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DEVELOPMENT OF R. I. SOLOUKHIN'S SCIENTIFIC LINE OF INVESTIGATIONS AT THE HEAT AND MASS TRANSFER INSTITUTE

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The history of development of works on physical gasdynamics and high-temperature thermal physics that were initiated by the outstanding scientist, Corresponding Member of the USSR Academy of Sciences, Academician of the BSSR Academy of Sciences, Lenin Prize Winner Rem Ivanovich Soloukhin at the A. V. Luikov Heat and Mass Transfer Institute of the National Academy of Sciences of Belarus is described. Particular emphasis is placed on investigations into physicochemical kinetics under nonequilibrium conditions, combustion, detonation, and the gasdynamics of explosions and reactive systems; these investigations have been carried out at the Institute during the last three decades. Also, R. I. Soloukhin's works at the Siberian Branch of the USSR Academy of Sciences, where the foundations of this scientific line of investigations were laid, are briefly described.

Introduction. The present work seeks to review in brief and to analyze investigations carried out by Academician R. I. Soloukhin at the A. V. Luikov Heat and Mass Transfer Institute, of which he was director from 1976 to 1988.

Rem Ivanovich began working in Minsk when he was already a well-known scientist of world renown and high international reputation. Rem Ivanovich Soloukhin was born on November 19, 1930 in the town of Gus'-Khrustal'nyi, Vladimir Region, to a family of school teachers. In 1953, he graduated from the Physics Department of Moscow State University (MGU) (Chair of Thermal and Molecular Phenomena). When he was still at the university, he took an active part in scientific investigations conducted at the Chair while working part-time as a laboratory assistant. Soloukhin's scientific manner was shaped under the influence of well-known scientists and teachers — Professors A. S. Predvoditelev and Ye. V. Stupochenko. He also attended lectures at the newly opened Moscow Physics and Technology Institute (MFTI), with which the Physics Department of MGU maintained close ties. Many students of that period who were trained in the MGU–MFTI school subsequently became well-known scientists — physicists, gasdynamics scientists, and thermal physicists. They include S. A. Losev, A. I. Osipov, L. A. Gvozdeva, I. M. Naboko, S. G. Zaitsev, S. S. Novikov, L. N. Pyatnitskii, and many others.

R. I. Soloukhin's Works in Moscow. The beginning of R. I. Soloukhin's independent research work can be dated back to 1953, when he arrived at the G. M. Krzhizhanovskii Institute of Power Engineering (ÉNIN) for pre-diploma training at the Laboratory of the Physics of Combustion headed by Prof. A. S. Predvoditelev. Here, Soloukhin performed his graduation diploma work on investigating the formation of a shock wave in electric discharge in water. The results of this work were published much later [1–3]. In 1955, R. I. Soloukhin became involved in the MGU post-graduate school and continued working at ÉNIN on the problem of formation of detonation in propagation of shock waves in a fuel (combustible) gaseous mixture. Together with T. V. Bazhenova and S. G. Zaitsev, he continued thorough experiments to investigate the ignition of explosive and fuel mixtures in a shock tube. Sweeps and frame photographs of the Töpler pattern that arises in reflection of a shock wave from the end of a tube and in the case of flow past a semiwedge behind the shock wave were obtained, and along with pressure oscillograms. These investigations disclosed the mechanism of formation of detonation in a homogeneous gaseous mixture, the essence of which is that behind the shock wave, ignition sites, develop from which propagates the flame front with a normal rate of combustion. Ahead of the flame front, compression waves develop, whose interaction initiates a volumetric explosion and a detonation wave which catches up with the primary shock wave [4, 5]; for more details, see N. A. Fomin's paper in this issue (pp. 1058–1071).

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Along with the investigation of ignition, combustion, and detonation in gases, in these years, Soloukhin conducted experiments with detonation of solid fuels (powders) and investigated shock waves in a liquid and shock waves that develop in the case of electric discharge. At the same time, while using original pressure transducers in these investigations, Rem Ivanovich made wide use of emission methods, interferometry, and shadow methods. The results of the investigations of the first stage of Soloukhin's research work are summed up in his widely known review in UFN (Uspekhi Fizicheskikh Nauk) "Physical Investigations of Gases Using Shock Waves" [6]. Many of his methodological developments of those years have been included in the monograph "Some Methods of Investigation of Fast Processes" (together with T. V. Bazhenova, S. G. Zaitsev, I. M. Naboko, G. D. Salamandra, and I. K. Sevast'yanova) [7], released in 1960 by the USSR Academy of Sciences Press. Based on the results of these investigations, Rem Ivanovich defended a candidate's dissertation in 1957.

Moving to the Novosibirsk Akademgorodok. In 1958, R. I. Soloukhin took up a position at MFTI's Chair headed by Academician M. A. Lavrentiev. Here the core of the future Novosibirsk Akademgorodok (Science City) was formed. In 1959, he moved to Akademgorodok, still under construction then, with a group of young scientists together with Academician M. A. Lavrentiev. There, at the Institute of Hydrodynamics of the Siberian Branch of the USSR Academy of Sciences, he developed the scientific line of investigations started at ÉNIN. V. V. Mitrofanov, M. Ye. Topchiyan, V. K. Kedrinskii, and B. V. Voitsekhovskii [8] became his colleagues and research associates. It is Academician M. A. Lavrentiev and V. V. Voevodskii, then a Corresponding Member of the USSR Academy of Sciences, who had a great influence on Soloukhin's works. In 1962, R. I. Soloukhin defended a dissertation for a doctoral degree in Physics and Mathematics on the subject "Fast Processes in Shock Waves." This was the first doctoral dissertation in Physics and Mathematics produced in the young Akademgorodok. He summed up the results of investigations of shock and detonation waves in the monograph "Shock Waves and Detonation in Gases" [9], published in 1963. In 1965, the monograph was translated and republished in the USA. It became widely known and enjoys its well-deserved prestige with specialists.

The young scientist was enthusiastic about spinning detonation — a new physical phenomenon that was important in its applied aspect, and Rem Ivanovich began investigations of the trail and acoustic phenomena that accompany spinning detonation and investigated multifront waves. After a cycle of fundamental investigations conducted at the Institute of Hydrodynamics of the Siberian Branch of the USSR Academy of Sciences, in 1965, Rem Ivanovich (together with B. V. Voitsekhovskii and Ya. K. Troshin) was awarded a Lenin Prize for investigations of detonation in gases. The development of research in this direction is reflected in the papers of this issue of Inzhenerno-Fizicheskii Zhurnal contributed by Academicians B. E. Fortov, V. A. Levin, V. M. Fomin, G. V. Sakovich, Z. A. Mansurov, Professors V. S. Babkin, A. S. Boreisho, B. Ye. Gelfand, V. V. Golub, A. V. Eremin, N. N. Smirnov, and others.

