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ABOUT THE DETONATION ENGINE

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ABSTRACT

The research objects of this study are new principles of gas turbine and rocket engines working process organization, based on the oscillatory motion of shock and detonation waves. Purpose is to identify the state of level technology, describe the subject area, state the direction of research and formulate the main problems hindering the implementation of wave technology into mass production. The results presented in the study can be recommended for developers of aircraft engines, power and technological turbo-machinery.

Keywords: Shock Wave, Detonation Wave, Shock Wave Structure, Detonation Engine, Impulse-Detonation Engine, Rotary Engine, Optimum Shock Wave Structures

1. INTRODUCTION

Modern development of aerospace machinery tools, engines, gas turbine power machines, turbo-refrigerating units is primarily associated with the switch to oil-free transmissions, which uses gas bearings, as well as with the use of more efficient thermodynamic cycles (Faleev, 2012). It is necessary to take into account the physics of wave processes occurring in the gas environment. It may be shock and detonation waves, stationary shocks, simple isentropic rarefaction and compression waves.

The aim of this study is a complete description of the pulse-detonation subject area systems.

The following is given:

- Description of the pulse detonation systems advantages of, from the perspective of the thermodynamic cycle
- Overview of the world's main research directions in the in the field of pulse and detonation engines and technological installations

This overview allows to pose the research problem in this subject domain for the near future, to formulate the main problems hindering the rapid implementation of pulse and shock wave technology in mass production.

2. THE CRYSIS OF MODERN TECHNOLOGIES

The combustion chamber of a typical jet engine consists of injectors for mixing the fuel with the oxidant, fuel mixture ignition device and flame tube, where the oxidation-reduction reactions (combustion) proceed. Flame tube ends with a nozzle. Typically, this is a Laval nozzle, which has a converging part, the minimum critical section, wherein the velocity of combustion products is equal to the local sonic speed and the expanding part, wherein the static pressure of combustion products is reduced to the environment pressure as close as possible.

Very roughly, the engine thrust can be estimated as the area of the nozzle throat section, multiplied by the difference between pressures in the combustion chamber and in the environment. Therefore, the higher the pressure in the combustion chamber, the higher is the thrust. If the energy of the gases out flowing from the combustor drives the turbine, it, in its turn, can be used for the accomplishment of effective work to drive the actuator and the compressor for compressing the air (an oxidizer).

Development of advanced propulsion and power machines by traditional schemes approached its technological limit. Rocket engines reached their limit values of specific pulses (a perfection characteristic of the rocket engine, approximately equal to the velocity of the combustion products outflow into the empty space from the ideal Laval nozzle) for the corresponding types of fuel.

In gas turbine devices the temperature of the fuel in combustion chambers approached stoichiometric temperature. Further increase of pressure in the combustion chamber can be achieved by increasing the air compression, which leads either to an increase of compressor diameter, or to increase of rotational speed.

Usage of the costly new materials, such as rhenium or ruthenium as well as special coatings, for example, made of silicium carbide, in the construction of promising turbines allows the combustion chambers to be uncooled.

As part of the evolutionary development of traditional technologies it is likely to expect the growth of specific parameters (thermodynamic efficiency, relative impulse, decrease in relative weight (the ratio between the engine weight and the produced thrust) and reduction of the relative fuel consumption) by 5-10% (Skabin and Solonin, 2004).

Further growth of relative parameters and maintainability requires the transition to other thermodynamic cycles, oil-free transmissions that use contactless gas or electromagnetic bearings, new power plant schemes.

3. COMPARSION OF THERMODYNAMIC CYCLES

Currently, the vast majority of jet engines and gas-turbine power machines operate in accordance with the Brighton cycle. This is the cycle of fuel combustion at constant pressure. Fuel is pumped into the combustion chamber at a pressure exceeding a given pressure in the combustion chamber. The oxidant is compressed and supplied into the combustion chamber by compressor, in the case of land power turbine, air inlet and the compressor in case of jet engine, the Turbo-Pump Unit (TPU), in the case of Liquid-propellant Rocket Engine (LRE). Both fuel and oxidant are supplied into the combustion area continuously. At the stationary regimes the combustion in the chamber proceeds at constant pressure. Combustion products, expanding, perform a useful work.

Can something better than Brayton cycle be offered? Yes, it's Humphrey cycle, in which the heat is supplied at constant volume of the working fluid. An example of the engine that implements this type of thermodynamic process is the Stirling engine, which is used on some submarines. **Figure 1** shows the advantage of Humphrey cycle compared to conventional thermodynamic cycles of heat engines (Brayton, Otto, Diesel).

