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Detonation Jet Engine. Part 1 – Thermodynamic Cycle

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ABSTRACT
We present the most relevant works on jet engine design that utilize thermodynamic cycle of detonative combustion. The efficiency advantages of thermodynamic detonative combustion cycle over Humphrey combustion cycle at constant volume and Brayton combustion cycle at constant pressure were demonstrated. An ideal Ficket-Jacobs detonation cycle, and the thermodynamic cycle of real detonation engine that utilizes over compressed detonation were discussed. Main trends in development of detonation engines were described. Relevant for nearest time problems and directions of research were formulated.

KEYWORDS
Detonation, detonation wave, detonation engine, rotational detonation engine, pulse detonation engine

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Introduction

Historically the most important investment into the development of detonative combustion was made by Soviet and then Russian scientists. Ya.B. Zeldovich (1940) was the first who proposed to utilize detonation in engines and energy devices. By examining problem of arbitrary discontinuity breakdown in reacting medium, G.M. Bam-Zelikovich (1949; 1952) has laid the theoretical foundation of pulse detonation engine. He also was the first to give a simple theoretical explanation of pulsation appearance during fuel mixture combustion in cylindrical channel. Later, works were carried out in laboratory of gas-dynamics at Central Institute of Aviation Motors, under the direction of L.I. Seedov and after a break under directions of G.G. Cherny (1967). V.A. Levin and G.G. Cherny (1967) has developed main statement of detonation theory and

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solved a set of important model problems. Later, he established scholar school of detonation at Institute of Mechanics of the Moscow State University. This scientific school own hundreds of scientific works, in which the most important aspects of detonation theory and its appendixes, has been brought to light.

Novosibirsk Institute of Hydrodynamics became the other scientific center of detonation problem research, at which Voitsekhovsky has discovered spin detonation phenomenon and propose a design of a rotational engine with continuous detonation. Nowadays these works are being continued by F.A. Bykovsky and S.A. Zhdan (2013) in broad cooperation with foreign specialists. The most complete data on research of rotational detonation engine is complied in their monograph.

Literature Review

A large amount of work on valve detonation engines was done at Institute of Chemical Physics. A relevant review of these works is given in S.M. Frolov's monograph (2006). Nowadays in Russia, this important, in theoretical sense, problem is being worked on at following universities and institutions of Russian Academy of Sciences: Central Istitute of Aviation Motors, Institute of Chemical Physics, Institute of High Temperatures, Novosibirsk Institute of Hydrodynamics, Institute of Theoretical and Applied Mechanics, Physical and Technical Institute, Moscow State University, Moscow State Aviation Institute, Novosibirsk State University, Cheboksary State University, Saratov State University and others.

The potential advantages of detonation engine thermodynamic cycle generated a lot of research works in this direction. The leading position in detonation engine's development is taken by a specialized center Seattle Aerosciences Center (SAC), which was bought in 2001 by Pratt and Whitney from Adroit Systems. Center's major part of work is financed by BBC and NASA from budget of Integrated High Payoff Rocket Propulsion Technology Program (IHPRPTP) inter departmental program, that is aimed at creation of new technology for various types of jet engines. Aside from Pratt and Whitney United Technologies Research Center (UTRC) and Boeing Phantom Works also take part in reaserch.

In USA, projects on detonative combustion are included in development of perspective engine program IHPTET (Bulat, Zasukhin &Prodan, 2012). In cooperation take part almost all research centers that work in field of engine design, numerous scientific centers at universities: ASI, NPS, NRL, APRI, MURI, Stanford, USAF RL, NASA Glenn, DARPA-GE C&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, and Princeton University.

In new program VAATE – the successor of IHPTET program – stated the problem of reducing production cost of gas generators for large dimension engines by 32…64%, and by 35…65% for small dimension engines and technology of cheaper pulse detonation engine is considered crucial.

The theory of detonation (Mitrofanov, 1982), detonation engine and detonation wave propagation in various mediums is examined in fundamental works of G.G. Cherny (1967), V.V. Markov (1981), V.A. Levin (1967) and V.P. Korobeinikov et al. (1972). The development perspective of engines in general is reviewed in J.M. Ting, T.R. Bussing & J.B. Hinkey's work (1995). The general development tendencies of detonation engines are presented in works (Bulat & Prodan, 2013a; Bulat & Prodan, 2013b; Bulat, 2014). The review of detonation engine is present in work by P. Wolanski (2013).