In 1967, R. I. Soloukhin was invited to take on the job of deputy director for scientific work by Academician G. I. Budker — director of Akademgorodok's biggest Institute of Nuclear Physics (Institute of Nuclear Physics of the Siberian Branch of the USSR Academy of Sciences). During this period, along with continued work to investigate combustion and detonation processes, Soloukhin began to actively work on the subject of plasma. The years of work at the Institute of Nuclear Physics enriched Soloukhin with investigations of gas conductivity behind the front of detonation waves and investigations of high-power water discharges, and also with the development of new methods of diagnostics for electron concentration, including interferometry in the IR region of the spectrum. At present, charged-particle accelerators, in the development of which R. I. Soloukhin took an active part together with E. A. Abramyan, A. G. Ponomarenko [10], and V. M. Logunov, have been widely introduced. Of fundamental significance are the results of investigations of megavolt energy compactors, high-power electric-discharge laser systems, and pumping systems for pulsed lasers.

However, Soloukhin did not neglect investigations of detonation. Soloukhin's program work of those years was his investigation of optical discharge in a fuel mixture initiating shock and detonation waves (together with V. F. Klimkin, A. F. Alkhimov, and A. G. Ponomarenko) [11].

In 1968, R. I. Soloukhin was elected Corresponding Member of the USSR Academy of Sciences, "Mechanics" section, and in 1971, he was appointed director of the Institute of Theoretical and Applied Mechanics (ITAM) of the Siberian Branch of the USSR Academy of Sciences. Here he continued his investigations aimed at developing laser systems with electric excitation that he began while working at the Institute of Nuclear Physics. During the same years, still before the discovery of gasdynamic methods of obtaining inversion, Soloukhin, together with other researchers, looked for ways of direct conversion of thermal energy into the energy of laser radiation. It is the well-known review "Application of Gasdynamic Flows in Laser Engineering" [12], made together with V. N. Karnyushin in 1972, that had a great impact on the development of these investigations in the USSR.

Persistent search for new ways of direct conversion of thermal energy into the energy of coherent radiation resulted in success: in the same year 1972, under Soloukhin's supervision and at the laboratory he headed, the young research associates V. N. Kroshko, N. A. Fomin, and P. Wolanski (Polish People's Republic) simulated, using a shock tube, the operation of a new gasdynamic laser system — GDL on the mixing of flows of exciting and radiating gases — and demonstrated the fundamental advantages of this system over the then-established "classical" GDL scheme. This work almost immediately continued in the USSR, France, the USA, Japan, Polish People's Republic, and other countries for many years, setting the direction for further investigations and the improvement of the GDL mixing scheme. The results of ten years of investigations were later on summed up in a monograph by R. I. Soloukhin and N. A. Fomin — "Gasdynamic Mixed Flow Lasers" [13]. R. I. Soloukhin was an enthusiast of investigations of gasdynamic converters of thermal and electric energy into the energy of coherent radiation. He often emphasized that investigations in the field of laser gasdynamics[1] are a profound reflection of the basic principles of physical gasdynamics, in which equations of macroscopic motion are organically interwoven with equations describing energy transfer at the molecular level, plasma motion, and transfer of laser radiation under nonequilibrium conditions.

The developments of electric-discharge laser systems with convective cooling of the medium also carried out during the same years at the Institute of Theoretical and Applied Mechanics of the Siberian Branch of the USSR Academy of Sciences, under the supervision of R. I. Soloukhin, by his associates Yu. A. Yakobi, Ye. I. Vyazovich, and A. I. Ivanchenko turned out to be quite successful. The efficient system of longitudinal electrodes and the procedure of their "training" also began to be widely used at many laboratories of the world. During the same period, Soloukhin continued to seek new schemes of pumping of electric-discharge laser systems, with A. G. Ponomarenko's, V. N. Karnyushin's, and other groups actively working on this subject in his laboratory. A number of the results obtained, including those from the A. V. Luikov Heat and Mass Transfer Institute of the BSSR Academy of Sciences, are summed up in the monograph "Macroscopic and Molecular Processes in Gas Lasers" (together with V. N. Karnyushin) [14] published in 1981.

Along with investigations into laser systems, Soloukhin became actively involved in dealing with applied aspects of radiation gasdynamics. One of the most important problems of this kind is allowance for the transfer of radiation in the pattern of heat exchange in high-temperature gasdynamic processes. This is as important for the protection against radiation of reentry spacecraft entering the dense atmospheric layers as it is for designing plasmachemical equipment and investigating the kinetics of powerful shock waves and laser systems. The results of investigations in this area are summarized in the monograph "Optical Characteristics of Hydrogen Plasma" [15]. After V. G. Sevast'yanenko moved to Minsk, work in this area continued both in Novosibirsk and in Minsk, and the result of these investigations was the publication of the handbook "Radiative Heat Transfer in High-Temperature Gases" of the authors V. G. Sevast'yanenko, I. F. Golovnev, V. P. Zamuraev, S. S. Katsnelson, and G. A. Kovalskaya [16], which was edited by R. I. Soloukhin. This handbook was republished in 1987 in the USA. At the same time, at the A. V. Luikov Heat and Mass Transfer Institute of the BSSR Academy of Sciences, work in this area was developed at the Laboratory of Thermal Protection under the supervision of F. B. Yurevich [17], and at the Laboratory of Energy Transfer under the direction of O. G. Martynenko [18, 19]. G. S. Romanov, V. V. Kondrashov, M. N. Rolin, Ye. F. Nogotov and others [20, 21] also took an active part in this research. In Novosibirsk, under the scientific supervision of R. I. Soloukhin, work continued on experimental and numerical simulation of combustion laser systems [22, 23] and on investigation of ignition, combustion, and detonation mechanisms; in particular, detailed consideration was given to the mechanism of hydrogen combustion (together with V. K. Bayev, V. I. Golovichev, and V. I. Dimitrov) [24].

