Introduction

During the period from 1998 to 2014, the U.S. Office of Naval Research (ONR) and the Russian Foundation for Basic Research (RFBR) have jointly sponsored nine International Colloquia on Pulsed and Continuous Detonations (ICPCD), in particular, those aspects of detonations that are directly relevant to the development of pulsed detonation engines (PDEs) and continuous detonation engines (CDEs). As a result of these meetings, a number of books have been already published which contain extended abstracts of all presentations [1–6] or full manuscripts of selected papers presented at the colloquia [7–10]. This volume is a continuation of this series of books. It contains selected condensed articles presented at the Colloquia of 2010, 2012, and 2014.

Cyclic operation of the PDE comprises several steps: filling the chamber with fuel mixture, ignition, flame acceleration and deflagration-to-detonation transition (DDT), burning of the fuel mixture in a traveling detonation wave, and exhaust of combustion products into the atmosphere through a nozzle. The advantages of PDEs include simplicity of design, ease of cooling, scaling, and thrust control, low level of pollutant emissions, and the ability to work at subsonic and supersonic flight without boosters. The disadvantages of such engines are the need for multiple ignitions, off-design mode of nozzle operation, low cycle frequency (up to 100–200 Hz), wave interference in multitube systems, and high level of noise and vibration. Continuous detonation engine is an annular channel formed by walls of two coaxial cylinders equipped with an injector head at one end and with a nozzle at another end. Detonation combustion in such an engine is arranged by burning the fuel mixture in a detonation wave continuously circulating over the injector head. The advantages of CDEs include simplicity of design, single ignition, quasi-steady outflow of detonation products, high-frequency cycles (kilohertz), short combustion chamber, and low pollutant emissions, noise, and vibration. The disadvantages of such engines include the need for a compressor or a turbopump, limited control, difficulty of scaling, and complexity of cooling. The worldwide research on PDEs and CDEs is now aimed at maximizing all the advantages and minimizing the impact of the disadvantages in order to compete the existing propulsion systems.

The book is organized in such a way that the reader first gets acquainted with the current understanding of ignition and combustion physics and chemistry (Ch. 1). Then, in Chs. 2 and 3, the most recent accomplishments in detonation initiation and propagating detonations are discussed. As the main focus of this book is the utilization of detonation for propulsion and other applications, Chs. 4 and 5 present the results of computational and experimental studies of pulsed and continuous detonations. Chapter 6 deals with heterogeneous and condensed-phase detonations. Finally, Ch. 7 contains contributions on the equations of state.

The articles included in each chapter are briefly outlined below.

Chapter 1 Ignition and Combustion

Frolov et al. study theoretically the effect of hydrogen admixing on spontaneous ignition of homogeneous and hybrid mixtures of heavy hydrocarbons (n-heptane and n-decane) in air based on the well-validated detailed reaction mechanism of n-hexadecane oxidation. It has been shown that the reactivity of hydrogen-containing mixtures is not always higher than that of the pure hydrocarbon–air mixture. Hydrogen addition to hydrocarbon–air mixture is shown to increase the overall self-ignition delay time at $T_0 < 1050$ K and to decrease it at $T_0 > 1050$ K, thus indicating that at low temperatures, hydrogen plays the role of self-ignition inhibitor, whereas at high temperatures, it plays the role of self-ignition promoter. These findings have to be taken into account when discussing the perspectives of practical applications of fuels blended with hydrogen.

Basevich et al. developed and thoroughly tested a relatively short detailed kinetic mechanism (DKM) of gas-phase oxidation and combustion of individual hydrocarbons of alkane homological series from methane to n-hexadecane. This mechanism is shown to provide satisfactory predictions of self-ignition delays, laminar flame velocities, and counterflow flame structure in homogeneous fuel–air mixtures as well as self-ignition delays and combustion constants of liquid fuel drops in air for heavy alkane hydrocarbons without any need of tuning the reaction rate parameters. Despite the mechanism is rather compact, it is capable of predicting satisfactorily the multistage self-ignition and negative temperature coefficient (NTC) of reaction rate constant at low temper-

atures and, therefore, can be readily applied for numerical simulations of DDT, the phenomenon which encounters both high-temperature fuel oxidation in a highly wrinkled flame front and low-temperature volumetric fuel oxidation in the preflame zones.

Leonov et al. present the experimental data of mixing intensification by a transverse short-pulse repetitive electrical discharge in a high-speed airflow of Mach number 2 and 2.5 with direct coflow/wall injection of He or CO_2 gas modeling injection of gaseous fuel. It is demonstrated that discharge-induced turbulent and directed motion in the afterspark channel can significantly enhance mixing rate, which can be used for mixing and combustion control in jet engines with short residence time of the working fluid in a combustor.

Leschevich et al. report the results of measurements of self-ignition of methane–air mixtures in a shock tube (ST) and in a rapid compression machine (RCM) at temperatures from 900 to 2100 K, densities from 2 to 4 kg/m^3, and equivalence ratios from 0.5 to 2. Experiments in RCM revealed a significant reduction of the effective activation energy of low-temperature methane–air mixture oxidation as compared to the corresponding value relevant to high-temperature oxidation obtained in ST. Arrhenius approximations for the overall self-ignition delays derived based on RCM and ST measurements reasonably correlate with each other in the overlapping temperature region. The generated database can be used for validation of chemical kinetic mechanisms in wide ranges of thermochemical conditions.

Borisov et al. study the possibility of syngas production in a regime of homogeneous self-ignition of associated petroleum gas (APG) — oxygen mixtures using a constant-volume static apparatus with fast admittance of premixed gases in a preheated reactor and fuel-rich (with equivalence ratio 3.3) propane–oxygen and $60\% \, CH_4 + 40\% \, C_3H_8$ – oxygen mixtures modeling APG after the first separation stage. Ignition delays are measured at temperatures ranging between 600 and 900 K and pressures of 1 and 2.3 atm. It has been shown that the lower boundary of the temperature range within which the model APG mixture self-ignites at atmospheric pressure is higher (740 K) than that for propane (595 K), whereas the ignition delays show no NTC region characteristic for propane. However, the effective activation energy for the APG self-ignition of 36.1 kcal/mol appeared to be closer to that for propane self-ignition rather than to that for methane oxidation

(about 50 kcal/mol), indicating that propane oxidation controls APG self-ignition.

