INTRODUCTION

During the last decade, there has been a growing interest in the development of a new type of engine for propulsion, namely, pulse detonation engine (PDE). Such an engine applies another phenomenon for the conversion of the chemical energy of the fuel to thrust — fuel is burned in repeatedly initiated propagating detonation waves rather than in the conventional deflagrative mode utilized in gas turbines, ramjets, and rocket engines. This offers several advantages.

(1) The thermodynamic efficiency of the detonation cycle considerably exceeds the efficiency of other known cycles.

(2) Pulse detonation engine can potentially operate on both special fuels and conventional fuels used in aerospace applications.

(3) In contrast to many existing concepts of jet engines, a PDE has a simple design and does not require sophisticated and expensive compressors and turbopump machinery. Moreover, a PDE is potentially robust as it requires fewer moving parts — none for the thrust chamber — and requires no boosters for acceleration to cruise flight conditions.

(4) Multicycle, multitube operation has added potential for thrust vectoring without external fins.

(5) The use of several identical PDE units for increasing the thrust output allows for easy scale-up and hence reduces the development cost.

Though several decades of research led to the understanding of the physics and mechanisms involved in repeated detonations, converting the knowledge into developing a propulsion engine did not occur due to the difficulties encountered in the initiation, maintenance, and control of detonation confined chambers, with fuels of choice, and with the available design methodologies. During 1998 to 2004, the U.S. Office of Naval Research (ONR) and the Russian Foundation for Basic Research (RFBR) have jointly sponsored four international colloquia on detonations in order to bridge the gap between science and technology development. In particular, those aspects of detonations that are directly relevant to the development of practical PDEs were addressed. In 1998, the International Colloquium on Advances in Experimentation and Computation of Detonations was held in St. Petersburg with the participation of more than 60 experts. In 2000, the International Colloquium on Control of Detonation Processes was organized in Moscow with more than 100 participants. In 2002, the International Colloquium on Advances in Confined Detonations was held in Moscow with more than 120 participants. Most recently, the International Colloquium on Application of Detonation for Propulsion was organized in St. Petersburg in 2004 and was attended by more than 120 participants from 12 countries.

As a result of these meetings, a number of books have been published containing condensed papers of all presentations [1–4] and full manuscripts of selected papers presented at the colloquia [5–7]. Selected papers presented at the recent International Colloquium on Application of Detonation for Propulsion are presented in this volume. The book is organized in three parts: (1) Fundamentals; (2) Continuous Detonation Propulsion; and (3) Pulse Detonation Propulsion. The articles included in each section are briefly outlined below.

Part 1: Fundamentals

Vasil'ev discussed some significant problems in gaseous detonation, namely, the detonation of free (without confining walls) charges, detonation diffraction, spontaneous onset of a detonation in an expanding rarefaction wave, direct detonation initiation and various approaches to minimize the initiation energy including multifocusing systems and jets of hot and active material, enhancement of deflagration-to-detonation transition (DDT), detonation wave propagation in subsonic and supersonic flows, propagation and the effect of various additives on gaseous detonation, etc. Application of detonation for propulsion and in material sciences for synthesizing nanoparticles is also discussed.

Penyazkov et al. presented experimental and numerical investigations of autoignition delay times and modes of propane–air mixtures behind reflected shock waves. Experiments were performed over the temperature range of 1000–1750 K, pressure range of 2–20 atm, and equivalence ratios of 0.5, 1.0, and 2.0. Two empirical correlations for ignition delay times have been deduced from the experimental data. Autoignition modes of the mixture (strong, transient, and weak) were identified by comparing velocities of reflected shock waves at different locations from the reflecting wall. Parametric autoignition domains and reactive flow dynamics for some selected postshock conditions were investigated via computer simulation. The data obtained can be directly used for propulsion applications, validations of reaction mechanisms, and for analyses of detonability limits and explosion hazard of propane–air mixtures.

