]. In 2004, Tobita, Fujiwara and Wolanski applied for a patent on the Rotating Detonation Engine (RDE) and the patent was issued in 2005 [15].

2. Detonation versus deflagration

In detonation the reaction front in fuel-air mixture propagates with the velocity of order of km/s, and produces a significant pressure increase. Detonation velocity for fuel-air mixtures is usually over 1,8 km/s, and creates pressure increase of more than ten times. In the mixtures with oxygen, detonation velocity can be as high as 3 km/s and the pressure rise can be higher than 20 times. For marginal conditions, quasidetonation (or degraded detonation) can propagate with the velocity of the order of one km/s. In past the detonation most often occurred in accidental explosions, and since, in detonation the pressure increases significantly, damages are usually much more severe than those in non detonative explosions. Up to now, practical applications detonative combustion has been very limited. Only recently the detonation process is being applied to Detonation Engines.

In contrast to detonation, deflagration flame velocity is of the order of dozens m/s, so combustion also has to be organized at the stoichiometric ratio (higher burning velocity) what results in a high combustion temperature and in production of high concentration of NO_x. Since in jet engine temperature of burned products is very high, it is necessary to mix extra air before turbine, which makes the design more complicated. Also in the combustion chamber the pressure drops due to the combustion.

In contrast to deflagration the combustion zone in detonation is very small. If the detonation propagates in a lean mixture, the combustion temperature is relatively low, so a low emission of NO_x is expected (also due to a small residence time). Thus there is no necessity to add extra air before the turbine (in turbojet engines). In addition due to the detonative combustion the pressure in chamber is increased. So application of the detonation to jet engines offers significant improvement to its performance.

3. Detonation engines

If detonation combustion is applied to jet engine, efficiency of the engine cycle can be theoretically increased even more then 15%. This is due to the fact that during detonation specific volume of reacting mixture is decreased, so the theoretical efficiency of the cycle is even higher than for constant volume combustion (Fig.1) and specific impulse for such propulsion systems is much higher than for conventional engines (Fig.2).

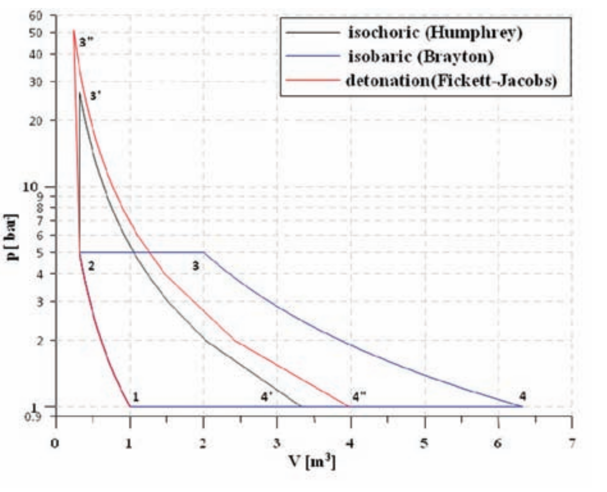

Fig.1. Comparison of different ideal thermodynamic cycle

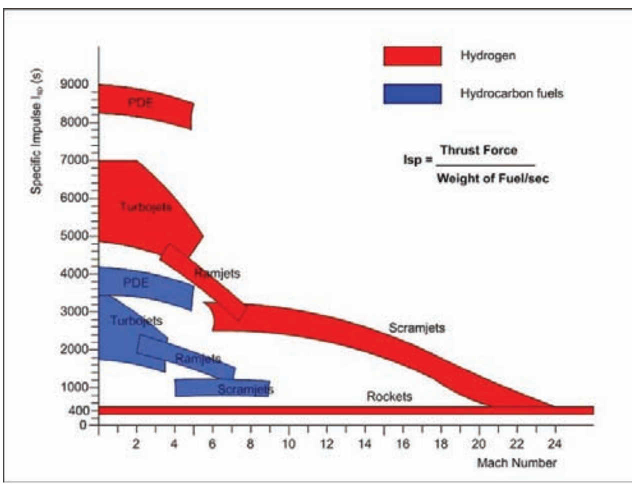

Fig.2. Theoretical dependence if specific impulse for a different propulsion systems and different fuel.(Source http://arc.uta.edu/research/pde.htm)