Penyazkov et al. report the results of measurements of self-ignition of n-hexadecane–heptamethylnonane–air and n-decylbenzene–1-methylnaphtalene–air mixtures in an ST behind reflected shock waves at temperatures 880–2175 K, pressures 4.0–11.7 atm, and equivalence ratios 0.5–2. Empirical correlations for n-hexadecane and heptamethylnonane self-ignition delay times have been deduced from experimental data. Strong, transient, and weak modes of self-ignition and ignition limits were identified by comparing the propagation velocities of reflected shock wave and reaction front at different distances from the ST end-wall. The generated database can be used for validation of chemical kinetic mechanisms in wide ranges of thermochemical conditions.

Assad and Penyazkov present extensive experimental work on the effect of hydrogen and syngas admixing to gasoline in HONDA D15B2 internal combustion engine. The engine was operating in idling and average load conditions at the crankshaft speed from 740 to 3800 rpm. Hydrogen additions were varied from 0% to 20% of the volume of air fed to the engine. It has been shown that the tendency to detonation-like combustion in the engine depends substantially on the air excess coefficient and hydrogen concentration in the mixture. Detonation was observed at large hydrogen additions (more than 15% in air) in fuel-rich mixtures. Performance of the engine operating on gasoline–syngas–air mixture differed only slightly from that operating on gasoline–hydrogen–air mixture with the exception of nitric oxide emission that had lower values.

Drakon et al. investigate experimentally the influence of CCl_4 and CF_3H additives on self-ignition of methane–oxygen mixtures behind reflected shock waves and reflected shock wave propagation at temperatures ranging from 1100 to 2700 K and additive concentration ranging from 0.5% to 10%. Significant shock wave attenuation in the presence of chemically active additives was observed. It has been shown that at given conditions, investigated halogenoalkanes do not demonstrate inhibiting effects; moreover, self-ignition of methane–oxygen mixture was considerably promoted by both additives. Kinetic analysis indicated that the promoting effect is produced due to reactions of intermediate products of additive pyrolysis, CF_2 and Cl, with O_2 and CH_4, namely, $CF_2 + O_2 \rightarrow COF_2 + O$ and $Cl + CH_4 \rightarrow CH_3 + HCl$ which initiate chain reactions.

xvi

Starik et al. compare specific features of syngas oxidation in air using DKMs without and with elementary reactions of CO molecules vibrationally excited by laser radiation at wavelength of 4.677 μm, thus applying the laser radiation energy either to mixture heating or to CO excitation. It has been shown computationally that excitation of CO molecule vibrations by laser photons allows significant intensification of chain processes leading to shortening of self-ignition delay time and ignition length in a supersonic flow and to decreasing the ignition temperature as compared to laser-induced thermal ignition. In the latter case, a noticeably greater energy is required than that needed for exciting CO-molecule vibrations.

Bityurin and Filimonova study theoretically multistage self-ignition of propane–air mixture without and with the action of electrical discharge. It has been shown that electrical discharge is capable of reducing appreciably (by a factor of 10 and even more) a part of self-ignition delay corresponding to the longest stage of low-temperature multistage self-ignition, that is cool flame, due to generation of radicals in the course of dissociation of fuel and oxygen molecules by electron impact. Duration of second (blue flame) and third (hot explosion) stages is not affected by the discharge. The effect of discharge on faster appearance of cool flame is associated with faster appearance of C_3H_7OOH and CH_3OOH and, as a consequence, partial release of chemical energy at decomposition of hydroperoxides.

Manuylovich and Markov examine computationally ignition of methane–oxygen mixture in an axisymmetrical enclosure by a single toroidal discharge with the deposited energy below the critical value required for direct detonation initiation based on reactive Euler equations. It has been shown that fast combustion regimes with apparent propagation velocities exceeding the normal burning velocity in methane–oxygen mixture by several orders of magnitude can be obtained. This phenomenon is explained by development of Richtmyer–Meshkov instability under the action of reverberating shock waves generated due to axial symmetry of the enclosure and its boundaries in radial direction. Similar to interaction between shock waves and a contact surface separating gases with essentially different densities, shock wave–reaction front interaction results in strong deformation of the reaction front so that it acquires turbulent nature.

Movileanu et al. investigate experimentally explosions of gaseous ethylene–air mixtures in vertical elongated cylindrical vessels with aspect ratios from 1 to 20 at different initial pressures (from 20 to 150 kPa) and initial concentrations of ethylene (from 3.0 to 14.0 %(vol.)) and at normal initial temperature. Mixtures were ignited by an electric spark located either in the geometrical center of vessels or near vessel bottom. For fuel-lean mixtures, smooth pressure histories were observed during the whole process. For stoichiometric and fuel-rich mixtures, pressure oscillations appeared even at initial pressures below ambient and resulted in significant overpressures. In the course of experiments, several characteristic stages of flame propagation have been detected.

Mitropetros and Fomin study experimentally shock-induced ignition of oxygen-containing bubbles in liquid cyclohexane, methanol, 2-ethylhexanal, and cumene. The authors report an important observation that bubble ignition can occur not only when bubble initially contains an explosive gas mixture but also when it contains initially nonexplosive fuel-lean gas mixture. Such explosions were observed for bubbles in 2-ethylhexanal and cumene at normal pressure and temperature conditions. Experiments showed that during bubble compression, its enrichment with vapor of surrounding liquid through shock-induced cumulative jet penetration and fragmentation into microdroplets occurred. It has been shown theoretically that fuel evaporation into a bubble caused by mechanical mixing of surrounding liquid with gas in the bubble can increase significantly fuel vapor concentration in bubble interior and shift chemical composition to flammable range. This process when accompanied with shock-induced increase in gas pressure and temperature results in bubble ignition.

Leitsin et al. present a theoretical study of the conditions for ultrafast solid-phase chemical transformations at shock compression of multicomponent reactive powder compacts. There exist a threshold value of initial compact average porosity, overcoming of which leads to an abrupt increase in the relative volumes where the nonstationary mode of dynamic compaction at the shock front is possible. The relative volume of areas with ultrafast reactions was shown to be virtually independent of the amplitude of dynamic loading. The estimates of the upper and lower values of product mass fraction in the course of shock synthesis are obtained.

Leschevich et al. conducted experiments on self-ignition of iron particle layers in oxygen at pressures up to 28 MPa and temperatures ranging from 660 to 1100 K for three powders with particle sizes from 20 to 45, from 56 to 63, and from 80 to 125 μm using RCM. The self-ignition temperature was shown to strongly depend on oxygen pressure and particle size, especially, at temperatures lower than 900 K. The smallest particles showed strong ability to self-ignition at low temperatures (less than 700 K) and high oxygen pressures (exceeding 20 MPa). At pressures above 20 MPa, these particles exhibit Arrhenius temperature dependence of self-ignition delay time with the activation energy of 172.6 kJ/mol.