In another paper by *Penyazkov et al.*, experimental investigations of autoignition phenomena at shock wave reflection from the end-walls of different geometry were reported. Experiments were performed with the propane–air mixture in a shock tube equipped with an optical window for ignition delay time measurements. Two-dimensional (2D) and axisymmetric end-walls of different shapes were used as focusing elements. Autoignition domains in stoichiometric propane–air mixture at postshock pressures of 3.2 ± 0.5 atm were determined at shock wave focusing with wedge and cone reflectors with apex angles of 90°, as well as with parabolic and paraboloidal reflectors. The critical Mach numbers required for direct detonation initiation were 2.76 and 2.69 in the cone and parabaloidal reflectors, respectively. For the cone reflector, the transient ignition resulting in DDT occurred at shock wave Mach number $M > 2.32$. The cone reflector with the apex angle of 90° was found to be most efficient for DDT or direct detonation initiation.

Tsuboi et al. presented the results of their comparative numerical studies of 2D and three-dimensional (3D) detonations in rectangular tubes of various cross sections. A comparison of maximum pressure histories between 2D and 3D simulations showed that the influence of the cross-section area was small, and the detonation cell lengths in 3D simulations were approximately equal to those in 2D simulations. Though the vertical and horizontal triple lines were shown to propagate nearly independently in transverse directions, the shock structure of their intersection point was found to be diagonal.

Pintgen & Shepherd reported their quantitative analyses of the complexity of the reaction front geometry by analyzing the particle laser-induced fluorescence images obtained. The front geometry was defined by examining two characteristics: the rectified length and the effective dimension. The geometric and stability characteristics of the mixtures were correlated using, as a figure of merit, the reduced effective activation energy as computed from detailed chemical reaction mechanisms. The mixtures studied varied in the degree of cellular regularity from "regular" to "highly irregular," corresponding to effective reduced activation energies between 5.2 and 12.4.

Ishii & Kojima focused their experimental study on detonation propagation in mixtures with the composition changing continuously in the direction normal to the propagation direction. The detonation chamber used a rectangular channel with a 40×20 mm cross-section and total length of 500 mm. The detonation chamber was filled with stoichiometric hydrogen–oxygen mixture. Concentration measurements were made by infrared absorption method using ethane as an alternate of oxygen. Smoked foil records showed that variation of cell size and the behavior of triple point trajectories correlate with concentration gradients.

Levin et al. reported the results of their extensive numerical investigations of detonation initiation and propagation in axisymmetric and plane 2D channels of complex shape, filled with stoichiometric hydrogen–air mixture at normal conditions. Their mathematical model was based on 2D Euler equations with a detailed chemistry of hydrogen oxidation. It was shown that detonation initiation can be facilitated by using the effect of imploding blast waves. For detonation diffraction, the minimal radius of the tube required for detonation transition into the unconfined space was found to decrease with increasing the tube length. The maximal cone angle for detonation transition from a tube into the unconfined space was also determined.

Khmel & Fedorov presented their 2D computational studies of confined heterogeneous detonations in aluminum particle – oxygen suspensions. The results of numerical simulations of cellular detonations in the mixture with particles of a fixed size were found to depend on the channel width. Depending on the channel width, the structures were either regular or irregular. Regular uniform structures formed in sufficiently wide channels when the channel width was divisible to a half of the transverse cell size of a detonation. Irregular structures exhibiting cell subdivisions or junctions formed if the channel width was close to the point of bifurcation. Analysis of the computational results indicated that the cell size was not determined unambiguously by other length scales of the problem.

Part 2: Continuous Detonation Propulsion

Trotsyuk et al. investigated numerically the feasibility of "stationary" detonation at the Mach reflection of an oblique shock wave generated by a double-wedge model in a supersonic stream of hydrogen–oxygen mixture. Numerical investigations of regular and Mach reflections have been performed by a high-order MUSCL TVD scheme. In the case of Mach reflection, the Mach stem was shown to be a section of an overdriven detonation front. It has been shown that at certain flow parameters, there may exist a standing Mach stem with a smooth front or with a system of unsteady transverse waves on its front. For a lean hydrogen–air mixture, an interesting regime of Mach reflection with a strongly oscillating Mach stem was obtained for the first time.