The work of heat engine in one cycle is equal to the area, bounded by the curve 1-2-3-4. Sector 2-3 shows the advantage of the thermodynamic Humphrey cycle, compared with the Brayton cycle. Sector 1-4 shows the area that is inaccessible to cycles of Otto and Diesel heat engines.

An example of a device, implementing benefits of the Humphrey cycle is the Pulsating Jet Engine (PJE). Today PJE are used, mainly, on cheap unmanned drones, which is explained by its simplicity. Heat efficiency ratio within one thermodynamic cycle of jet engine, operating in accordance with the tradition Brayton cycle, is much smaller in the whole range of pressure increase coefficients P/P_0 (**Fig. 2**).

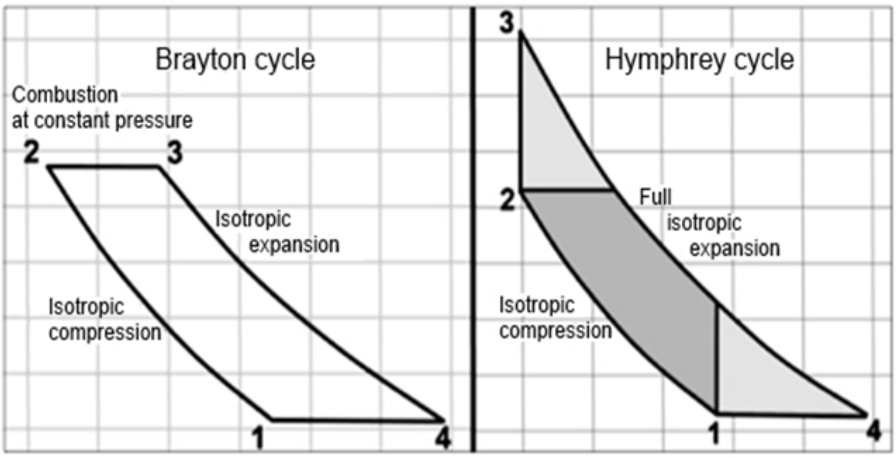


Fig. 1. Comparison of brayton and humphrey thermodynamic cycles

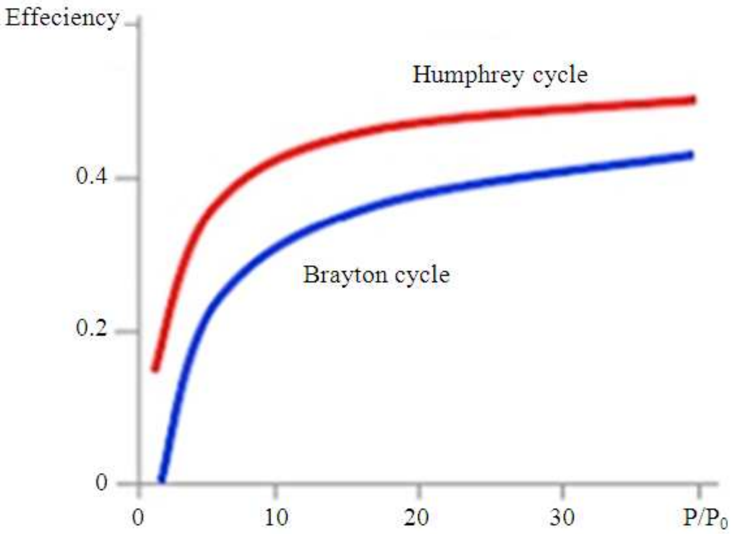


Fig. 2. Thermal efficiencies comparison of Brayton and Humphrey cycles at different degrees of pressure increase