Korotkikh et al. present the method for calculating the nonstationary burning rate of homogeneous solid propellants based on Zel'dovich–Novozhilov phenomenological theory without using analytical formulae for the dependence of stationary burning rate on initial temperature. The method is demonstrated on the example of transient combustion of solid propellant in a semiconfined volume at sharp pressure drop.

Babuk and Nizyaev study evolution of agglomerating particles on the surface of burning aluminized solid propellant in terms of their physical and chemical transformations and their influence on the properties of condensed combustion products. Based on available experimental data on gas-phase combustion of metal, chemical interaction of condensed Al and Al_2O_3, change of particles structure, and merging of particles, they develop mathematical models of different individual phenomena and couple these models to obtain the model of particle agglomeration. Numerical implementation of the model to experimental test cases allowed important conclusions to be made. Formation of hollow agglomerates was shown to be a consequence of changes in the structure of agglomerating particle at last stages of agglomeration process; periodic changes in the size of agglomerating particles was shown to be a consequence of chemical interaction between condensed Al and Al_2O_3; combustion of metal in gas phase was shown to influence the properties of condensed combustion products at the surface of burning propellant.

Chapter 2 Initiation of Detonation

Rakitin and Starikovskiy study experimentally detonation initiation in stoichiometric propane–oxygen mixture at initial pressure 0.2–1 atm by

xix

high-voltage nanosecond gas discharge in a smooth tube with a four-cell discharge chamber to realize Zel'dovich gradient mechanism. Detonation was shown to form within the distance of 4 tube diameters at discharge energy input of 0.2–0.3 J. The estimated gradient of self-ignition delay time due to nonuniform radical production during streamer discharge and following rapid plasma thermalization was shown to be consistent with the value predicted based on Zel'dovich criterion.

Ivanov et al. present a two-dimensional (2D) numerical study of flame propagation in stoichiometric hydrogen–air and hydrogen–oxygen mixtures in semiopen and closed channels based on gasdynamic equations of viscous compressible flow with chemical reactions. It has been shown that the main characteristics of flame (flame speed, surface area, and structure) strongly depend on hydrodynamic instability, flow deceleration near sidewalls, nonlinear interactions of perturbations at the flame surface, and flame interaction with counterflows arising in the course of flame propagation.

Kagan and Sivashinsky apply a simple ignition-temperature kinetics for reactive gas to simulate numerically DDT in narrow smooth-walled channels based on gasdynamic equations of viscous compressible flow in 2D approximation. The results of calculations indicate that all intrinsic phenomena inherent in DDT are qualitatively reproduced by this simple kinetics. The authors substantiate this approach by the fact that in combustion of hydrogen–oxygen and ethylene–oxygen mixtures, the effective activation energy is temperature-dependent, i. e., it is high at low temperatures and low at high temperatures and, therefore, in modeling of DDT, the extreme assumption on ignition-temperature kinetics can be applied.

Voronin presents the results of numerical simulations of gas detonation initiation in stoichiometric hydrogen–oxygen mixture by a semi-cylindrical shock in a plane smooth-walled channel based on nonstationary 2D gasdynamic conservation equations for ideal compressible gas with a two-stage model of chemical kinetics. It has been shown that owing to ignition of gas in a Mach stem at channel walls at initiation energy close to a critical value, the pulse detonation mode with large-amplitude detonation velocity fluctuations is established and transformation of such a pulse mode of detonation propagation to a self-sustained mode with cellular structure occurs when the minimum velocity of initiating shock wave exceeds 1300 m/s.

xx

Gray et al. conduct a comparative study of the effect of mechanical orifice plate and fluidic pseudoorifice with an effective blockage ratio of 0.43 on the flow structure for the purpose of DDT in a straight tube using particle image velocimetry. The pseudoorifice is arranged by injecting fluid perpendicular to the flow and creating a jet-in-crossflow configuration using either an array of 13 round 1.4-millimeter jets or a uniform slot of 0.4-millimeter width. It has been shown that pseudoorifices can increase turbulence intensity in comparison with a conventional mechanical orifice up to 20% and change spatial distribution of turbulence by producing much higher turbulence in the center rather than at tube walls.

Borisov et al. determine the conditions under which fast deflagration modes with intense shock waves, similar to the detonation mode, can arise in stoichiometric methane–air (SMA) mixture as a result of mixture ignition with a weak source that does not generate initial shock waves. It has been shown experimentally that the combined effect of acceleration of the flow due to the passage of the combustion wave from a larger-diameter tube (booster) into a smaller-diameter tube (test section) and through turbulizing obstacles significantly reduces the run-up distance of the strong shock wave–reaction zone complex: such a complex can be formed in a tube with turbulizing obstacles within a distance of ~ 1 m (~ 14 diameters of the test section) from the ignition source and can propagate in such a tube at a velocity of 1300–1400 m/s. All this suggests that transient combustion processes in systems composed of connecting channels of different diameters and containing portions with turbulizing obstacles can be more dangerous and destructive than combustion in obstructed constant-diameter tubes.

Frolov et al. report the results of numerical simulations of shock-to-detonation transition (SDT) in SMA mixture in a tube with the profiled central body using reactive Euler equations in axisymmetric approximation with 5-step overall kinetics of methane oxidation. The shape of central body was optimized to minimize the length of detonation onset. As a result of numerical calculations, the optimal geometrical parameters of the central body were suggested for further experiments. It has been shown that for detonation initiation, the Mach number of incident shock wave must exceed 3.5.

In their another contribution, *Frolov et al.* performed experiments on SDT in stoichiometric natural gas–air mixture in a straight round

ST 4500 mm in length and 94 mm in diameter with the convergent-divergent nozzle of special shape installed at a distance of 1600 mm from the bursting diaphragm. It has been shown that for detonation initiation, the incident shock wave velocity must exceed 1150 ± 30 m/s. This result is of importance for the development of new-generation burners using pulse detonation combustion of natural gas and for better understanding of the dynamics of accidental gas explosions in mine working.