Since in detonation the energy release rate is much higher than in deflagration, also engines utilizing detonation have higher thermodynamic efficiency, and they are easier to scaling as compared to conventional engines which use deflagrative combustion. All this is giving strong motivation to apply detonative combustion to jet engines. Basically, we can distinguish three types of jet engines which can utilize detonation for energy release in engine combustion chamber. They are: Pulse Detonation Engine, Standing Detonation Engine and Rotating Detonation Engine.

3.1 Pulse Detonation Engine

Pulse Detonation Engine typically consists of a sufficiently long tube which is filled with fresh fuel-oxidizer mixtures and ignited by sufficiently strong energy source. Flame initiated by ignition must in relatively short time accelerate to detonation velocity, so the transition from deflagration to detonation must happen in relatively small distance. Detonative combustion produces high pressure which is converted to thrust. After all mixture is consumed by detonation, combustion products have to be evacuated from the tube and fresh mixture must be quickly resupplied, and the cycle is repeated. Typical frequency of such engine operation is usually in range of dozen Hertz.

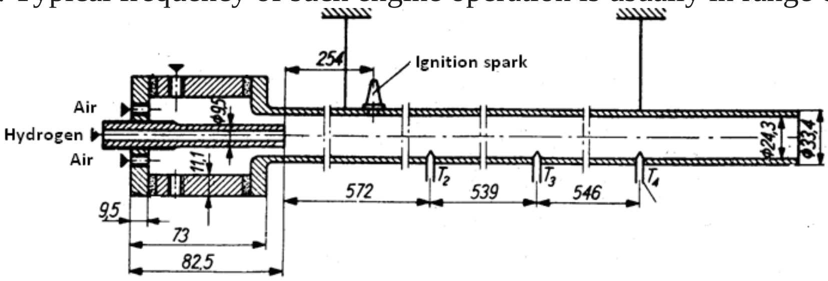

Fig.3. First PDE designed by J.A. Nicholls at the University of Michigan

PDE can operate in wide flight Mach number, ranging from 0 and up to M4+, but the engine operates in a pulsed mode, so the thrust is varying in time and the detonation must be initiated each time. The system is complicated because fast purging and refilling are required. Also the engine is operating in the stoichiometric condition (due to necessity of fast initiation of detonation), and the frequency is relatively low. If the pulsed detonation could be applied for turbojet combustion chambers, it would be necessary to add an extra air to decrease the temperature before the first turbine stage. Also the production of NO_x would be high. Many such research are already carried out by different laboratory and different research centres [4,5] and research on possible application of PDE to rocket propulsion is also carried out [16,17].

3.2. Standing Detonation Engine

Principle of operation of the Standing Detonation Engine is relatively simple. Fuel is injected into supersonic flow and detonation wave is stabilized inside the engine by wedge or other means, and products are expanding inside nozzle. Typical scheme of such engine is shown on the Fig.4.

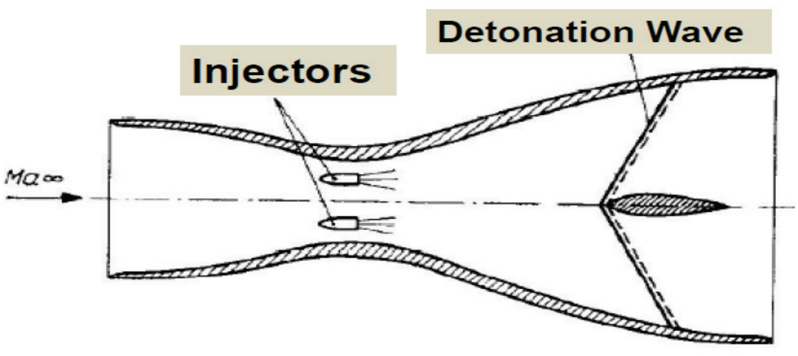

Fig. 4. Schematic diagram of the Standing Detonation Engine

The biggest disadvantages of such engine is very limited (very narrow as related to Mach number) range of operation conditions. Velocity, at which such system can operate must be higher the C-J detonation velocity, but should not exceed Mach number greater than 7. For higher than Mach number equal to 7, the pressure losses on outer engine contour will be higher than thrust generated inside engine core and the use of such engine will not be justified for obvious reasons.