Based on the velocity of detonation wave propagation in coordinate system conjugated with the engine, differentiate stationary detonation (Nicholls & Dabora), rotating detonation (Hishida, Fujiwara & Wolanski, 2009), when detonation is stationary in rotating coordinate system (Bukovskii, Zhdan & Vedernikov, 2006), transient detonation and pulsating detonation (Phylippov, Dushin & Nikin, 2012). Accordingly, the following engine types can be created: continuous detonation engine (CDE) (Jianping, Yetao & Meng, 2010; Dabora & Broda, 1993) rotating detonation engine (RDE) (Adamson & Olson, 1967), and pulse detonation engine (PDE) (Bussing, Hinkey & Kaye, 1994). Physical foundations and principles of detonation engine work cycle organization, are examined in the work (Roy et al., 2004), and question regarding computational modeling are examined in this one (Westbrook et al., 2005).

The experimental treatment methods of detonation engine construction are reviewed in the literature (Hinkey, Bussing & Kaye, 1995; Eidelman & Grossman, 1992, Lu et al., 2014). Examples of experimental realization and computational modeling of physical-chemical processes in combustion chambers of detonation engine of various designs are presented (Remeev et al., 2003).

Regardless of numerous researches and present prototypes, the real working unit of jet or rocket engine, that utilized detonative combustion, has not been created yet.

Aim of the Study

Aim of this paper is to highlight history of works on creation of fundamentally new engines that utilize thermodynamic cycle of detonative combustion.

Research questions

To analyze the most relevant on jet engine design that utilizes thermodynamic cycle of detonative combustion;

To demonstrate the efficiency of the thermodynamic detonative combustion cycle over Humphrey combustion cycle at constant volume and Brayton combustion cycle at constant pressure;

To discuss an ideal Ficket-Jacobs detonation cycle, and thermodynamic cycle of real detonation engine that utilizes over compressed detonation;

To describe main trends in development of detonation engines;

To formulate main trends in development and directions of research.

Method

The modern aviation propulsion system is represented by gas turbine engines (GTE) that are based on thermodynamic Brayton cycle (a cycle with combustion at constant pressure). Brayton cycle is also utilized by ramjets and liquid rockets. Fuel and oxidizer are constantly supplied to combustion chamber. By expanding, combustion products perform useful work.

The enhancement of modern engines and energy machines of traditional design, has reached its technological limit. Based on CIAM evaluation, in context of evolutionary traditional technology development we can expect a growth of specific indicators (thermodynamic energy conversion efficiency, specific impulse, reduction of specific weight – a ratio between engine's weight to delivered thrust, reduction of specific fuel usage) by 5-10%, which is conjugated with improvement of particular junction and solutions (Sehra & Whitlow, 2004).

A typical jet engine combustion chamber consists of injector for mixing fuel with oxidizer, and the chamber itself where redox reactions (combustion) occur. The chamber ends with a nozzle. It is usually a de Laval nozzle, which consists of converging part, a throat, in which combustion products speed is equal to regional speed of sound, and a divergent part, in which static pressure of combustion products decreases to environmental pressure, for as much as possible. An engine thrust can be roughly quantified, as a throat area multiplied by difference between pressure inside of combustion chamber and in the environment. Thus the higher the pressure in combustion chamber the higher the thrust.

If energy of gas flowing out of the combustion chamber operates the turbine which can be used to perform useful work by powering operating mechanism and air (oxidizer) compressor. The pressure inside combustion chamber can be raised by increasing combustion temperature, and by supplying oxidizer (air in case of GTE) at higher possible pressure. This leads to the need of using more expensive heat retardant materials, and to increase of compressor mass and price. The combustion temperature of modern GTEs is close to the limit, and such rare metals as rhenium and ruthenium, which are far more expensive than gold, are being used in construction.

There is another way to increase pressure in combustion chamber – the increase of mixture's combustion speed.

Because of its thermodynamic efficiency, the detonation is the most attractive mode of fast combustion (Tarasov & Shchipakov, 2011).