It is sophisticated diagnostic equipment that is an indispensable attribute of the modern physical laboratory, determining its character and scientific level. Rem Ivanovich always gave paramount importance to the physical methods of diagnostics; because he was a recognized expert in diagnostics, the investigations of which R. I. Soloukhin

[1]Despite the great number of dissertations on problems of the gasdynamics of high-power flow laser systems, the USSR High Attestation Commission (VAK) did not establish a new speciality. At that time, the closely related specialities included "Fluid Mechanics," "Thermal Physics and Molecular Physics," "Plasma Physics," and "Physical Electronics, including Quantum Electronics."

was the author, supervisor and initiator always gained international recognition. A simple and intelligible form of exposition, brevity, and physical capacity — these are distinctive features of his first monograph on methods of diagnostics, a book that had a very great influence on the development of experimental equipment in gasdynamics in many laboratories of the world — "Methods of Fast Measuring in the Gasdynamics and Physics of Plasma" (together with Yu. Ye. Nesterikhin) [25]. The description of new methods of diagnostics is dealt with in a number of review works and sections published by R. I. Soloukhin in fundamental foreign publications, including those in an encyclopedia of current measurement methods — the two-volume collective monograph "Methods of Experimental Physics" published in the USA and edited by Professor R. Emrich (1981) [26]. A significant event in the development of diagnostic methods was R. I. Soloukhin's monograph "Optical Methods for Recording Fast Processes" (together with A. N. Papyrin and V. F. Klimkin) [27], which describes current electron-optical converters, pulse holography, optical interferometry, and also laser-Doppler velocity meters with direct spectral analysis. The work on IR diagnostics started at the Institute of Nuclear Physics was actively continued at the Institute of Theoretical and Applied Mechanics of the Siberian Branch of the USSR Academy of Sciences. Here, Soloukhin, together with Yu. A. Yakobi and Ye. I. Vyazovich, proposed and implemented for the first time a fundamentally new design of a laser spectrograph with space separation of generation lines [28]. After the death of Yakobi, at the suggestion of the invention's creators, this design of the laser spectrograph was called the Yakobi design. It is to diagnostics developments by Soloukhin at the A. V. Luikov Heat and Mass Transfer Institute of the BSSR Academy of Sciences based, in particular, on the use of a Yakobi fast laser spectrograph, that the Soloukhin's monograph "Diagnostics of Nonequilibrium States in Molecular Lasers" (together with O. V. Achasov, N. N. Kudryantsev, S. S. Novikov, and N. A. Fomin) was devoted [29]. In 1987, this monograph was republished in the USA. Remembering R. I. Soloukhin's work on diagnostics, one cannot but mention a fundamental monograph [30] written jointly with Academician N. N. Yanenko and then Candidates of Sciences V. M. Fomin and A. N. Papyrin. This monograph laid the foundation for many years of cooperation between the Institute of Theoretical and Applied Mechanics of the Siberian Branch of the USSR Academy of Sciences and the A. V. Luikov Heat and Mass Transfer Institute of the BSSR Academy of Sciences.

First Works of R. I. Soloukhin in Minsk. It is with this rich scientific record that R. I. Soloukhin began his work at the Heat and Mass Transfer Institute. The first experimental investigation at the new place in Belarus was devoted to the investigation of the kinetics of thermal disintegration of propane heated behind a shock wave. In the summer of 1976, one of the best shock tubes of the Institute of Theoretical and Applied Mechanics of the Siberian Branch of the Russian Academy of Sciences was transferred to and installed at the Heat and Mass Transfer Institute by a group of ITAM associates — G. G. Zavarzin, I. G. Voroshilin, and N. A. Fomin. In October 1976, the ITAM associates V. N. Karnyushin and N. A. Fomin relocated to work at the Heat and Mass Transfer Institute, while practically at the same time the Heat and Mass Transfer Institute saw the arrival for joint research of a well-known scientist from France — Prof. J. Brossard, together with whom the first experiments start on the first shock tube of the Heat and Mass Transfer Institute of the BSSR Academy of Sciences had already begun in mid-October of 1976. These investigations were treated under the supervision of R. I. Soloukhin by a small Nonequilibrium Processes Group at the Laboratory of Energy Transfer headed by the Doctor of Technical Sciences O. G. Martynenko. Based on the results of the investigations carried out in 1978, N. A. Fomin defended a candidate's dissertation on experimental investigations of nonequilibrium flows of vibrationally excited molecules at the Institute of Physics of the BSSR Academy of Sciences and became the leader of this line of investigation at the Institute [31]. A more detailed account of subsequent investigations in this area is given in N. A. Fomin's paper in the present issue of the journal.

In 1977, these investigations were further developed both by this growing Nonequilibrium Processes Group, later on the Laboratory of Convective and Wave Processes headed by N. A. Fomin, and by other teams of the Institute under the supervision of Candidates of Technical Sciences V. A. Borodulya, G. S. Romanov, and later on V. N. Karnyushin, Doctor of Technical Sciences O. G. Martynenko, Professors Z. P. Shul'man, B. M. Smolskii, O. I. Yas'ko, and many others. The Institute was joined by graduates from MFTI (S. A. Zhdanok), the N. E. Bauman Moscow Higher Technical College (Ye. A. Shirokov), the Novosibirsk State University (S. M. Khizhnyak), and the V. I. Lenin Belarusian State University (O. V. Achasov, S. A. Labuda, D. S. Ragozin), A. V. Krauklis was invited from the Institute of Theoretical and Applied Mechanics of the Siberian Branch of the USSR Academy of Sciences, and cooperation was developed with the Belarusian State University, the Institute of Physics of the BSSR Academy of Sciences, and others organizations in Minsk and beyond.

Development of Works on the Kinetics of Nonequilibrium Processes. From the very beginning of his work at the Heat and Mass Transfer Institute of the BSSR Academy of Sciences, S. A. Zhdanok became actively involved with investigations of the influence of vibrationally excited molecules on the kinetics of nonequilibrium physicochemical processes in high-temperature flows. Following up on the work done in Moscow, he defended at MFTI a candidate's dissertation on theoretical description of highly nonequilibrium distributions of diatomic molecules by vibrational levels [32].[2)] In this work, in particular, Zhdanok constructed an analytical theory of a stationary CO laser and demonstrated that in the case of significant excess of the generation threshold, the boundary of the generation spectrum is, as a rule, more to the left of the Treanor number [33]. Zhdanok's subsequent investigations made a detailed analysis of the possibilities of stimulating ionization processes and chemical reactions under nonequilibrium conditions in the case of significant excitation of vibrational degrees of freedom [33–40]. Based on the approaches and calculations he developed in [34–36], Zhdanok theoretically predicted the possibility of obtaining superequilibrium ionization in a vibrationally nonequilibrium gas, and the experiments on shock tubes performed by O. V. Achasov, A. V. Krauklis, P. P. Samtsov, S. A. Labuda, D. S. Ragozin, and others confirm the existence of a new physical phenomenon — the increasing density of electrons in cooling of a vibrationally nonequilibrium gas. Soon the discovery was confirmed on the shock tube of Prof. I. Mashtovsky (Czechoslovak Socialist Republic), and at the Heat and Mass Transfer Institute, superequilibrium ionization was immediately used for additional discharge pumping of the active medium in a mixed flow gasdynamic laser [13]. At present, these ideas are used in nanotechnologies for production of carbon nanomaterials (see below).