Bezgin et al. reported their results of 2D computational studies of oblique detonation wave formation in a supersonic flow of premixed hydrogen–air mixture over a compression wedge. Their particular interest was to explore the possibility to promote detonation formation by electronic excitation of molecular oxygen in an electric discharge. It was shown computationally that with such an excitation, the detonation could arise at relatively short distances on the order of 1 to 2 m from the wedge apex. This effect was attained at relatively small values of the specific energy delivered to molecular oxygen in the electric discharge and at low initial temperature and pressure of 600 K and 5 kPa, respectively. In the absence of oxygen molecule activation, this distance was as long as 8.3 m. The reduction in the induction and transition zone lengths under activation of molecular oxygen was caused primarily by the production of electronically excited oxygen molecules in an electric discharge that enhanced the chain mechanism of combustion. For detonation initiation, it was sufficient to activate molecular oxygen in a narrow near-axis region, i.e., in a thin layer adjacent to the wedge apex.

Alexandrov et al. studied an alternative design of the PDE referred to as the supersonic pulsed detonation ramjet engine (SPDRE). The main characteristic features which distinguished this engine from other PDE designs were: (*i*) the flows of air and reactive mixture were supersonic all throughout the engine duct; (*ii*) detonation wave propagated always upstream in both fuel-rich and fuel-lean mixtures, controlled by a fuel supply system; (*iii*) the pulse process was established due to propagation of the detonation wave along the engine duct toward the inlet when the chamber was filled with a fuel-rich mixture and by drift of the wave toward the nozzle when the mixture was fuel-lean; and (*iv*) the continuity of the detonation process made it unnecessary to periodically activate an external detonation initiation source during engine operation (it was only needed to start the engine). The authors presented the experimental results substantiating the potential to realize such a combustion mode in a supersonic flow.

Zvegintsev et al. focused their research on the SPDRE concept as well. They presented the experimental results on detonation propagation in a tube upstream to supersonic Mach 4 flow of hydrogen–air mixture with various air excess coefficients. Their systematic study involved measurements of pressure, flow velocity, and concentration profiles in the supersonic flow. The measured values of the detonation velocity were found to exceed the calculated Chapman–Jouguet values within a wide range of excess air coefficients.

Zhdan & Bykovskii reported the results of their experimental studies of continuous spin detonation in a scramjet-type combustor with a varied flow rate of the oxidizer through an annular slot. The experiments were performed in chambers of two types: with expanding and constant cross-sections of the annular duct. The reactive mixture components, acetylene and oxygen, were supplied separately. Under certain conditions, stable regimes of mixture combustion in spinning transverse detonation waves were obtained.

Part 3: Pulse Detonation Propulsion

Endo et al. provided the overview of their analytical models for predicting the propulsive performance of fully- and partially-fueled simplified PDEs and optimizing the PDE systems. The results obtained by using these models were compared with available experimental data. It was shown that system optimization could achieve specific impulses approximately 20% higher than that for a single-straight-tube PDE.

Ma & Yang focused on modeling and simulation of the internal flow field in a valveless air-breathing PDE, which is currently under experimental development at the U.S. Naval Postgraduate School. The PDE utilized a predetonator to initiate detonation in the main combustor and required no valves in the air-flow path. The isolation between the inlet and combustor was achieved through gas dynamics in a special isolator. The analysis accommodated the full conservation equations in axisymmetric coordinates, along with a calibrated one-progress-variable chemical reaction scheme for both stoichiometric ethylene–air and ethylene–oxygen mixtures. The governing equations and their associated boundary conditions were numerically solved by means of a space–time conservation element/solution element method. The transmission of detonation from the initiator to the main chamber, combustion and flow dynamics in both single and multicycle operations, as well as propulsive performance of the PDE were calculated and analyzed.