In detonation wave which propagates at 1500-2500 m/s, the maximum concentration of chemical energy, that was stored in fuel is reached (energy emits in thin layer of strike-compressed mixture).

Because in detonation engine the combustion occurs in shock wave approximately 100 times faster than at slow combustion (deflagration), this type of engine differs by its record power per unit of volume, compared to other type of heat engines (Fig. 1).

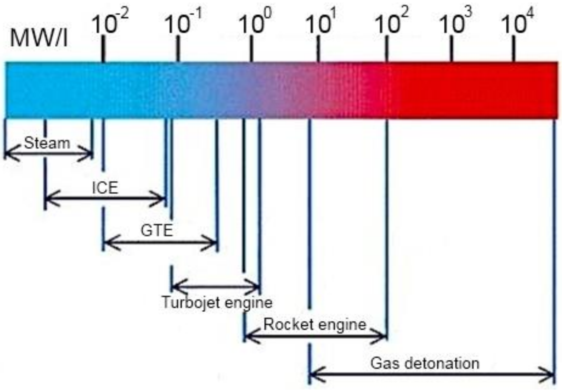

Figure 1. Comparison of power, megawatt (MW) per liter (l) of modern heat engines

High specific power aside, the detonation engines potentially have other major advantages. For instance, during cycle of detonative combustion the burning temperature is very high. However, the combustion speed is high as well so nitrogen oxides are to slow to form, thus the detonation engine is potentially environmentally friendly (Vasilev, 2013). It is also easier to design cooling for combustion chamber wall. Despite higher temperature of combustion and higher pressure in detonation wave front, fast processes flow has lesser impact on the engine compared to classical designs.

The detonation engines are also advantageous to use in liquid rockets, where pressure inside combustion chamber is higher than 200 bar. In order to create similar condition of fuel combustion in detonation wave, the fuel must be supplied at pressure lower than 10 bar, which allows to discard turbopumps and reinforced piping (Bulat & Ilina, 2013).

Data, Analysis, and Results

The detailed analysis and comparison of various thermodynamic cycles is presented in a work (Wintenberger & Shepherd, 2006) (Fig. 2).

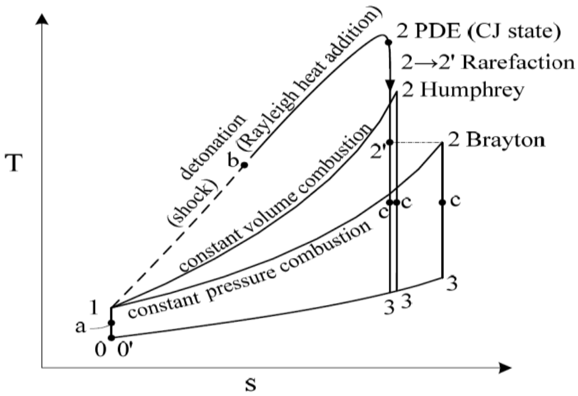

Figure 2. Comparison of different thermodynamic cycles in coordinates temperature (T) - entropy (S) (Tangirala & Dean, 2007). (CJ) - Chapmen-Jouguet detonation

When switching from combustion at constant pressure cycle (Brayton cycle) to combustion at constant volume cycle (Humphrey cycle), the thermodynamic efficiency rises by about 20%. At compression rate of 5, the thermodynamic efficiency of Brayton cycle is 36.9% for hydrogen, and 31.4% for methane. When switching to Humphrey cycle, the thermodynamic efficiency is 54.3% for hydrogen and 50.5% for methane.

The example of in engine that utilizes such thermodynamic process is a Sterling engine that is used on some submarines. Amongst engines that work according to Humphrey cycle, is a pulse jet engine that was used for German flying bomb V-1, during WW2.

An even higher is the efficiency of the ideal thermodynamic Fickett-Jacobs cycle (FJ). Fickett, by using earlier ideas of Jacobs, independently from Ya.B. Zeldovich, developed the concept of using detonative fuel combustion in rocket engines. In Fig. 3 the typical transition of PDE work phases are shown.