The first success in theoretical description of complex nonequilibrium processes was in many ways conditioned by the simplicity and, at the same time, rigor of the analytical approach developed by S. A. Zhdanok toward the description of relaxation processes in the system of anharmonic oscillators. It has as its basis a transition procedure in balance equations for populations of vibrational levels from a set of quantum numbers ν to a continuous variable. At the same time, the system of kinetic equations describing the evolution of the distribution function of populations by vibrational levels $f(\nu)$ is reduced to a single differential equation which is similar to the Fokker–Planck equation in diffusion approximation. The development of this approach to describing the evolution of the distribution function $f(\nu)$ in the process of adiabatic expansion in a supersonic nozzle led to an analytical dependence of the form

$$f(\nu) = \begin{cases} f(0)\exp\left\{-\nu\left[\dfrac{E_1}{T_{\text{v}}} - \dfrac{\Delta E}{T}(\nu-1)\right]\right\}, & \nu \le \nu_{\text{T}}; \\[2ex] \dfrac{\left(\dfrac{3}{4}\varepsilon^* E_1^{-1}\right)^{1/4}}{\sqrt{\nu+1}\,(\tau-\tau_0)^{3/4}} - \dfrac{1}{2(\tau-\tau_0)}, & \nu^{**} \ge \nu \ge \nu_{\text{T}}; \end{cases} \tag{1}$$

where $\nu_{\text{T}} = \dfrac{1}{2}\dfrac{E_1 T}{\Delta E T_{\text{v}}} + \dfrac{1}{2}$ is the Treanor number corresponding to the distribution minimum $f(\nu)$, ε^* is the frozen content of vibrational energy, $\tau + \int_{x^*}^{x} \dfrac{v}{u}\,dx$ is the effective number of V–V processes, ν is the frequency of V–V exchange, u is the flow velocity, x is the coordinate along the nozzle, τ_0 is the number of collisions necessary for forming the distribution plateau $f(\nu)$; ν^{**} is the vibrational quantum number used to compare the rates of V–V and V–T processes, and x^* is the coordinate of freezing of vibrational energy.

Using this relation, new efficient schemes to obtain inversion in CO gasdynamic lasers were proposed in [37, 38] and subsequently implemented experimentally. A detailed description of the analytical theory of vibrational relaxation of anharmonic oscillators is given in a monograph by S. A. Zhdanok, B. F. Gordiets, et al. edited by Prof. M. Capitelli and published by Springer [41]. The theory of nonequilibrium processes had a substantial influence on the

[2)]The first two dissertations on the new subject of research at the A. V. Luikov Heat and Mass Transfer Institute of the National Academy of Sciences of Belarus [31, 32] were executed under the 01.04.04 specialized research category — Physical Electronics, including Quantum Electronics, and were defended at Scientific-Research Boards outside the Institute.

subsequent development of investigations of combustion processes, including a superadiabatic process, processes of conversion under nonequilibrium conditions, and many other lines of research [42–53], which is summarized in monographs by S. A. Zhdanok and K. V. Dobrego, S. A. Zhdanok and S. I. Fut'ko [54, 55]. Those involved in these investigations included S. K. Pogrebnya, V. I. Borodin, A. P. Chernukho, A. N. Migun, and many others. The investigations were carried out in close cooperation with Moscow State University (A. I. Osipov), the P. N. Lebedev Institute of Physics of the USSR Academy of Sciences (B. F. Gordiets), the Kurchatov Institute of Atomic Energy (E. P. Velikhov and A. P. Napartovich), and the Moscow Physics and Technology Institute (B. K. Tkachenko, S. S. Novikov, N. N. Kudryavtsev, and A. P. Zuev).

Development of Works to Investigate Processes of Combustion, Detonation, and Explosions. *1. Pulse detonation engine.* It is the proposal by Academician V. A. Levin to investigate the possibilities and prospects of a pulse detonation engine that gave impetus to the resumption of research into detonation processes at the A. V. Luikov Heat and Mass Transfer Institute of the National Academy of Sciences of Belarus in the early 1990s. These investigations started under the supervision of the Candidate of Sciences (Physics and Mathematics) O. V. Achasov and was the basis for his doctoral dissertation [56–58]. In recent years, the developments in this line of research were supervised by the Candidate of Sciences (Physics and Mathematics) O. G. Penyazkov, who defended his doctoral dissertation on a related subject in 2004 (59–61].

2. Three-dimensional structure of gas detonation. The foundations of the one-dimensional theory of a detonation wave with account taken of its structure were developed in the middle of the last century by Ya. B. Zeldovich, D. Neumann, and V. Dühring (ZND). According to the ZND theory, the structure of detonation is a one-dimensional complex made up of a bow shock wave, which heats and compresses the original substance layer, and an ignition zone moving behind the shock wave with the same velocity at a distance determined by the mixture's induction period. As shown by numerous experimental data and theoretical investigations, a one-dimensional structure of the detonation wave that would correspond to the ZND model is almost never realized. The spinning detonation phenomenon has been known since 1926 and consists of the fact that in tubes near the distribution limits, the brightest smoldering (glow) in the wave front is concentrated near the wall — in the head of the spin, which rotates in a circle simultaneously with the progressive motion of detonation. Experimental methods with sufficiently high spatial and temporal resolution always record, in the zone behind the leading shock front, strong three-dimensional and two-dimensional irregularities: transverse waves with secondary shocks and detonation shocks, i.e., the wave turns out to be a multifront wave. This means that, instead of a one-dimensional stationary structure of the detonation wave that would correspond to the simplest solution of equations of hydrodynamics and chemical kinetics, detonation propagation in gases is accompanied by the formation of a complex non-one-dimensional and nonstationary flow in its front. Thus, the main distinctive feature of the processes occurring in the front of stable and unstable detonation is their three-dimensional character. It is precisely this character that is illustrated in the classical photographs of the glow of spinning detonation as it exits into a large-cross-section channel obtained by R. I. Soloukhin at the very beginning of the 1960s (see Fig. 1) [9].

3. Cells in gas detonation. The past few decades have been marked by increased interest in the phenomenon of gas detonation, which was due to technological and energy challenges, as well as explosion safety in mining, new technologies, and power engineering.