3.3. Rotating Detonation Engine

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 schematic diagram of such chamber is presented in Fig. 5. Air (or oxygen) is supplied through a narrow slit at critical conditions and fuel is injected through a numbers of small holes. Initiator and pressure transducer are placed on the outside wall of the cylindrical detonation chamber. Typical pressure measurements are shown in Fig.6. Such chamber can be applied to different king of jet engines, such as: turbojet or gas turbine, ramjet or rocket.

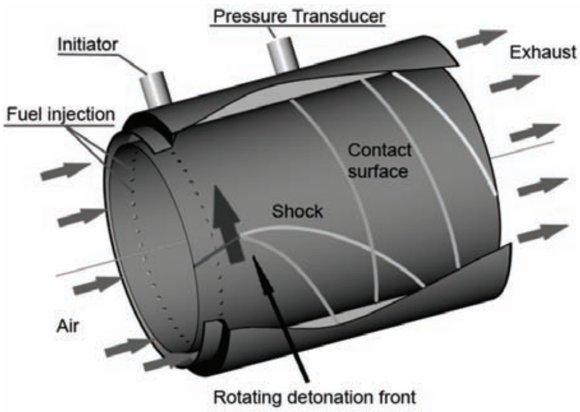

Fig.5 Schematic diagram of detonation chamber

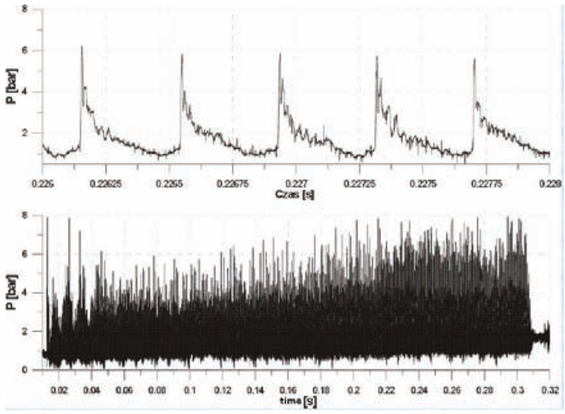

Fig.6. Typical pressure variation for detonation in research chamber

3.3.1. Engines using continuously rotating detonation

The simplest engine utilizing continuously rotating detonation is the rocket engine. In the engine, the fuel and oxidizer are injected into cylindrical detonation chamber, and rotating detonation continuously propagates, as long as the fuel and oxygen are supplied into the chamber. Since the products from detonation chamber will be flowing out with supersonic velocity, there is no need to apply the diverging convergence nozzle and the aerospike nozzle can be attached directly to the detonation chamber. At Warsaw University of Technology, a small model of the rocket engine, operated at different gaseous oxygen-fuel mixtures was tested. Hydrogen, methane, ethane and propane were used as fuels. For all mixtures, the rotating detonation was achieved, however, a detailed measurement of thrust was performed only for the methane-oxygen mixture. Rotating Detonation rocket engine as well as recorded pressure variations in time and measured thrust are presented in Fig.7.