Emelianov et al. present experimental observations of so-called detonation waves (DWs) of condensation propagating in acetylene C_2H_2 and in argon-diluted carbon suboxide C_3O_2 initiated by a reflected shock wave using an ST with pressure gauges and ICCD (intensified charge-coupled device) camera. The mechanism of wave propagation due to condensation of carbon nanoparticles at thermal decomposition of C_2H_2 and C_3O_2 has been suggested and substantiated by measurements of condensed particle concentrations by laser light extinction on a wavelength of 633 nm. Analysis of kinetics of heat release has shown that in C_3O_2-containing mixtures, the condensation of carbon particles starts immediately after decomposition reactions; therefore, the detonation is quickly formed even at low pressures on the level of 6 bar. In contrast, in C_2H_2-containing mixtures, the zone of condensation is separated from the shock wave by a zone of hydrocarbon polymerization reactions; hence, the detonation is formed at higher pressures of about 30 bar.

Kulichkov and Kosyakov study theoretically the dynamics of the front structure of a strong spherically diverging blast wave propagating in air and, in particular, the effect of front thickening at large distances from the explosion source, using a nonlocal three-flow gasdynamic model of the phenomenon. It has been shown that in the structure of a weak shock wave, the static pressure may reach its maximum sooner than the mass velocity if the process is considered in time at a fixed distance. In other words, a weak pressure wave splits into, at least, two wave processes: a higher-frequency process of pressure variation and a lower-frequency process of mass velocity variation.

Chapter 3 Propagating Detonations

Azatyan discusses the applicability of overall one-step reaction to simulations of combustion, detonation, and explosions in gases. On the

one hand, such a simplification based on empirical values of Arrhenius parameters and implying purely thermal self-acceleration of chemical reactions allows explaining many specific features of various combustion phenomena. On the other hand, it does not take into account a fundamental fact that reaction end products cannot be formed in a one-step reaction between molecules of initial species, since molecular reactions cannot provide noticeable self-heating in view of large activation energies. Observed large reaction rates can only be realized by the participation of free atoms and radicals — chain carriers in chain-branching reactions. The results of special experiments, calculations, and analysis of published data show that the chain mechanism determines combustion and detonation of gases not only at low pressures, as it was accepted earlier, but also at higher pressures, important for practice.

Levin et al. present the results of numerical simulations of spontaneous formation of three-dimensional (3D) cellular and spin detonation in stoichiometric propane–air mixture in channels of square, rectangular, circular, and elliptical cross sections using the parallelized software package solving reactive Euler equations by Godunov method modified for multiblock computational grids with billions cells.

Trotsyuk et al. report the results of 2D numerical simulations of detonation front structure in stoichiometric methane–air and methane–oxygen mixtures using Euler equations with a two-step model of chemical kinetics. Irregular cellular structure with all basic specific features was reproduced. It has been shown that the predicted transverse size of detonation cells agrees well with available experimental data.

The work of *Semenov et al.* is dedicated to the numerical investigation of detonation initiation and propagation in planar channels and in the tube with profiled walls filled with an SMA mixture. The tube walls geometry is obtained which provides SDT for the initiating shock wave Mach number near 3.3. Mathematical model is based on Euler set of equations. Numerical procedure adapted for multiprocessor systems is based on the finite-volume approach and Godunov's scheme for fluxes approximation. Two- and three-dimensional numerical investigations of initiation and propagation of DW in SMA mixture were performed. The reasonable agreement with experimental data for averaged velocity of the DW and for averaged transverse detonation cell size was obtained with using global and reduced kinetics models. The shape of parabolic

xxiii

contraction and divergence angle of cone expansion are found which provide SDT for the initiating shock wave Mach number about 3.3.

Lopato and Utkin investigate one-dimensional (1D) problem of direct detonation initiation and propagation in hydrogen–air mixture using Euler equations with one-step chemical kinetics and numerical methods of different orders of approximation. The key point in the solution procedure is the combination of essentially nonoscillatory (ENO) reconstruction approach, monotone Courant–Isaacson–Rees numerical scheme in conservative formulation, and Runge–Kutta time stepping. Recursive ENO-reconstruction algorithm allows construction of numerical schemes of different required orders in a unique manner. It has been shown that none of finite-difference chemes used in the study provides a longtime evolution of a DW.

Desbordes et al. study the overall heat release laws in the reaction zone of a DW within Zel'dovich – von Neumann – Döring (ZND) model and experimentally. They distinguish three classes of global heat-release law, namely, (*i*) one-step heat release; (*ii*) two-step heat release; and (*iii*) two-step hybrid heat release, presenting either one maximum; or two maxima; or one maximum of thermicity. In experiments, these heat-release laws correspond to cellular detonations with different properties, namely, (*i*) one-step/one-cell; (*ii*) two-step/two-cell, and (*iii*) two-step/one-cell structures. It has been shown experimentally that depending on the detonation class, detonation behavior can change drastically. Thus, the well-known criterion for the critical tube diameter of detonation diffraction established for one-step/one-cell detonations is no longer valid for the other classes. Besides, both normal and low velocity detonation propagation regimes can be observed in two-step/two-cell mixtures.

Hasslberger et al. performed 3D underresolved simulations of direct detonation initiation and propagation in 25.5 %(vol.) hydrogen–air mixture in a large-scale confined geometry using unsteady Reynolds averaged Navier–Stokes (URANS) equations with a two-step combustion model and adaptive mesh refinement (AMR). The method used proved to reliably predict the destructive potential in real-world accident scenarios. The code successfully reproduced key safety characteristics such as the detonation propagation velocity and associated pressure loads. The model used requires no tuning of the reaction rate, particularly depending on hydrogen content and grid size.

xxiv

Gordopolova studies the chemical mechanism inherent in inhibition of propagating detonations in hydrogen–air mixtures by small additives of unsaturated hydrocarbons (propylene and isobutylene) and concludes that the inhibiting effect is due to thermal reasons rather than due to the effect of inhibitor on chain reaction self-acceleration as suggested before.

Boeck et al. investigate experimentally the influence of hydrogen concentration gradients on detonation propagation in nonuniform hydrogen–air mixtures using pressure measurements and shadowgraphy to characterize detonation fronts. Steep concentration gradients were shown to lead to strongly unstable detonations similar to single-headed fronts in homogeneous mixtures. However, even steep gradients with regions outside the detonation limits allowed self-sustained detonation propagation with a velocity deficit. Wall pressure measurements showed high local pressure peaks due to strong transverse waves caused by concentration gradients. It has been shown that self-sustained detonation propagation is generally possible in hydrogen–air mixtures with steep concentration gradients in an entirely confined channel. As local pressures depend on the 3D detonation structure, the reproducibility of experiments with respect to the maximum measured pressure was reported to be poor.