The fundamental feature of the mechanism of propagation of detonation waves in all gaseous mixtures without exception is the formation of a complex cellular structure of its front. The period of repetition of the elements of the cellular structure as the detonation wave moves — the dimension of the detonation cell — plays the role of the main characteristic distance at which, due to self-organization of the flow in the wave front, local values of maximum energy release are restored and, thus, a self-sustaining propagation regime is maintained. Due to this, the length and width of the detonation cell became the main characteristic dimension for comparing the scale of observed phenomena: dimensions of chemical-reaction zones, diameters of detonation tubes and charges, geometric dimensions of the channels, and energy-distribution zones during initiation. The average dimension of the cell continues to play the role of a determining linear scale and in nonstationary motion of the detonation wave as a whole, e.g., in critical phenomena of passage from a narrow channel to a wide one and initiation of gas detonation. In this connection, the development of three-dimensional concepts of the flow structure and energy release in the detonation-wave front and diagnostic methods for three-dimensional structures in nonstationary flows (investigations by O. V. Achasov and O. G. Penyazkov) is quite topical both in terms of theory and many practical applications (see Fig. 1). Figure 2 shows a photograph of a

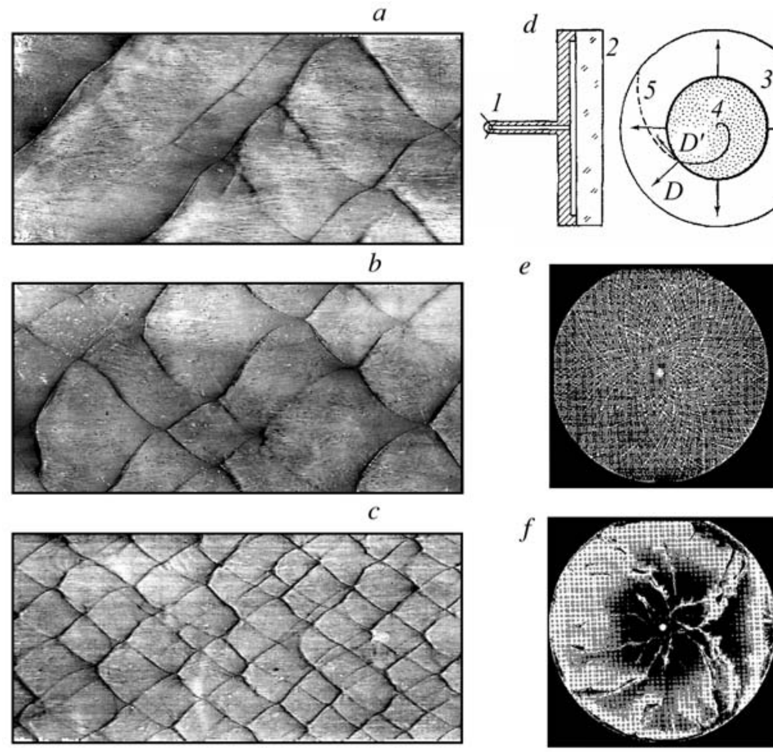

Fig. 1. R. I. Soloukhin's photographs of spinning detonation and the trace imprints of the irregular structure of the detonation-wave front in the regular (3.5% $C_2H_2 + 26.5\% \, O_2 +$ 70% Ar) mixture at different initial pressures, obtained by O. V. Achasov and O. G. Penyazkov: a) P_0 = 80.9 mm Hg; b) P_0 = 90.3 mm Hg; c) P_0 = 179.6 mm Hg; d) R. I. Soloukhin's experimental scheme [1) detonation tube with a detonator, 2) optical window; 3) divergent detonation front; 4) region of burnt gas; 5) spinning-detonation trajectory; D' and D, tangential and normal spinning-detonation velocities]; e) and f) photographs of smoldering of detonation waves, taken with an open photographic shutter, for regular and damping detonations respectively [9].

double cellular structure discovered experimentally at the Laboratory of Combustion and Detonation (LCD) at the Higher National School in Poitiers, France, under the supervision of Professors D. Desbordes and H. N. Presles. This structure is characteristic of detonating media for their two-stage chemical kinetics with strongly differing rates of chemical reactions determining the process of detonation. In these investigations, a double detonation structure was discovered in gaseous nitromethane (CH_3NO_2), and also in using an oxidant — nitrous oxide NO_2. The fast chemical reaction in this case was the formation of nitrogen oxides in the reaction $O_2 + NO_2$, and the slow one — subsequent combustion of nitrogen oxides NO.

It is noteworthy that since the 1970s R. I. Soloukhin had cooperated for many years with this laboratory — the LCD. The results of these fundamentally important investigations were reported at a Colloquium on the Physics of Shock Waves, Combustion, Detonation, and Nonequilibrium Processes devoted to the 75th birth anniversary of R. I. Soloukhin (Minsk, November 14–19, 2005) [65].

4. Burning in the internal combustion engine (ICE). Combustion is one of the most important natural processes and has been the subject of observations, investigations, and technological applications in human history. One of the most complex manifestations of combustion is detonation, which is a process of propagation, at a supersonic velocity, of a wave of chemical reaction in a fuel mixture of gases or gas suspensions. The explosion wave is accompanied by a pressure jump and transforms the original substance into chemical-reaction products within microseconds. Investigations of such processes have always been determined by urgent practical problems. The special interest in investigations of detonation is due to the discovery of the effects of space self-organization by the flow in a detonation wave leading

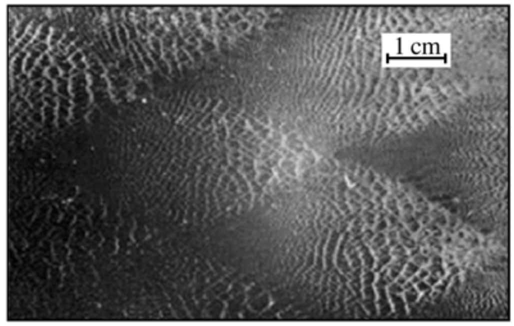

Fig. 2. Photograph of the double cellular detonation structure, obtained at the Laboratory of Combustion and Detonation[3] of the Higher National School of France in Poitiers under the supervision of Professors D. Desbordes and H.-N. Presles (see [62–65]).

to the formation of the complex three-dimensional cellular structure of the detonation wave described above, and also the phenomenon of spinning detonation and detonation in gas suspensions and porous media. Investigations of ignition and combustion of gases and gas suspensions under dynamic conditions behind transmitted and reflected shock waves have been actively conducted both in Belarus and Russia and abroad. This is due to the applied problems of creating highly efficient combustion chambers, the improvement and development of new types of internal combustion engines, the problems of suppression of detonation processes, fire and explosion safety, and many other fundamental processes in mechanics, thermal physics, and the theory of heat and mass transfer. Figure 3 shows the first results of investigations of combustion processes in the internal combustion engine, obtained using digital interferometry and speckle photography [66]. The subsequent investigations in this area conducted at the A. V. Luikov Heat and Mass Transfer Institute of the National Academy of Sciences of Belarus have recently been summarized in [67].