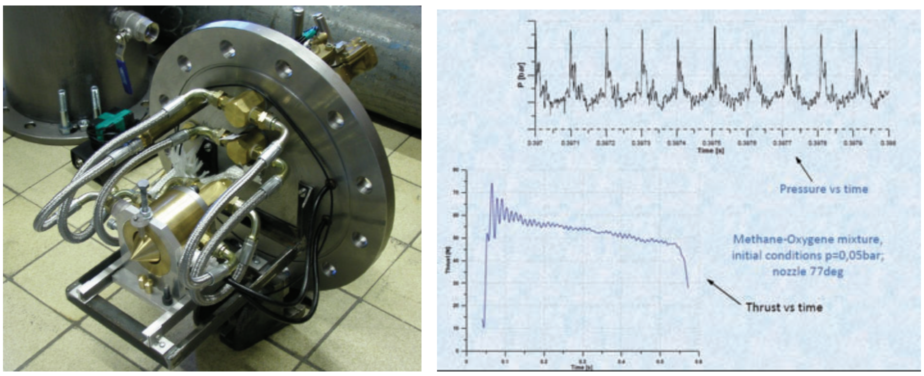

Fig.7. Warsaw University of Technology laboratory model of rotating detonation rocket engine and example of pressure and thrust measurements

The continuously rotating detonation can be also applied in the supersonic ramjet engine. In such case, the detonation can be organized in a special sub-chamber, where a rich fuel-air mixture can detonate (Fig. 8) or in a whole cross-section behind the normal shock wave. In both cases, the engine length will be much smaller than that in conventional ramjet. Successful laboratory operation of the ramjet like RDE with ejection mode was already reported by Bykovskii and Zhdan [18].

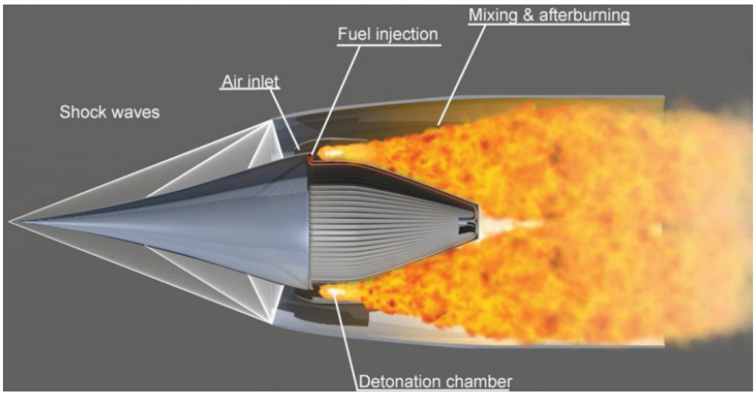

Fig. 8. Schematic diagram of the supersonic ramjet based on RDE

The continuously rotating detonation can be also applied in turbojet engines. Schematic diagrams of the engines with combustion chambers utilizing the continuous rotating (wave) detonation are shown in Fig.9 and Fig.10.

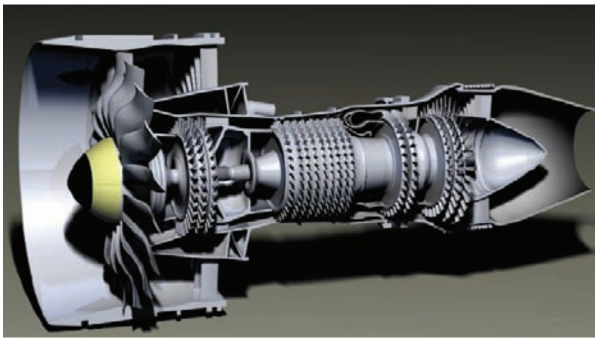

Fig.9 Schematic diagram of classical turbofan engine

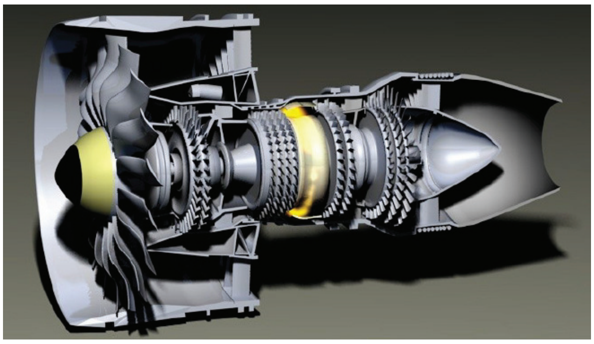

Fig.10. Schematic diagram of the turbofan engine utilizing detonative combustion

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 the 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. The engines will also be more environmental friendly, since the rotating detonation could be organized for lean mixtures. Less emission of pollutants and smaller or no emission of CO_2 (if hydrogen will be used as fuel) can be practically achieved.