Bondar and Ivanov performed a numerical study of detonation in hydrogen–oxygen mixture at the molecular kinetic level using direct simulation Monte Carlo (DSMC) method taking into account recombination, dissociation, and exchange chemical reactions as well as translation-rotation/translation-vibration energy transfer in collisional processes. As a test problem, the process of homogeneous adiabatic self-ignition of stoichiometric hydrogen–oxygen mixture diluted by argon was solved numerically. It has been shown that the model provides qualitatively correct description of self-ignition process and shows good agreement with the numerical solution of equations of chemical kinetics. The DSMC modeling of a nonstationary DW yielded the detonation velocity that corresponds to the Chapman–Jouguet velocity. The internal structure of the DW agrees qualitatively well with the ZND structure.

Chapter 4 Pulse Detonations

Falempin and Le Naour performed theoretical and experimental work on PDE in cooperation with LCD laboratory at ENSMA Poitiers. These

studies were aimed at obtaining a preliminary demonstration of the feasibility of PDE in both rocket and air-breathing modes and at determining effects of filling coefficient and nozzle, thermal, mechanical, acoustic, and vibrational impacts on environment, different fuels, as well as performance code development. Despite the PDE has theoretically a higher performance than other classical propulsion concepts based on combustion process (20% to 25% in terms of thermal efficiency), the authors intended to verify that this advantage is not fully compensated by the difficulties which could be encountered in practice or by the complex technology that could be needed to implement it in an operational flying system.

Presles et al. study experimentally detonation of nitromethane–tetranitromethane (NM–TNM) blends as liquid monopropellant for detonation propulsion. Experiments were conducted at initial temperature of 85 °C and initial pressure from 0.02 to 0.3 bar. Nitromethane (CH_3NO_2) is known to be a fuel-rich monopropellant with fuel-to-oxygen equivalence ratio 1.75, whereas tetranitromethane (CN_4O_8) is fuel-lean monopropellant with fuel-to-oxygen equivalence ratio 0.25. These monopropellants can be easily mixed in any proportion and, therefore, the fuel-to-oxygen equivalence ratio of NM–TNM blends can be varied within the range limited by the equivalence ratio of each component. First experimental results with NM–TNM blends with the equivalence ratio ranging from 0.25 (pure NM) to 1.75 (pure TNM) show the high detonation-induced compression ratio of these blends which indicate their high potential propulsive performance. Detonation of overall fuel-lean NM–TNM blends was shown to exhibit a double cellular structure: NO_2 as a part of an NM molecule is responsible for nonmonotonous chemical energy release in the reaction zone of a DW.

Sinibaldi and Brophy review their recent accomplishments on pulse detonation propulsion at Naval Postgraduate School. Transient plasma ignition and DDT in air mixtures of liquid (JP-10) and gaseous (ethylene) fuels at pressures and temperatures representative of nominal supersonic flight conditions have been demonstrated at frequencies up to 70 Hz. The use of transient plasma ignition systems allowed ignition delays up to three times shorter than most conventional systems under dynamic flow conditions. The subsequent use of swept-ramp obstacles in the DDT process allowed substantial improvements in total pressure losses and associated thrust levels with pulse detonation combustor op-

eration by maintaining total pressure losses below 3% for combustor refresh conditions. Additionally, the use of dynamically adjusting fluidic nozzles appeared to provide the necessary frequency response and potential performance to optimally expand the high-enthalpy flow for these transient systems. It has been reported that the final integration of these systems into a multitube system is underway and is expected to proceed after near-term heat transfer measurements are completed for thermally steady-state conditions.

Frolov et al. tested a PDE operating on liquid propane–air mixture in the mode of repetitive DDT using a laboratory test stand allowing for measurements of thrust and fuel mass flow rate. Their test campaign included two experimental series. In the first series, the PDE detonation tube had no nozzle extension. In the second, the PDE detonation tube had a conical nozzle extension. In the tests, two parameters were varied, namely, the cycle fuel-fill time (from 30 to 100 ms) and the operation frequency (from 2 to 20 Hz). It has been shown in the experiments of the first series that there exists the minimum value of the cycle fuel-fill time (30 ms at given experiment settings) required for the DDT which is explained by the existence of the minimum run-up distance for the detonation to arise. The increase in the cycle fuel-fill time from 30 to 100 ms at 2-hertz operation, other conditions being equal, results in the gradual decrease of the specific impulse from 1020 to 410 s. The increase of the operation frequency from 2 to 20 Hz at the cycle fuel-fill time of 30–40 ms, other conditions being equal, results in the growth of PDE thrust from 6.5 to 47 N, while the specific impulse decreases from 1020 to 503 s. The latter is most probably caused by deterioration of fuel–air mixing at higher frequencies and incomplete combustion of fuel. The use of nozzle extension in the second experimental series resulted in the increase of PDE thrust performance. Thus, at a fixed cycle fuel-fill time (30 ms) and the operation frequency (10 Hz), the PDE with nozzle extension exhibited both a higher thrust (33 against 28 N) and a higher specific impulse (880 against 730 s) indicating that partial fuel fill makes the PDE more efficient.

Vlasenko and Shiryaeva review their numerical studies of the operation process in a hydrogen-fueled PDE of valveless scheme proposed in N. E. Zhukovsky Central Aerohydrodynamic Institute (TsAGI) using 2D axisymmetric URANS equations supplemented by the q–ω-model of turbulence and by Moretti kinetic scheme for hydrogen oxidation in air.

xxvii

Calculations showed that such a PDE allows obtaining a useful force higher than the outer drag. Despite the necessity to damp a shock wave propagating upstream towards the PDE inlet deteriorates the PDE performance, the corresponding damping losses can be optimized by the geometry and location of bypass shrouds with perforated walls.

In their another contribution, *Vlasenko and Shiryaeva* compare theoretical thrust performances of a model PDE of valveless scheme and a conventional ramjet both operating on hydrogen using numerical calculations based on 2D axisymmetric URANS equations supplemented by the q–ω-model of turbulence and by Moretti kinetic scheme for hydrogen oxidation in air. A model PDE had the same geometry as the ramjet but contained a pulsed chamber inside a duct. The authors conclude that the thrust performance of the valveless PDE is worse than that of the equivalent ramjet and advantages of such PDEs are limited by the simplicity of design without moving parts and operation in a wide range of flight Mach numbers starting from zero.