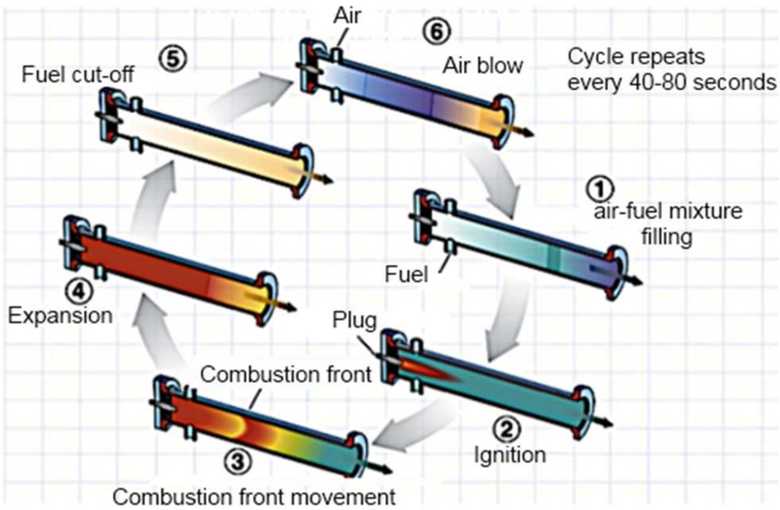


Fig. 3. Functional principle of pulse jet engine

The idea of creating PJE was patented in 1906 by Russian engineer V.V. Karavodin. In 1930, Paul Schmidt offered single-valve combustion chamber of resonance type for PJE. Subsequently, it was used in unmanned aircraft-missiles "V-1". Significant contribution into solving the problem of creating the PJE was made by B.S. Stechkin.

Functional principle of PJE is clear from the scheme in **Fig. 3**.

During the first step of the cycle the engine's chamber is filled with air-fuel mixture. On the second step the ignition occurs. During the third step the combustion front runs through the combustion chamber, raising the pressure in it at constant volume. On the fourth step the working fluid expands and performs the work. On the fifth and sixth step the camera is vented by fresh air.

Despite high efficiency of fuel combustion itself, the estimated useful work in PJE is usually significantly lower than traditional gas-dynamic engines. The reason is that the compression of the air-fuel mixture occurs in simple isentropic compression waves, which have large length. As a result, the pulse recurrence rate at of PJE is low and total mechanical efficiency is not so high.

Logical development of PJE ideas are Pulse-Detonation Engines (PDE), in which the compression waves are replaced by shock waves (**Fig. 4**).

Phase of PDE's operation "a -f" correspond to phases 1-6 of PJE. The difference lies in that the combustion in PDE occurs on phase "c" in a detonation wave front and not in a front of slow-burning (PJE phase 3). Combustion takes place in a very narrow region immediately behind the shock wave, which have a length about the average free length of the gas molecules. As a result, the velocity of detonation combustion is by the orders of magnitude higher than of the slow burning in the flame front (deflagration).

Fast compression and combustion in PDE cycle gives extra useful work compared with Humphrey cycle (see area 2-3-3" in **Fig. 5**). A significant advantage is also the fact that combustion can occur at much high temperature (**Fig. 6**).

It should be noted that despite the high thermodynamic efficiency of single pulsations, the drawbacks, typical for pulsating jet engines, such as low repetition rate of the shock waves and, consequently , low thrust efficiency are inherent to classical PDE.