5. Joint investigations in cooperation with the S. A. Khristianovich Institute of Theoretical and Applied Mechanics of the Siberian Branch of the Russian Academy of Sciences. Investigations into detonation of gas suspensions were conducted at the A. V. Luikov Heat and Mass Transfer Institute of the National Academy of Sciences of Belarus in close cooperation with the Institute of Theoretical and Applied Mechanics of the Siberian Branch of the Russian Academy of Sciences. The special interest in investigations of the detonation of fuel gas suspensions is due to their wide use in industry, where similar mixtures are used as working substances in the chemical, aerospace, mining, and other industries. In particular, undesirable situations can occur here, when, under the influence of some wave action, unstable deposits of reacting dust (regular and nanosized metal particles, coal particles, and others) form a dangerously explosive and fire-hazardous mixture and are capable of reproducing detonation-like combustion conditions. To prevent these undesirable phenomena and to evaluate the effects of catastrophic explosions in industry, it is necessary to create scientific foundations of safe operation of various technical devices under conditions of a dusty atmosphere and also in porous media. This is also necessary for developing scientifically substantiated criteria for explosion and fire safety. To create them, multi-aspect investigations of this kind of phenomena were conducted for many years at the S. A. Khristianovich Institute of Theoretical and Applied Mechanics of the Siberian Branch of the Russian Academy of Sciences and at the A. V. Luikov Heat and Mass Transfer Institute of the National Academy of Sciences of Belarus; these investigations were initiated in the early 1970s by the Academician of the Russian Academy of Sciences N. N. Yanenko, Corresponding Member of the Russian Academy of Sciences R. I. Soloukhin, and the then Candidate of Sciences in Physics and Mathematics (at present, Academician of the Russian Academy of Sciences) V. M. Fomin. Doctors of Sciences A. V. Fedorov, V. M. Boiko, and G. M. Zharkova [68, 69] have taken an active part in theoretical and experimental research on problems of the mechanics of flows of reacting mixtures of gases and the dispersed phase (regular and nanosized) conducted at the Institute of Theoretical and Applied Mechanics of the Siberian Branch of the Russian Academy of Sciences under the supervision of Academician of the Russian Academy of Sciences V. M. Fomin.

At the Heat and Mass Transfer Institute of the BSSR Academy of Sciences, investigations into combustion and detonation started after Academician R. I. Soloukhin moved to Minsk from Novosibirsk in 1976 and have been

[3]See website of the Laboratory of Combustion and Detonation (LCD): http://www.lcd.ensma.fr/content/view/290/314.

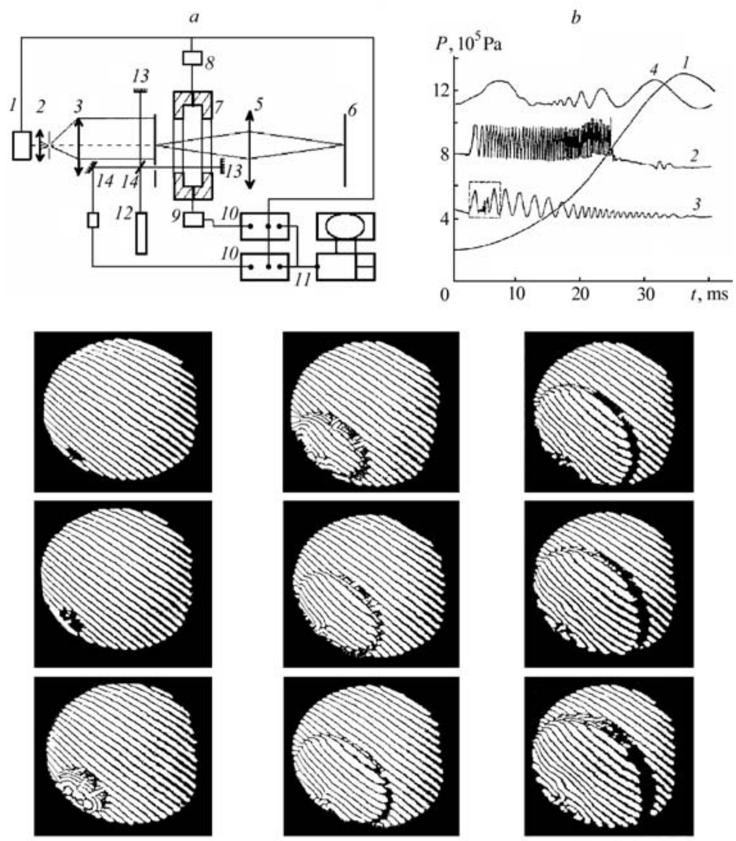

Fig. 3. Investigation of combustion processes in the ICE using digital interferometry (see [66]): a) diagram of the Michelson digital interferometer matched with the speckle interferometer [1) probing laser of the speckle interferometer, 2 and 3) collimators; 4 and 7) optical windows of the model of the combustion-chamber ICE; 5) focusing lens; 6) photorecorder; 8 and 9) pressure transducers; 10) analog-to-digital converter; 11) personal computer; 12) probing laser of the Michelson interferometer; 13 and 14) mirrors of the Michelson interferometer; 15) photodetector (photomultiplier (PM)]); b) pressure in the ICE chamber vs. time and the form of interference fringes (2–4) with different enhancement with time 2) 1:1, 3) 10:1, and 4) 100:1; c) temporal progress of the interferograms of combustion processes in the ICE chamber.

conducted to date. Belarusian scientists under the guidance of Academician R. I. Soloukhin, and subsequently his disciples — Academician of the National Academy of Sciences of Belarus S. A. Zhdanok, Professor N. A. Fomin, and Corresponding Member of the National Academy of Sciences of Belarus O. G. Penyazkov, created a powerful arsenal of pulse gasdynamic test beds on the basis of shock tubes, developed new methods of diagnostics for shock waves and detonation processes, and obtained a number of fundamentally important scientific results in investigations of regularities of high-temperature ignition and detonation combustion of reactive mixtures, and also shock-wave interaction in various channels of complex configuration. In 2009, these investigations were distinguished with the award of the Academician V. A. Koptyug Prize.