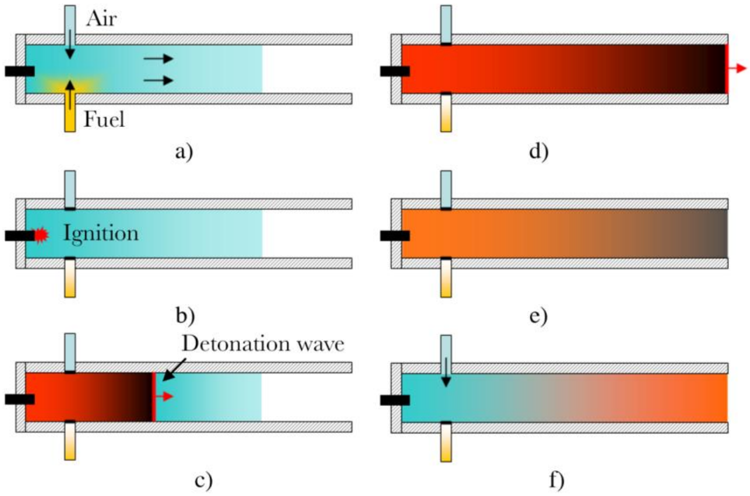

Figure 3. Work cycle of PDE
a) Fuel mixture filling, b) ignition – detonation's initiation, c) detonation, d) detonation products, e) deto-nation products' expansion into the environment, fair purge.

After the initiation the detonation wave of constant intensity propagates through fuel-air mixture. Its velocity relatively combustion products is precisely equal to speed of sound, so chemical transformations and compression wave, that occur during combustion, cannot reach the detonation wave and affect its intensity. Such detonation is call the established Chapmen-Jouguet detonation (CJ), and is differentiate by lowest possibly velocity of detonation wave propagation.

Fast compression and combustion in PDE cycle produces additional work compared to Humphrey cycle (Fig. 2). The FJ cycle differs from Humphrey cycle in that heat supply occurs not through and isochor (cycle's section 1-2), but through Rankine-Hougoniot adiabat (section 1-b). The next is non-uniform heating, or so-called Rayleigh specific heat, which corresponds to section (b-2).

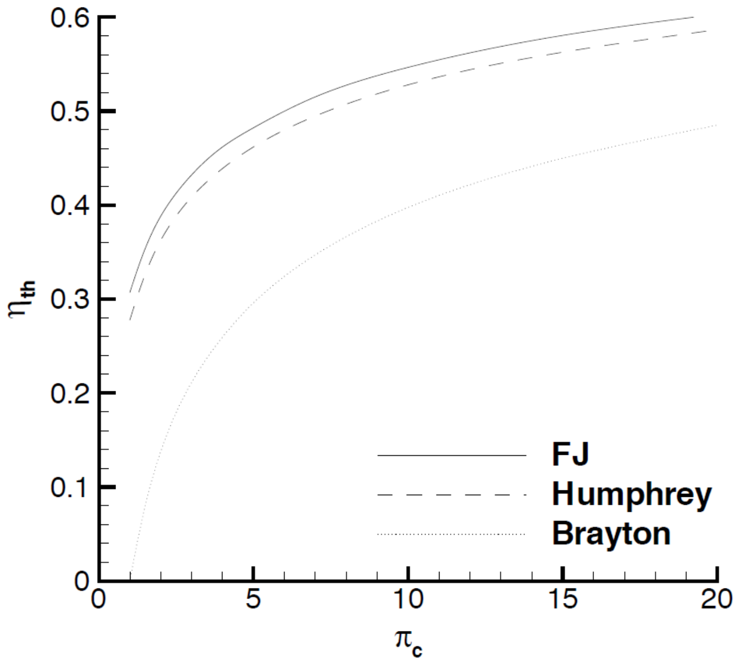

Figure 4. Thermodynamic energy conversion coefficient at various compression rates in compressor

The FJ cycle is superior to Humphrey cycle in terms of thermodynamic efficiency, and exceeds Brayton cycle (Fig. 4) in all diapason of pressure increase rates during compression. Thus, to reach the same energy conservation coefficient as FJ cycle, the traditional jet engine mast have compression rate in the compressor 5 times higher.