Remeev et al. directed computational study to the PDE operating process and the analysis of the thrust-efficiency performance of a single-chamber supersonic (Mach 3) ramjet PDE. The engine consisted of a supersonic air inlet, perforated entrance compartment, combustion chamber equipped with igniter, and exhaust nozzle. The results of numerical simulations showed the possibility to implement a PDE scheme considered with stationary gas flow in the air inlet. First estimations of the thrust-efficiency characteristics did not reveal essential advantages of the PDE compared to the conventional ramjets. The authors, however, claim that further performance optimization of the PDE of a chosen design should indicate improvements.

Kailasanath reviewed the experimental and computational studies on nozzles for PDEs. They claimed that direct comparisons of the results from various studies were not possible due to the differences in the system parameters (nozzle shape, length, expansion ratios, and ambient pressures) as well as the detonable mixtures considered. However, several common trends in the observations were noted. In addition, numerical simulations were used by the authors to reconcile the apparently contradictory observations made in previous studies and to highlight the various issues.

Hayashi et al. studied the mechanism of flame jet ignition in the PDE by visualizing the phenomena with a Schlieren system. The experiments were performed in a PDE 40×40 mm in cross-section and 1 m long with separate delivery of fuel (hydrogen) and air. To promote DDT, a Shchelkin spiral 500 mm long, 3.5 mm in diameter, and 15-millimeter pitch was attached to the tube end. Both single- and multipulse at 16-hertz operation was tested. Schlieren movies were taken to visualize injection, ignition, and flame propagation processes. It has been demonstrated that the DDT time could be shortened using flame jet ignition instead of a conventional automobile spark ignition.

Conrad et al. studied the performance of an air-breathing PDE with a predetonator. The PDE was composed of three sections. Either a 2.020- or a 1.718-meter-long rectangular tube, 133 mm in width and 58 mm in height, was used as the predetonator, and a 1.082-meter-long rectangular tube, 133 mm in width and 183 mm in height, was used as the thrust tube. A transition section with a 15-degree divergence angle joined the two tubes. A series of plate obstacles was used in the predetonator to accelerate the flame and to produce a detonation wave at the entrance of the transition section. Ethane–oxygen–nitrogen mixtures, with a fixed equivalence ratio of 1.0 and a nitrogen-to-oxygen molar ratio of 3.76, were injected at the head end of the predetonator through an impinging jet injector which assured *in situ* rapid and uniform mixing of the reactants. The proposed design strategy implied that the region containing the predetonator obstacles should be long enough to accelerate the deflagration wave up to the Chapman–Jouguet detonation velocity and should terminate at this point. In addition, the distance between the last obstacle and the entrance to the transition section should be chosen such that an overdriven detonation wave entered the transition section. The results obtained supported the proposed design strategy, although some intermittency in successful detonation transition was noticed when a short predetonator was employed. The results also showed that generating an overdriven detonation wave in the predetonator was a key parameter for obtaining detonation transition to the thrust tube.

Yatsufusa et al. described their experimental results obtained from the liquid-fueled air-breathing PDE facility at Hiroshima University. The PDE was equipped with a predetonator operating on liquid fuel (white gasoline) and oxygen gas and with a rotary mechanical valve. The main detonation chamber was a tube 100 mm in diameter and 2.25 m long. Automobile fuel injectors providing mean drop size of 18 μm at injection pressure of 10 MPa were used to inject fuel in the main tube and in the initiator. The thrust produced by the PDE was measured by the ballistic pendulum method. It has been shown that the maximum impulse produced by the PDE was attained when the overall equivalence ratio in the main chamber was 2, which is an indication of incomplete combustion. Partial fill was shown to result in a larger specific impulse. The initiator fuel–oxygen mixture overfill was shown to play an important role in the PDE performance.