It is also possible to build combined cycle RDE. Schematic view of such engine is depictured on Fig.11. This configuration might be suitable for supersonic transport plane. Plane will initially accelerate on rocket mode, then gradually transfer to ramjet for cruising. Initially engine will require liquid oxidizer (for rocket mode), thus the takeoff mass of the plane will be higher (due to mass of oxidizer for rocket motor) but this will be later compensated by low mass of ramjet engines as compare to complicated and heavy combined cycle turbo-rocket engine. During whole cussing at supersonic velocity engines will work on the ramjet RDE mode.

RDE engines will have many other direct applications in many areas, ranging from commercial aircrafts to supersonic transport, as well as in rocket propulsion.

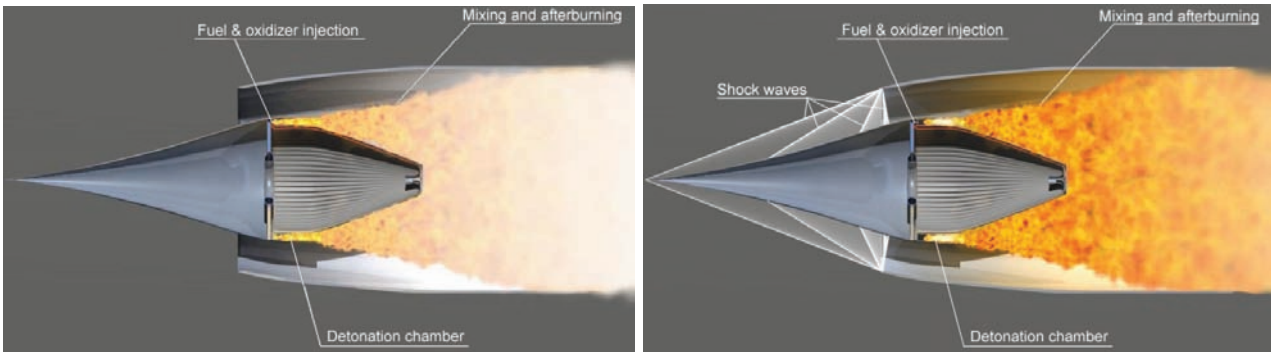

Fig.11. Schematic diagrams of combined cycle rocket-ramjet RDE. Subsonic rocket mode with afterburning in ejector is on the left and supersonic mode using rich rocket mode followed with afterburning of partially reacted produces

In Poland the research on RDE are carried out at the Institute of Heat Engineering, Warsaw University of Technology (WUT) and in the Institute of Aviation. At WUT the rotating detonation was achieved for acetylene-air and hydrogen-air mixtures in very different initial conditions and for mixtures of hydrogen, methane, ethane and propane with oxygen in cylindrical chambers of different geometry. Also at the Institute of Aviation in Warsaw a special research related to application of rotating detonation to GTD-350 helicopter engine is under way. The goal of this project is to test this engine in two years.

4. Discussion and conclusions

Application of the detonation into jet propulsion combustion chamber offers significant advantages over the conventional solution with deflagrative combustion mode. In the detonation chamber, combustion occurs at a very small distance and the combustion chamber is compact. Since the pressure in detonation is increasing, the thermal efficiency of the system is also increasing. It also seems that RDE will be superior over PDE, since they offer continuous thrust generation and can be applied basically to any Mach number.

At the present stage, the development of the PDE and RDE is carried out in many countries including:, China, France, Japan, Poland, Russia, USA and other. The experiments were conducted for all kind of possible configuration of the PDE and RDE. It is just only matter of time that the PDE and RDE will be utilized in the majority of jet propulsion systems.

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