Because compression in shock wave intensity is proportional to a square of Mach number (wave propagation velocity), the energy convection coefficient of FJ cycle increases significantly with increase of Mach number (Fig. 5). In the Mach number range from 2 to 4, the specific impulse of PDE is around 8500 s for hydrogen and 3800 s for hydrocarbon fuel (Wolanski et al., 2005).

Energy conversion coefficient of real detonation engine differs from an ideal FJ cycle. It can be increased even more if over compressed detonation is utilized. The explanation is presented in Fig. 6. In Humphrey cycle, the compression occurs at constant volume (cycle's section 1-2H), in FJ cycle along Rayleigh curve (1-2 CJ) to point that correspond to the established Chapmen-Jouguet detonation (Pukhnachov, 1963). In real detonation engine, however, the mixture is compressed in a shock wave at first (1-1'), and then it is expanded in a process of Rayleigh specific heat (1'-CJ).

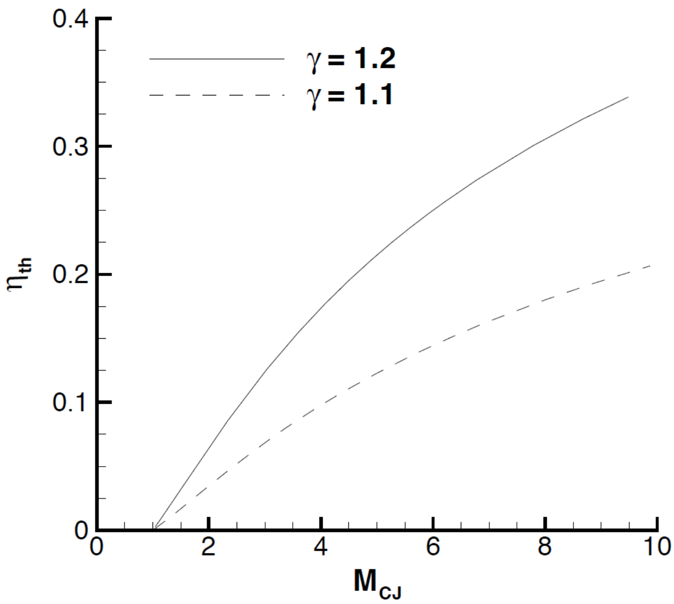

Figure 5. A thermodynamic energy convection coefficient at various Mach numbers of Chapmen-Jouguet detonation wave's propagation

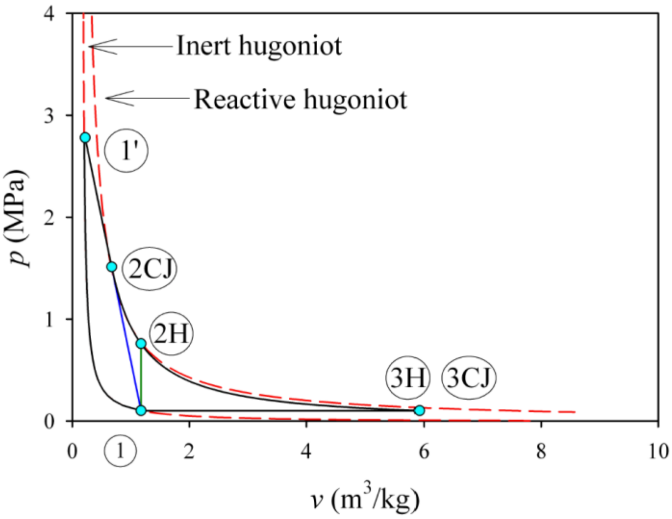

Figure 6. Diagram pressure(p) - specific volume (v) for Humphrey (H), Fickett - Jacobs (CJ) cycles and real detonation engine

However, nothing stops from moving from initial point 1, to any point on Hugoniot shock adiabat, that corresponds to a set intensity of shock wave in the initial fuel mixture, and then descent to point 3 along Hugoniot adiabat for combustion products. An over compressed detonation wave in this case is not established, such mode gain additional useful work, which increases energy conversion coefficient.

During the research arises a problem of developing a design that allows to realize the potential benefits of the thermodynamic cycle detonation engine.

Discussion and Conclusion

The construction of detonation engines differs based on design and operation method. Differentiate Pulse Detonation Engines (PDE) amd Pulse Detonation Rocket Engines (PDRE). Alternative to them are Continuous Detonation Engines (CDE) and Rotation Detonation Engines (RDE) that work in continuous mode, and don't need valves and periodic detonation initiation.