Zangiev et al. performed numerical calculations of main thrust characteristics such as thrust, fuel-based specific impulse, specific fuel consumption, and specific thrust of a propane-fueled air-breathing PDE comprising an air intake, mechanical valve, and a nozzle in conditions of subsonic flight at Mach number 0.8 at various altitudes (from 0 to 12 km above sea level). Calculations are based on 2D axisymmetric URANS equations supplemented by the k–ε model of turbulence and by Flame Tracking – Particle combustion model taking simultaneously both frontal combustion and multistage (with cool and blue flames and hot explosions) volumetric oxidation and combustion into account. The calculations include external and internal aerodynamic drag, turbulence–chemistry interaction, and finite time of turbulent flame acceleration and DDT. It has been shown that a PDE can operate effectively (with fuel-based specific impulse of ~ 1500 s) at subsonic flight conditions.

Frolov et al. review their accomplishments in the development of the world's first energy-saving pulse-detonation burner (PDB) with controlled pulse-detonation combustion of natural gas. The PDB exhibits thermal power up to 2500 kW; adjustable maximum speed of detonation products in the outlet section from 400 to 1500 m/s; adjustable operation frequency from 0.01 to 5 Hz; adjustable maximum temperature of detonation products in the outlet section from 1400 to 2500 °C;

adjustable maximum overpressure of detonation products in the outlet section from 2 to 14 atm; low NOx emission on the level of 200 ppm; and low noise emission on the level of 105 dB (after noise suppression). These performances are obtained with the cycle-to-cycle ignition energy not exceeding 1.0 J and at the length of the burner duct not exceeding 5–6 m.

Golub et al. investigated experimentally a feasibility of free-piston PDE based on demonstrating its single-cycle operation on stoichiometric hydrogen–oxygen mixture in a detonation tube equipped with a detonation and compression chambers, free piston, pressure transducers, light gauges, and detectors of piston displacement. The length and internal diameter of the detonation chamber were 2000 and 16 mm and the length and internal diameter of the compressor chamber were 450 and 11 mm, respectively. It has been shown that the concept of free-piston PDE allows precompression of oxidizer without using compressors and, therefore, shortening of DDT distance and increasing in the thermodynamic efficiency as compared with cycle without precompression.

Paniagua et al. address the issue of a successful turbine design for a PDE in terms of maximizing the aerodynamic performance and thermal management. They consider a DW traveling at Mach number 3.5 directly into the turbine vane and, as the first attempt, design the turbine using steady conditions corresponding to the case, when the inlet conditions are axial flow at Mach number 3.5. The design strategy is similar to engine intakes that should be able to duct a high-speed flow while minimizing the pressure loss with the use of oblique shocks. This design resulted in a rather thin leading edge which is difficult to cool down. The turbine velocity triangle has been optimized to maximize the work extraction in the turbine neglecting pressure loss. Afterwards, the leading edge wedge angles in both vane and rotor were considered to keep the oblique shock wave attached. The turnings across vane and blade were then selected to maximize the work for given wedge angles. Thereafter, the method of characteristics was utilized to design the pressure side, suction side, and the diverging nozzle of the airfoil. The vane and blade passages were designed to ensure continuity in the curvature of the airfoil surface.

Sousa et al. explore theoretically the transient performance of a supersonic channel when exposed to axial supersonic pulsating inlet con-

ditions. The investigated geometry has the objective to deviate the supersonic flow in 20°. The inlet Mach number and the inlet angle were independently modified following a sinusoidal variation in time ($-M = \pm 0.7$ and $-\alpha = \pm 8°$) at three different frequencies (10, 50, and 100 Hz). It has been shown that flow responds differently to the incoming fluctuations depending on its past history and exhibits hysteresis at different fluctuating frequencies. In addition, the inlet fluctuations were shown to strongly damp throughout the flow passage. This knowledge is important for the development of suitable design tools for such operating conditions.

Ivanov et al. study experimentally the possibility of creating devices for needleless injections based on detonation of stoichiometric hydrogen–oxygen and hydrogen–air mixtures using narrow tubes of subcritical diameter at initial pressures of 1 and 2 bar and end-wall diaphragms covered by liquid to simulate impact-induced injection. To obtain a DDT in a 3-millimeter-diameter tube, they use a prechamber of a larger diameter with obstacles to mechanically turbulize and accelerate flame. It has been shown experimentally that the predetonation distance did not exceed 47 tube diameters. Time histories of the speed of impact-induced motion of liquid drops were obtained for diaphragms of different thickness and material. The maximum drop speed was about 70 m/s.

Chapter 5   Continuous Detonations

Kailasanath and Schwer conducted numerical simulations for investigating the operation and performance of rotating detonation-wave engines (RDE). Despite the flowfield within the engine is fairly complicated, it is shown to follow the thermal detonation (Zel'dovich) cycle quite closely. Parametric studies varying the pressure conditions both upstream at the inlet and downstream through the back pressure revealed that the overall specific impulse is a function of the ratio of the inlet stagnation pressure to the chamber backpressure. Sources of losses occur when reactant is burned away from the DW and also when detonated reactants are traversing through both the oblique and secondary shock waves. A numerical procedure has been developed for investigating the flowfield for RDE, applying algorithms that have been used extensively for detonation and PDE work in the past.

xxx

Frolov et al. designed, fabricated, and tested a large-scale continuous detonation chamber (CDC) to study the effect of different design elements on the operation process and CDC propulsion performance. It has been shown experimentally that widening of the air-inlet gap from 2 to 15 mm leads to a decrease in the number of DWs simultaneously circulating in the combustor from four to one and, finally, to transition to the operation mode with intermittent (pulse) longitudinal reaction waves resembling pulse detonations. The number of DWs and the thrust produced by the CDC can be increased by installing a shaped obstacle at the CDC exit providing the blockage of the combustor cross section. The maximum net thrust produced by the CDC attained 6 kN at the total mass flow rate of fuel components of 7.5 kg/s, whereas the maximum fuel-based specific impulse attained ~ 3000 s.

Dubrovsky et al. applied a computational technology created for computer-aided design of jet engines operating on continuous detonations to design a large-scale hydrogen–air CDC of outer diameter 406 mm and total mass flow rate of fuel mixture up to 7 kg/s. The technology is based on 3D URANS equations supplemented with two-equation turbulence model and particle method for taking turbulence–chemistry interaction into account. Based on the simulations, the experimental CDC was fabricated and tested to validate the computational predictions in terms of different qualitative and quantitative features (existence of the detonation mode, mass flow rates of air and hydrogen, DW velocity and height, the number of simultaneously rotating DWs, thrust, specific impulse, etc.). It appeared that the computational technology taking into account finite-rate chemistry of hydrogen oxidation and turbulence–chemistry interaction provides excellent agreement with experimental data and can be used for design optimization aimed at the improvement of CDC propulsion performance.