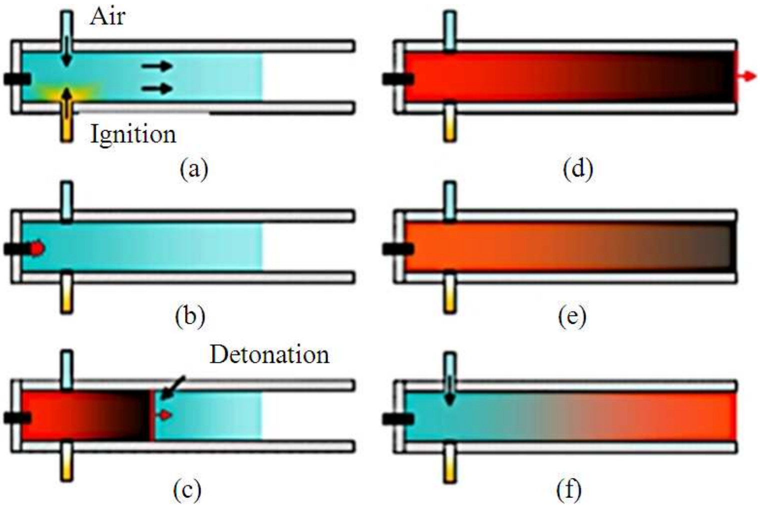


Fig. 4. Functional principle of pulse- detonation jet engine

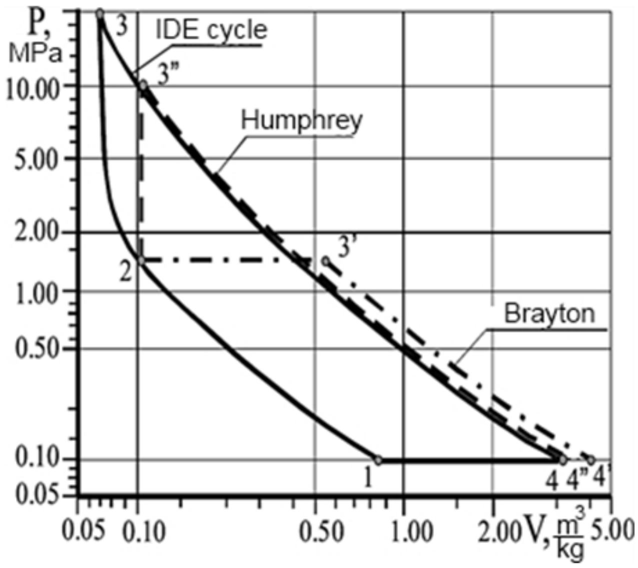


Fig. 5. Comparison of Brayton and Humphrey PDE cycles on coordinates pressure-relative volume (pV) (Tarasov and Shipakov, 2011)

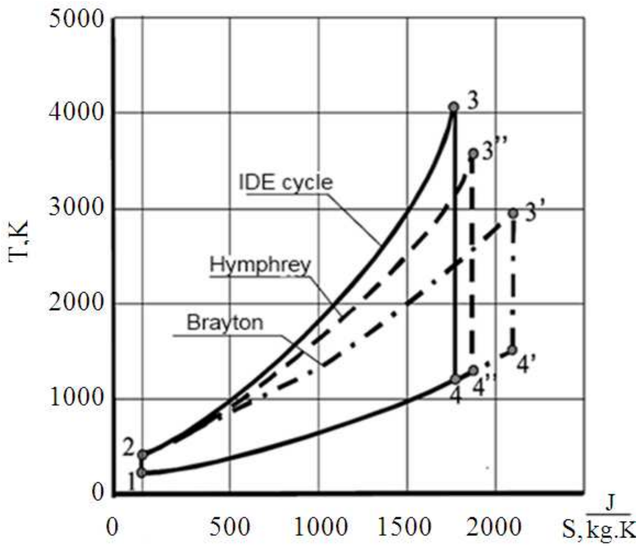


Fig. 6. Comparison of brayton and humphrey PDE cycles on coordinates Temperature-entropy (TS) (Tarasov and Shipakov, 2011)

4. DESIGN AND POTENTIAL ADVANTAGES OF THE PDE

Simplicity of PDE's design is its undeniable virtue. Classical appearance of PDE is a cylindrical combustion chamber that have a flat or specially profiled wall, called "thrust wall" (**Fig. 7**).

Thrust of the pulsed-detonation engine is determined by the transition of the momentum to the thrust wall by the shock wave. Nozzle, in some cases, is not even necessary. In traditional PDE the shock waves repeat with low frequency and, along with rarefaction waves, automatically adjust the supply of fuel and oxidant. Due to low repetition frequency of shock waves (Hz) the time, during which the combustion of fuel proceeds, is short compared to the typical cycle time. As a result, despite the high efficiency of detonation combustion itself (20-25% more than in Brayton cycle engines), total efficiency of such constructions is low. Valveless pulse detonation engines have their niche-cheap and disposable aircraft. In this niche they are successfully developing in the direction of increasing the pulse repetition rate. Obvious is also the transition to usage of the valves, which provide the periodic supply of the working fluid with a predetermined frequency.

Due to the fact that the fluid combustion proceeds in the shock waves about 100 times faster than in conventional slow combustion (deflagration), this type of engine is theoretically distinguished by record power per unit of volume compared to all other types of thermal engines (**Fig. 8**).

Apart from the high relative power the detonation engines potentially have other significant advantages. For example, during the cycle of detonation combustion is possible to achieve very high temperatures. But the combustion speed is also very high and nitrogen oxides do not have time to form, therefore the detonation engines are potentially environmentally friendly (Vasilev, 2013). The problem of cooling the combustion chamber is as well easier to solve. Despite the higher temperature and pressure in the detonation wave front due to the transience of detonation combustion processes their impact on the engine's structure is less than that of classical motors (Roy and Frolov, 2006). Usage of detonation combustion provides tangible advantages in the LRE as well. As an example, to evaluate the benefits of PDE, the parameters of "Space Shuttle" marsh LRE can be used. Pressure for liquid hydrogen behind the TPU is about 500 atm. Combustion chamber pressure-210 atm. To ensure similar conditions of fuel combustion in PDE the fuel components must be supplied under pressure not higher than 10 atm, which eliminates the need for Turbo-Pump Units (TPU) and strengthened pipelines (Bulat and Ilina, 2013).