6. Development of digital methods of diagnostics for combustion processes and shock-wave processes. As has already been mentioned above, R. I. Soloukhin always gave paramount importance to physical methods of diagnostics. Even before the discovery of lasers, optical methods of diagnostics were widely used and enjoyed a well-deserved recognition in many areas of scientific research, thanks to their numerous advantages, the most important of which include the nondisturbing character of measurements, high spatial and temporal resolution, noninertia, and high accuracy and informativeness. The development of optical methods of diagnostics was given a powerful impetus by the discov-

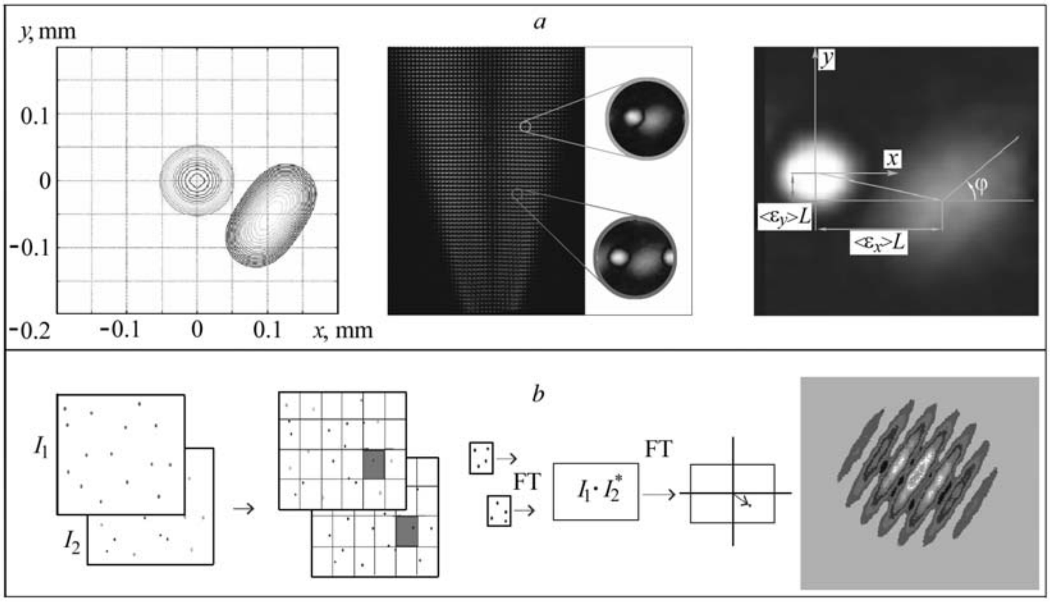

Fig. 4. Illustration of the basic steps of digital processing of talbotgrams (a) and speckle images (cross-correlation analysis of successive images using fast Fourier transformations) (b).

ery and wide introduction into practice of laser measurement systems, digital technologies for recording of images and their computer-aided statistical processing. It is with the arrival of lasers that we also saw the development of investigations into spectral diagnostics of combustion processes, and also into optical diagnostics in diffusion coherent radiation in the presence of pronounced speckle fields. This line of research in optical diagnostics turned out to be the most prepared for transition to digital systems of recording and processing of images, which introduced revolutionary changes into the potentialities of quantitative measurements and "certification" of complex three-dimensional turbulent flows in many technological processes and new technical devices that use detonation and combustion.

One convenient algorithm of digital processing of successive images I_1 and I_2 is shown in Fig. 4. The sought shift of light rays due to refraction of probing radiation in the flow under investigation is determined in each assigned averaging window using the computation of a two-dimensional cross-correlation function of these images. With account taken of experimental noise in each of these zones $\tilde{\sigma}(m, n)$, the cross-correlation function is a convolution of corresponding domains of the analyzed images:

$$\mathbb{R}_{1,2}(m, n) = I_1(m, n) \otimes I_2^*(m, n) + \tilde{\sigma}(m, n) . \tag{2}$$

Convenient for analysis is the transition to a Fourier plane, where this relation has the form

$$\mathbb{F}\left\{\mathbb{R}_{1,2}\right\}(u, v) = \mathbb{F}\left\{I_1\right\}(u, v) \bullet \mathbb{F}\left\{I_2^*\right\}(u, v) + \sigma(u, v) , \tag{3}$$

where $\sigma(u, v)$ is the corresponding noise in the Fourier plane. The strategy of subsequent cross-correlation analysis of successive images lies in searching for the function $\mathbb{R}_{1,2}(m, n)$ by means of filtration of noises of specklograms in both the initial physical and Fourier plane for each subdomain $I_1(m, n)$ and $I_2(m, n)$. The sought function can be evaluated from the relation

$$\tilde{\mathbb{R}}_{1,2}(m, n) = \mathbb{F}^{-1}\left\{\mathbb{F}\left\{\tilde{I}_1\right\}(u, v) \bullet \mathbb{F}\left\{\tilde{I}_2^*\right\}(u, v)\right\} , \tag{4}$$

where $\tilde{I}_1$ and $\tilde{I}_2^*$ are the filtered specklograms; * means complex conjugation.

The final calculation of the parameters of three-dimensional flow using the obtained experimental data always involves solution of the inverse problem of mathematical physics. Thus, in measuring the parameter $f(\vec{r}, t)$, with al-

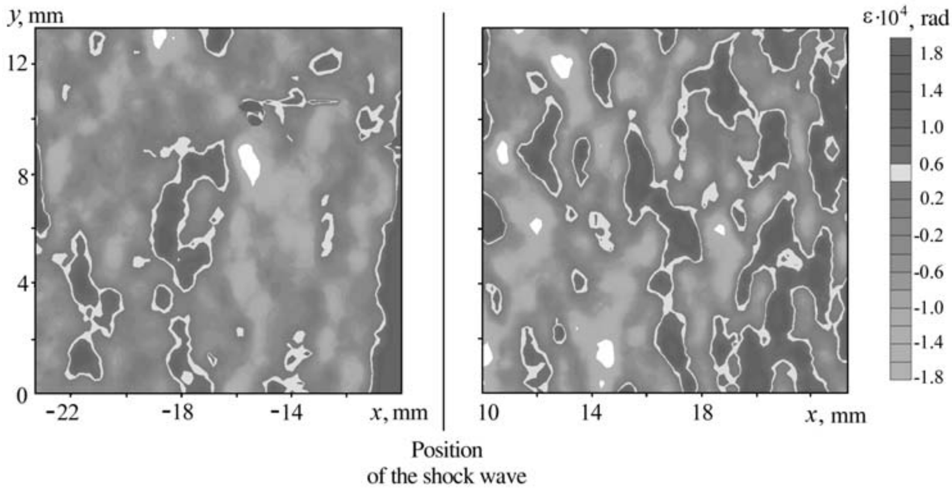

Fig. 5. Changes in the coherent structures in turbulent flow on passage of the shock wave, which have been obtained in determining turbulence parameters using the integral Erbeck–Merzkirch transformation [71].