Eude and Davidenko applied the method of AMR for 2D and 3D numerical simulation of internal flow in a Continuous Detonation Wave Rocket Engine (CDWRE) characterized by a large spectrum of spatial and temporal scales. The efficiency of AMR is evaluated based on simulations performed with an Euler solver integrated in an AMR code for a model problem of detonation propagation in a layer of stoichiometric H_2–O_2 mixture. The efficiency is evaluated in terms of parallel speedup and total runtime. The parallel speedup is defined as a ratio of runtimes

obtained for a single processor and for parallel code execution, and the total runtime is estimated for a physical time period of 17 μs, during which the DW propagates to the end of computational domain. In spite of the loss of parallel efficiency, the use of AMR provides runtime reduction by a factor of 2 or more and an important memory saving as the total number of computational cells appeared to be less by 60%. With AMR, the runtime cannot be reduced to the same ratio as the number of cells because the AMR realization is linked to a significant computational overhead, which can vary from 10% to 50% of the total computational cost.

Davidenko et al. theoretically evaluate and compare thrust performances of ideal CDWRE and conventional rocket engine using a realistic thermochemical model for hydrogen–oxygen mixture. The mass flow rate and nozzle diameter were taken corresponding to the Vinci rocket engine. It has been shown that CDWRE possesses a higher theoretical specific impulse with respect to the conventional rocket engine. Thus, the maximum specific impulse of CDWRE was shown to be higher by about 100 m/s. Despite the dependences of specific impulse on mixture equivalence ratio are quite similar, the CDWRE performance is flatter at fuel-rich conditions and the maximum of the specific impulse occurs at a lower equivalence ratio. It permits to increase the payload not only by reducing the propellants mass but also by making the propulsion system more compact.

Liu et al. performed 2D numerical simulations of rotating detonation in $H_2/O_2/Ar$ mixture using a detailed chemical reaction mechanism and 0.1-millimeter grid scale. The governing Euler equations were solved with fifth-order weighted ENO scheme. For temporal terms, the equations were discretized by a second-order Runge–Kutta method. It has been shown that grid resolution affects the flowfield structure. When grid resolution of reaction zones was insufficient, transverse waves, triple points, and cellular structure of DWs were not resolved. However, when grid resolution was high, all these specific features of DW structure were well resolved. In the study, this was achieved by changing the value of injection coefficient from 1.0 to 0.35, i.e., by changing the mass flow rate at the combustor inlet resulting in longer reaction times.

Bykovskii et al. determined experimentally the domain of existence of continuous spin detonation of hydrogen–air mixture in the air ejection

mode in a flow-type annular combustor in terms of the specific flow rate of hydrogen, the width of the air ejection slot, and the size of fuel injector orifices. Hydrogen was injected in the combustor through the injector orifices promoting the initial ejection of air. The resultant combustible mixture was ignited by a heat pulse with approximately 5 J of energy released during blasting of an aluminum foil strip by electric current. The initiation was performed at a distance of 15 cm from the air ejection slot. Depending on the type of the orifices and test duration (0.6–8 s), the flow rates of hydrogen were varied from 0 to 140 g/s. The optimal width of the air ejection slot was obtained for the combustor. The existence of an optimal injector-orifice geometry, which increases the domain of existence of detonation regimes, was elucidated. Also, tests with long-time operation of the combustor were performed. It was proved by experiments that the combustor can operate up to 8 s without cooling.

Braun et al. used the OpenFoam solver to model the continuous detonation-wave phenomena in a small annular combustor 20 mm in diameter and 30 mm long operating on stoichiometric hydrogen–air mixture. Both detonation and deflagration of hydrogen–air mixture were taken into account in the source terms of the species transport equation. The deflagration source term was modeled using Weller model. Detonation was modeled using the self-ignition delay time rather than solving reaction equations. The self-ignition delay time was calculated with Cantera code. The detonation model was verified on the test case with DDT in hydrogen–air mixture in a tube with obstacles.

Levin and Zhuravskaya investigated numerically stabilization of a cellular DW in a supersonic flow of stoichiometric hydrogen–air mixture through a plane channel of constant or variable cross section using 2D Euler equations. It has been shown that the DW can be stabilized by weak electrical discharges located in the supersonic flow if the deposited energy exceeds a certain critical value which is nearly independent of discharge location but significantly dependent on the flow Mach number. The possibility of detonation stabilization without additional energy input has been also investigated. It has been shown that a channel with contraction allows stabilization of detonation without additional energy deposition. A method of determining the channel shape ensuring detonation-wave stabilization in the supersonic flow without additional energy input is proposed.

xxxiii

Chapter 6 Heterogeneous and Condensed-Phase Detonations

Veyssiere et al. performed experiments and numerical simulations of liquid spray detonations in air under normal ambient conditions without fuel preheating. Experiments have been performed with iso-octane with droplets of different initial diameter: 8, 30, and 45 μm at different overall fuel-to-air equivalence ratios as well as with n-heptane, n-octane, n-decane, and n-dodecane sprays. For all fuels, domains of detonation existence in terms of mixture composition and initial droplet size were found to depend on fuel volatility and droplet size. Numerical simulations showed that for coarser droplets 30 and 45 μm in diameter, it is necessary to consider shock-induced mechanical disintegration whereas for smaller droplets 8 μm in diameter, the account for droplet disintegration is not necessary. Concerning the influence of droplet diameter on the detonation cell size, the results of numerical simulations appeared to be in reasonable agreement with experimental data.

In their another contribution, *Veyssiere et al.* present the results of experimental and numerical investigations of critical conditions for direct initiation of unconfined detonations in stoichiometric suspensions of aluminum particles in gaseous oxygen. Experiments were performed with suspensions of aluminum flakes in pure oxygen with the overall equivalence ratio ranging from 1 to 1.28. The mass of initiation charges of C4 high explosive (HE) was varied from 125 to 250 g. In the experiments, a typical detonation front velocity of 1600 m/s has been recorded and the cellular structure of detonation was detected with the cell width on the level of 10 to 20 cm. Numerical simulations showed that the predicted pressure profiles in a spherical detonation are in good agreement with the measured profiles and the minimum velocity of the initiating shock wave is attained at a distance of about 1.25 m from the initiator.

Fedorov and Khmel proposed a simple dynamic criterion for shock-induced ignition of fine aluminum particle suspensions in oxidizing gas neglecting the reactions of preflame oxidation and particle melting. The Arrhenius-type dependence of the critical ignition temperature on gas temperature, oxidizer content, and particle diameter is obtained. Despite the critical ignition temperature was shown to vary in a wide range,

according to the authors, at postshock temperatures less than 1000 K, the ignition temperature for aluminum–oxygen and aluminum–air suspensions can be taken equal to 830 and 900 K, respectively.