Frolov et al. designed and tested a liquid-fueled air-breathing PDE demonstrator. Unlike the existing designs of PDE demonstrators, in which a detonation wave in the predetonator was initiated using a fuel–oxygen mixture, their demonstrator exhibited stable operation with periodic detonation of liquid fuel without using additional oxygen. Replacement of the straight explosion tube 51 mm in diameter by a curved predetonator tube 28 mm in diameter with Shchelkin spiral, tube coil, and expansion cone from the 28- to 51-millimeter tube decreased the initiation energy of detonation of two-phase n-hexane– and n-heptane–air mixtures by two orders of magnitude: from 3300 to 24 J. The predetonation distance in the narrower tube was close to 1 m, i.e., about 36 tube diameters. One of the most intriguing findings was the existence of the 'detonation peninsular' in the section of the predetonator comprising the Shchelkin spiral followed by the tube coil. The curvilinear reflecting surfaces in the coil might lead to gas-dynamic focusing of compression waves generated by the accelerating flame, their interaction with a lead shock wave, and to detonation. The PDE demonstrator was tested in a pulse detonation mode with the operation frequency up to 8 Hz.

Taki & Fujiwara discussed the results of their numerical analysis of resonant detonation phenomena occurring in a 7-centimeter-diameter hemispherical cavity and suggested the physical mechanism governing high-frequency detonation formation in a resonator PDE. In such a PDE, two-stage combustion was utilized to generate continuous resonant detonations with high frequency of 25 kHz. As a result of the calculations, it was possible to optimize various parameters of the PDE (geometries, combustible mixtures, ambient conditions, etc.).

Kasahara et al. described the results of ground tests with an ethylene–oxygen single-tube pulse detonation rocket (PDR) engine. The tube length and inner diameter were 2 m and 100 mm, respectively. The total weight of the engine flight model was 17 kg and its maximum thrust was about 200 N. The PDR flight-model engine operated for 5 s at a 20-herz frequency. Liquid ethylene (312 K, 250 g), oxygen gas (10 MPa, 240 g), and helium gas (15 MPa, 8 g) were used as the fuel, oxidizer, and purge gas, respectively. The supply systems were composed of fuel-oxidizer-purge gas tanks, high-power parallel solenoid valves, and check valves.

We have outlined the contents of the articles included in the book to enable the reader easy selection of the subject of choice. It can be clearly noticed that there has been a considerable progress in detonation research during recent years.

Those who are interested in recent accomplishments in basic and applied research on PDE and numerous PDE design concepts can find the information in the previously cited references [1–7] and in references [8] and [9].

REFERENCES

1. Roy, G., S. Frolov, K. Kailasanath, and N. Smirnov, eds. 1998. *Advances in experimentation and computation of detonations*. Moscow: ENAS Publ.
2. Roy, G., S. Frolov, D. Netzer, and A. Borisov, eds. 2000. *Control of detonation processes*. Moscow: ELEX-KM Publ.
3. Roy, G., S. Frolov, R. Santoro, and S. Tsyganov, eds. 2002. *Advances in confined detonations*. Moscow: TORUS PRESS.
4. Roy, G., S. Frolov, and J. Shepherd, eds. 2004. *Application of detonation to propulsion*. Moscow: TORUS PRESS.
5. Roy, G., S. Frolov, K. Kailasanath, and N. Smirnov, eds. 1999. *Gaseous and heterogeneous detonations: Science to applications*. Moscow: ENAS Publ.
6. Roy, G., S. Frolov, D. Netzer, and A. Borisov, eds. 2001. *High-speed deflagration and detonation: Fundamentals and control*. Moscow: ELEX-KM Publ.
7. Roy, G., S. Frolov, R. Santoro, and S. Tsyganov, eds. 2003. *Confined detonations and pulse detonation engines*. Moscow: TORUS PRESS.
8. Roy, G., S. Frolov, A. Borisov, and D. Netzer. 2004. Pulse detonation propulsion: Challenges, current status, and future perspective. *Progress Energy Combustion Science* 30:545–672.
9. Roy, G., ed. 2006. Pulse detonation engines, combustion processes in propulsion. *Control, noise, and pulse detonation.* Oxford, UK:Elsevier. 271–412.

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