5. FIELDS OF WORK ON DETONATION ENGINES

The main task at the current stage is the development of engines with high shock waves repetition frequency in the combustion chamber (Frolov, 2005) or the creation of an engine with Continuous Detonation (CDE).

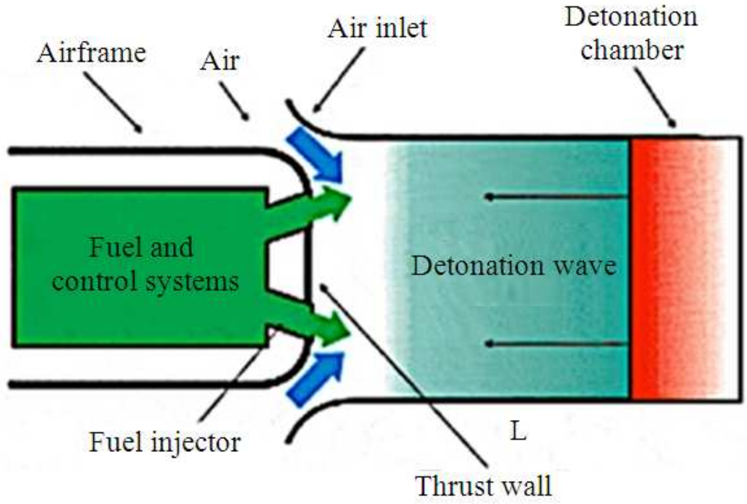


Fig. 7. Schematic diagram of the Pulse-Detonation Engine (PDE)

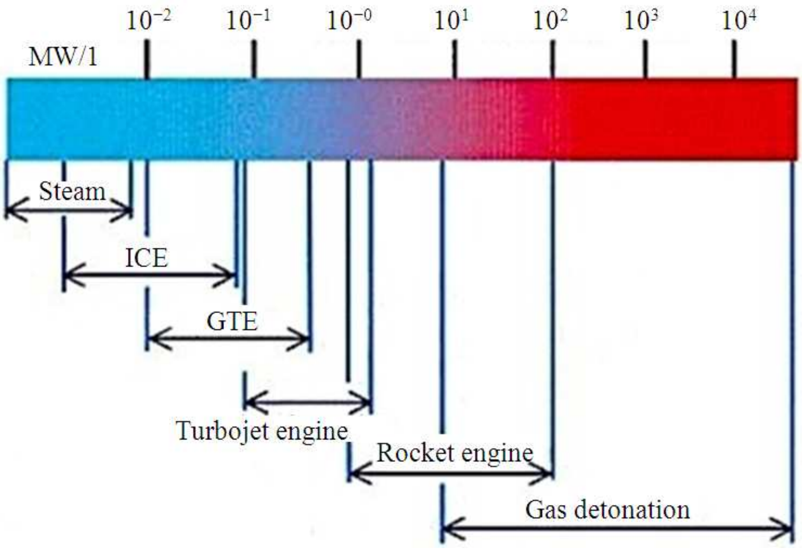


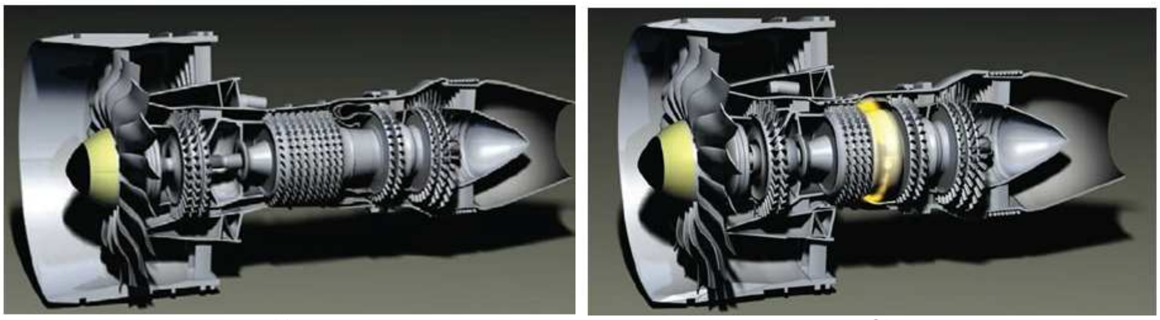
Fig. 8. Comparison of power per liter of modern thermal engines

The main tendency in the developing of PDE is the transition to multitube scheme (**Fig. 9**). In such engines the operating frequency of the single pipe remains low, but by alternating pulses in different tubes the developers hope to achieve acceptable specific characteristics (Frolov *et al*., 2004). Such scheme appears to be quite serviceable if the problem of vibration and thrust asymmetry, as well as the problem of bottom pressure (in particular, the possibility of low-frequency oscillations in the bottom area between the pipes) will be solved. However, it is still not possible to reduce the dimensions of the engine.