Fedorov and Kratova investigated numerically the propagation of planar and cellular detonations in polydisperse mixtures of fine aluminum particles in oxygen through finite-size clouds of nonreactive particles using 2D flow equations for interpenetrating continua. As a result of interaction of a DW with a cloud of inert particles, the DW could either survive or decay depending on the size and mass fraction of nonreactive particles. The minimum size of the cloud required for detonation suppression has been found. The importance of the spatial distribution uniformity of nonreactive particles in a cloud for detonation suppression has been also demonstrated.

Khmel and Fedorov presented a model of gas–particle flow taking into account random motion of particles and their collisions using the extended system of Euler equations with the collisional pressure in the discrete phase and molecular-kinetic approach. The model is validated against available experimental data on the propagation velocity of rarefaction waves in loose materials at a sudden pressure drop. Shock jump conditions in the collisional two-phase mixture are analyzed and two types of strong discontinuities are determined. The existence of two different types of steady-state shock wave structure has been proved and the conditions of their realization are derived.

Utkin investigated the problem of shock wave interaction with the dense bed of particles using the 1D nonconservative nonstrictly hyperbolic set of reduced Baer–Nunziato equations for the two-phase compressible flow with algebraic source terms in right-hand side taking into account the interphase friction force. The problem is solved numerically using the Godunov method and is validated against several Riemann problems. The important feature of the Godunov method is the correct treatment of special cases with vanishing dispersed phase on one side of initial discontinuity. The calculated histories of shock wave amplitude and propagation velocity appeared to be in good agreement with experiments.

Aksenov et al. performed experimental studies of magnetohydrodynamic (MHD) effects of pulsed heterogeneous (spray) detonations, which have been detected by the authors previously. Heterogeneous detonations were shown to be capable of generating regular voltage pulses

in a reliable and reproducible manner with the pulse frequency prede-
termined by the operation frequency of a micro-PDE. This conclusion
is not trivial because the two-phase reactive flow in the MHD-channel
is accompanied with various side processes like wetting of electrodes
by liquid fuel, etc., which can unpredictably deteriorate MHD effects.
Since the heterogeneous detonation is expected to be the most appro-
priate combustion mode in practical PDEs, this outcome demonstrates
the feasibility of MHD for the corresponding applications. The para-
metric studies of MHD effects indicate that the magnitude of voltage
pulses increases with the magnetic field intensity and with the resistive
load in the electric circuit, whereas the pulse frequency does not affect
the voltage pulse magnitude. The voltage pulses were shown to exhibit
three different shapes: single-peak, double-peak, and double-peak with
sign reversal.

Chapter 7 Equations of State

Anikeev et al. presented their study of shock compression of molecular
nitrogen and carbon dioxide applying the thermodynamic perturbation
theory and the distribution function integral equations with the aim to
demonstrate the limitations of van der Waals effective one-fluid model
(vdW1f) for multicomponent system of products for temperatures up to
6000 K. The predictions were compared with the results of Monte-Carlo
simulations.

Gubin et al. performed a thermodynamic study aimed at estimating
the reactivity and responsiveness of aluminum behind DWs by means
of comparing calculated and experimental parameters of detonations
of aluminized HEs (RDX, HMX, BTEN, TEN) with different degrees
of Al particle reaction and by predicting initial densities of HEs with
a sharp change in detonation parameters due to phase transformation
of aluminum and aluminum oxide in a DW and expansion of deto-
nation products. Detonation of HE charges with uniformly distributed
monodispersed aluminum particles and subsequent expansion of detona-
tion products has been considered using 1D Chapman–Jouguet model.
A modified approach for determining the excess Helmholtz free energy
of the exponent-6 (Exp-6) fluid with the KLRR (Kang, Lee, Ree, and
Ree) perturbation theory has been developed. This approach proved
to provide a model of equation of state which reproduces the results of

Monte-Carlo simulations on the compressibility factor and excess internal energy very accurately.

Bogdanova et al. studied the influence of unlike-interaction Exp-6 potential on the accuracy of calculations of thermodynamic parameters (pressure and internal energy) for H_2–He and CO_2–O mixtures based on effective single-component model (vdW1f-model) and theoretical binary model (2f-model). The accuracy is defined based on the agreement of the calculations with the results of Monte-Carlo simulations. It has been shown that for calculating the thermodynamic parameters of binary systems using the exact two-component theory, it is necessary to use the parameters of unlike-interaction potential determined by independent experiments.

Veretennikov and Trofimov investigated the mechanism of HE detonation failure at critical charge dimensions and put forward a new explanation to the observed independence of reaction time in a DW on the HE structure based on the theory of turbulent detonation. The basic formulae of this theory turned out to be essentially the same as those in the classical Zel'dovich theory of 1D detonation but, in contrast, the theory of turbulent detonation assumes that transition from the initial state to the shock-compressed state in the pressure — specific volume plane is gradual rather than jumpwise.

Yu et al. performed numerical studies aimed at better understanding of experiments with driving an oxygen-free 2-millimeter thick heavy copper (OFHC) shell by insensitive semispherical JB-9014 charges of different densities. For investigating the effect of charge density, empirical adjustments of the detonation velocity and the modified equation of state for detonation products were used. The predicted results were found to be in excellent agreement with experimental data. Both computational and experimental results showed that the free surface velocity of the OFHC shell increased with the charge density.

Lan et al. studied the evolution of the speed waveform of a flyer driven by a spherically converging detonation of HE in vacuum and in different media (Al, Fe, and Ta) using a 2D Lagrangian finite-volume numerical simulation code. The results of simulations indicate that the evolution of the flyer speed waveform goes through three stages, namely, improving stage, steady stage, and worsening stage.

Miao and Yong applied a 2D Lagrangian finite-element numerical simulation code to study the effect of the shock wave driven by

spherically-converging HE detonation emerging in the air-filled cavity between HE and metal body at initial air pressure of 1 atm, 500 Pa, and 1000 Pa on the pressure at metal surface and metal displacement. The results of calculations showed that at air pressure of 1 atm, the air shock wave could bring metal displacement of less than 0.1 mm whereas at air pressures of 500–1000 Pa, it has a little effect on the shock wave velocity in the metal and on the waveform in the metal inner face.

As can be seen from the brief synopsis of the articles, there has been a noticeable progress in our understanding of detonation related phenomena.

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