With great design variation few major directions in the development of detonation engines can be differentiated.

Direction №1 - The classic pulse detonation engine (PDE).

Direction №2 – Multi-piped PDE. In such engine the work frequency of a single pipe is low, but by switching impulse in difference pipes the achievement of satisfactory specific characteristic is attempted.

Direction №3 – PDE with high-frequency resonator. The pre-activated fuel mixture is supplied to resonator in which compression waves are focused with creation of over compressed detonation wave.

Direction №4 – Detonation liquid rocked engine with expulsion fuel supply.

Direction №5 – Organization of detonative combustion in stationary wave system (CDE) or in periodically moving shock wave (CPDE).

Direction №6 – Nickols rotational detonation engine.

Direction №7 – Voitsekhovsky rotational detonation engine.

Implications and Recommendations

The analysis of thermodynamic detonative combustion cycles has showed that it is not easy to realize its potential advantage. The main difficulty consists in the need to provide repetition of detonative motion work cycles. This is conjugated with problems of periodically filling the combustion chamber with fresh fuel mixture, its initiation, and removal of combustion products. The established Chapmen-Jouguet detonation provides the lowest detonation waves propagation velocity and fuel mixture compression rate, which lead to decrease of integral effectiveness of detonation engines that utilize this mode. The solution appears to be in use of over compressed detonation, which can be acquired, for instance, in resonator that focus shock waves.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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References

Adamson, T. C. & Olsson, G. R. (1967). Performance analysis of a rotating detonation wave rocket engine. *Astronautica Acta, 13(4),* 405–15.

Bam-Zelikovich, G. M. (1949). Arbitrary discontinuity breakdown in the combustible mixture. *Theoretical Hydromechanics*, *4*, 112–41.

Bam-Zelikovich, G. M. (1952). On the oscillations during combustion of gas in pipes. *Theoretical Hydromechanics*, *2(9),* 184–208.

Bulat, P. V. (2014). About the detonation engine. American Journal of Applied Sciences, *11(8),* 1357–64.

Bulat, P. V., Ilina, E. E. (2013). The problem of creating detonation engine-current trends in aerospace engine manufacturing. Fundamental Research, *10(10),* 2140–2142.

Bulat, P. V. & Prodan, N. V. (2013a). Overview of projects detonation engines. Pulse ramjet engine. *Fundamental Research*, *10(8),* 1667–71.

Bulat, P. V. & Prodan, N. V. (2013b). Trends in the development of projects detonation engines. Rotating detonation engines. *Fundamental Research*, *10(8),* 1672–75.

Bulat, P. V. & Zasukhin, O. N., Prodan, N. V. (2012). Application features of turbulence models in the calculation of flows in supersonic tracts of advanced jet engines. *Engine*, *1(79),* 20–23.

Bussing, T., Hinkey J. & Kaye L. (1994). Pulse detonation engine preliminary design considerations. *Proceedings of 30th Joint Propulsion Conference and Exhibit,* 94–3220.

Bykovsky, F. A. & Zhdan, S. A. (2013). *Continuous spin detonation*. Novosibirsk, Branch of the Russian Academy of Sciences, 413 p.

Cherny, G. G. (1967). The asymptotic law of propagation of a plane detonation wave. *USSR Academy of Science reports*, 172(3), 558–60.

Dabora, E. & Broda, J. C. (1993). Standing normal detonations and oblique detonations for propulsion. *Proceedings of 29th Joint Propulsion Conference and Exhibit*, 93–2325.

Eidelman, S. & Grossman, W. (1992). Pulsed detonation engine: experimental and theoretical review. *Proceedings of 28th Joint Propulsion Conference and Exhibit*, 92–3168.

Frolov, S. M. (2006). *Pulse Detonation Engines: Introduction*. Moscow, Torus press, 326 p.

Hinkey, J., Bussing, T. & Kaye, L. (1995). Shock tube experiments for the development of a hydrogen-fueled pulse detonation engine. *Proceedings of 31st Joint Propulsion Conference and Exhibit*, 95–2578.