Engines with Continuous Detonation (CDE) and Rotary Detonation Engines (RDE), working not in a pulsating, but in continuous regime are an alternative to PDE. The main and only advantage of CDE/RDE compared with PDE is the compactness of such devices. This can significantly reduce the size of (Davidenko, 2011), for example, gas turbine machines (**Fig. 10**).

Potential advantages of the detonation engines thermodynamic cycle caused numerous of research in this direction.

Fig. 9. Multitube Pulse-Detonation Engine (PDE)



(a) (b)

Fig. 10. (a) Schematic of the classical two-circuit turbofan engine (b) Scheme of the turbofan engine that uses detonation combustion

Projects on detonation combustion in the United States are included in the development of promising engines IHPTET. The cooperation includes virtually all research centers working in the field of engine designing, many scientific centers and universities: ASI, NPS, NRL, APRI, MURI, Stanford, USAF RL, NASA Glenn, DARPA-GE C and RD, Combustion Dynamics Ltd, Defense Research Establishments, Suffield and Valcartier, Uniyersite de Poitiers, University of Texas at Arlington, Uniyersite de Poitiers, McGill University, Pennsylvania State University, Princeton University. NASA alone allocates $130 million for this purpose per year.

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In the new program VAATE-successor of IHPTET program-American specialists are aiming to reduce the production cost of gas generators by 32 ... 64% for air-jet engines of large dimensions, 35 ... 65% for GTE of small dimensions and technology for creating even cheaper pulse detonation engine is considered as “key” (Bulat and Prodan, 2013).

Leading position in the development of detonation engines takes specialized center Seattle Aerosciences Center (SAC), bought by Pratt and Whitney company from Adroit Systems firm in 2001.

Most of the center’s work is financed by the Air Force and NASA form the budget of interdepartmental program Integrated High Payoff Rocket Propulsion Technology Program (IHPRPTP), aided for the creation of new technologies for jet engines of different types.

In total, more than 500 bench tests of experimental samples were carried out by SAC center's specialists since 1992. Works on Pulse-Detonation Engine (PDE) with the consumption of atmospheric oxygen, performed by SAC are commissioned by U.S. Navy.

Taking into account the complexity of the program, the BMC attracted specialists of practically all organizations, working with detonation engines to its realization. Apart from the Pratt and Whitney Company, the United Technologies Research Center (UTRC) and Boeing Phantom Works firm participate in the works.

Currently in Russia the following universities and institutes of Russian Academy of Sciences (RAS) work on this actual problem theoretically: Institute of Problems of Chemical Physics (IPCP), the Institute of Mechanical Engineering, Institute for High Temperatures (IVTAN), Joffe Institute.

6. CONCLUSION

The paper discusses the principles of operation of the pulse-jet engine, detonation jet and liquid rocket engines. The advantage of using the thermodynamic cycle of detonation combustion compared with the Brayton cycles (combustion at constant pressure) and Humphrey (combustion at constant volume) is shown.

The main research centers, conducting research on the new generation of engines are listed. The main directions and tendencies of detonation engines construction are discussed. The main types of detonation engines are presented.

The paper illustrates the difference in the method of thrust creation compared to the classical jet engine equipped with a Laval nozzle and describes the concept of thrust wall.

7. FINDINGS

Pulse detonation engines are being improved in the direction of pulse repetition rate increase and this direction has the right to exist in the area of light and cheap pilotless aircrafts, as well as in development of various ejector thrust amplifiers.

The main advantage of using detonation combustion in LRE must be considered not a potential efficiency and relative momentum increase, but a drastic decrease of engine's cost.

The market strategy of the world's leading manufacturers is aimed not only for development of the new detonation jet engines, but also for modernization of existing by replacing them conventional combustion chamber for detonation one.

In addition, the detonation engines can be part of a combined air units of various types, for example, be used as an afterburner for JDE, as the lift ejector engine in aircraft with vertical takeoff and landing.

8. ACKNOWLEDGEMENT

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