Hishida, M., Fujiwara, T. & Wolanski, P. (2009). Fundamentals of rotating detonations. *Shock Waves*, *19(1),* 1–10.

Jianping, W., Yetao, S. & Meng, L. (2010). Continuous detonation engine and effects of different types of nozzle on its propulsion performance. *Chinese Journal of Aeronautics*, *23*, 647–52.

Korobeinikov, V. P., Levin, V. A., Markov, V. V. & Chernyi, G. G. (1972). Propagation of blast waves in a combustible gas. *Acta Astronautica*, *17(5),* 529–37.

Levin, V. A. & Cherny, G. G. (1967). Asymptotic laws of detonation waves behavior. *Journal of Applied Mathematics and Mechanics*, *31(3),* 383–405.

Lu, J., Zheng, L., Wang, Z., Peng, C. & Chen, X. (2014). Thrust measurement method verification and analytical studies on a liquid-fueled pulse detonation engine. *Chinese Journal of Aeronautics*, *27(3),* 497–504.

Markov, V. V. (1981). Numerical simulation of the formation of multi-front structure of the detonation wave. *USSR Academy of Science reports*, *258(2),* 158–63.

Mitrofanov, V. V. (1982). *The Theory of Detonation*. Novosibirsk State University press. 91 p.

Nicholls, J. A. & Dabora, E. K. (1961). Recent results on standing detonation waves. *Proceedings of the Combustion Institute, 8*, 644–55.

Phylippov, Yu. G., Dushin, V. R. & Nikitin, V. F. (2012). Fluid mechanics of pulse detonation thrusters. *Acta Astronautica*, *76*, 115–26.

Pukhnachov, V. V. (1963). On the Chapman-Jouget detonation stability. *USSR Academy of Science reports, 149(4),* 798–801.

Remeev, N. H., Vlasenko, V. V., Rakhimov, R. A. & Ivanov, V. V. (2003). Numerical simulation and experimental study of the working process in the detonation combustion chamber. *Russian Journal of Physical Chemistry B, 22(8),* 45–56.

Roy, G. D., Frolov, S. M., Borisov, A. A. & Netzer, D. W. (2004). Pulse detonation propulsion: challenges, current status, and future perspective. *Progress in Energy and Combustion Science*, *30(6),* 545–672.

Sehra, A. K. & Whitlow, W. Jr. (2004). Propulsion and power for 21st century aviation. *Progress in Aerospace Sciences*, *40(5),* 199–235.

Tangirala, V. & Dean, A. (2007). Performance on a pulse detonation engine under subsonic and supersonic flight conditions. *Proceedings of 45th AIAA Aerospace Sciences Meeting and Exhibit,* 2007–1245.

Tarasov, A. I. & Shchipakov, V. A. (2011). Using pulse detonation technology to increase traction the efficacy engines. *Aerospace technic and technology*, *9*, 46–50.

Ting, J. M., Bussing, T. R. & Hinkey, J. B. (1995). Experimental characterization of the detonation properties of hydrocarbon fuels for the development of a Pulse Detonation Engine. *Proceedings of 31st Joint Propulsion Conference and Exhibit (AIAA, San Diego),* 95–3154.

Vasilev, A. A. (2013). The Principal Aspects of Application of Detonation in *Propulsion Systems. Journal of Combustion*, *1*, 1-15.

Westbrook, C. K., Mizobuchi, Y., Poinsot, T. J. & Smith, P. J. (2005). Computational combustion. *Proceedings of the Combustion Institute*, *30(1),* 125–57.

Wintenberger, E., Shepherd, J. E. (2006). Thermodynamic cycle analysis for propagating detonations. *Journal of Propulsion and Power*, *22(3),* 694–98.

Wolanski, P. (2013). Detonative propulsion. *Proceedings of the Combustion Institute*, *34(1),* 125–58.

Wolanski, P., Kindracki J., Fujiwara T., Oka Y. & Shimauchi K. (2005). An Experimental Study of Rotating Detonation Engine. *Proceedings of 20th International Colloquium on the Dynamics of Explosions and Reactive Systems. Montreal,* 40-44.

Zeldovich, Ya. B. (1940). On the energy use of detonation combustion. *Technical Physics, 1(17),* 1453–61.