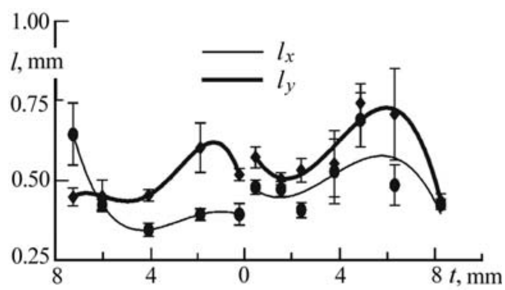

Fig. 6. Changes in Kolmogorov's spatial microscale on passage of the shock wave, which have been obtained in determining turbulence parameters using the integral Erbeck–Merzkirch transformation [71].

lowance for the finiteness of temporal and spatial resolution and for the error ε_f, one determines the integrated quantity (reaction) $R = \int f(\vec{r},\ t)d\vec{r}dt + \varepsilon_f = \Re\ \{f(\vec{r},\ t)\} + \varepsilon_f$. Here integration is in the limits of resolution of the experimental scheme. The sought parameter, to be more specific, its estimate $\hat{f}(\vec{r},\ t)$, is reconstructed by solution of the inverse integral relation: $\hat{f}\ (\vec{r},\ t) = \Re^{-1}(R)$ [70, 71].

In a series of recent publications, the correctness and accuracy of such a reconstruction have been analyzed as applied to determination of both the averaged and pulsation characteristics of three-dimensional turbulent flows by the laser-probing method; also, the results of direct numerical simulation of the interaction of laser radiation and different combined flows have been given. Certain experimental and simulation results are also used to illustrate the reconstruction of three-dimensional flows in recording images with the above-described digital laser technologies (see Figs. 5 and 6).

7. Filtration combustion and detonation in gases are comparatively new divisions of the science of combustion, detonation, and explosions, studying the combustion of gaseous mixtures under filtration conditions (thermal and hydrodynamic interaction with the solid phase) and combustion-to-detonation transition. The distinctive features of such two-phase heterogeneous media are spatial heterogeneity, unsteadiness, and complex hydrodynamics. However, the steady growth in the past two decades in the capabilities of computational physics and accumulation of experimental data and physical knowledge in this field have made it possible to considerably refine the understanding of a wide range of issues of filtration combustion of gases. It is well known that the detonation velocity in a porous medium is generally much smaller than the Chapman–Jouguet detonation velocity, and this difference increases with decrease in the initial pressure of the fuel mixture. The mechanisms of initiation and transfer of ignition to a porous medium significantly differ from combustion in free space. The reason for this difference is that a porous medium is characterized by a higher coefficient of hydraulic resistance of the medium and a higher thermal-loss level, which leads to a substantial loss of momentum and energy from the wave front and to a strong turbulization of the gas flow. In the general case, the mechanism of propagation of deflagration in a porous medium includes the processes of adiabatic heating and ignition of the mixture behind the shock wave and elementary processes of convective energy and diffusion transfer and of heat exchange between the gas and the porous body, which are still only slightly understood. At low propagation velocities, we have initiation due to the penetration of the burning gas from the adjacent pores and to the acceleration of the flame front in interaction with the reflected shock waves followed by the self-ignition of the compressed mixture. As the velocity increases, the gas begins to ignite mainly as a result of adiabatic compression behind the reflected shock waves.

A wide class of unsteady processes, related to the phenomena of passage and reinitiation of detonation, can also appear when combustion waves from a porous medium pass to free space. Normally, the formation of detonation in tubes and closed volumes is often preceded by the formation of a shock wave, whose intensity is maintained by the combustion-wave front. The velocity of propagation of the flame front and the flow behind the bow shock wave, which is attained by the time of establishment of detonation, is nearly coincident with the velocity of sound in combustion products. It is well known that an efficient method for increasing rapidly the flow velocity is injection of hot jets into the unreacted mixture. Such injection, under supersonic-outflow conditions, is accompanied by the formation of the bow shock wave related to the turbulent-flame front. Furthermore, the local regions of stagnation of the flow due to the reflections of the shock wave from the bounding walls and to the interaction of transverse waves give rise to zones of increased energy release, i.e., "hot spots." The local growth in the temperature and pressure in these spots considerably diminishes delays of ignition of the mixture and can maintain the intensity of the "shock wave–flame front" system with expansion of the mixture in the volume of the basic combustion chamber. Thus, the mechanism of formation and multiplication of "hot spots" makes it possible to largely force, in certain cases, the process of passage and reinitiation of the detonation wave.

The effect of initiation by hot jets is greatly enhanced in the case of their spatial distribution. The simplest model of such an initiator can be based on the concept of "porous combustion." In porous media, the flame can rapidly be accelerated to supersonic velocities, whereas passage of the formed quasidetonation into the volume occupied by the fuel mixture can stimulate the development of explosion phenomena. For certain practical applications, it is pressing to evaluate conditions necessary for successful transition to detonation, which is dependent on both the characteristics of the fuel mixture and the parameters of the porous medium. Furthermore, this requires that simplified engineering approaches to calculation of the critical initiation conditions be developed.

Experiments have shown that in reflection of the shock wave in a hollow tube, the induction-zone length is 20 to 80 mm in mixtures with a 25% and 50% dilution with nitrogen. Since the level of initial pressure of the mixture at the same quasidetonation velocity in a porous medium is much lower (see Fig. 7) and the induction time in the first approximation is in inverse proportion to the mixture's pressure, extrapolation of measurements of the induction length in the hollow tube to the corresponding conditions and velocities of detonation in the porous medium gives values of ≈40–160 mm. This means that over the period between the compression and heating of the mixture in normal reflection of the shock wave in the porous medium and self-ignition of the mixture, the quasidetonation front has time to cover a distance of 1–5 tube diameters or ≈80 pore sizes. At the same time, a comparison of the signals of pressure and those of ionization gauges shows that the distance between the shock wave and the reaction front does not exceed a value of 1.5–3 mm or 1–2 pore sizes. This result is evidence that self-ignition of the mixture by the mechanism of normal reflection of the shock wave is inadequate to sustain the mechanism of propagation of detonation in the porous medium near the pressure limits.

Thus, at the A. V. Luikov Heat and Mass Transfer Institute of the National Academy of Sciences of Belarus, detonation velocities of the porous medium have been measured for a wide range of initial pressures in the stoichiometric acetylene–oxygen mixture with different degrees of dilution with nitrogen. It has been shown that the wave velocity can take on values from $0.3V_{\mathrm{C-J}}$ in a less sensitive acetylene–air mixture near the propagation limit ($V_{\mathrm{C-J}}$ is the Chapman–Jouguet velocity of propagation of the wave) up to the detonation velocity in an acetylene–oxygen mixture at atmospheric pressure. Realization of one velocity regime or another is determined by the ratio of the critical detonation-tube diameter, which is a function of the mixture's initial pressure, to the average pore size. These

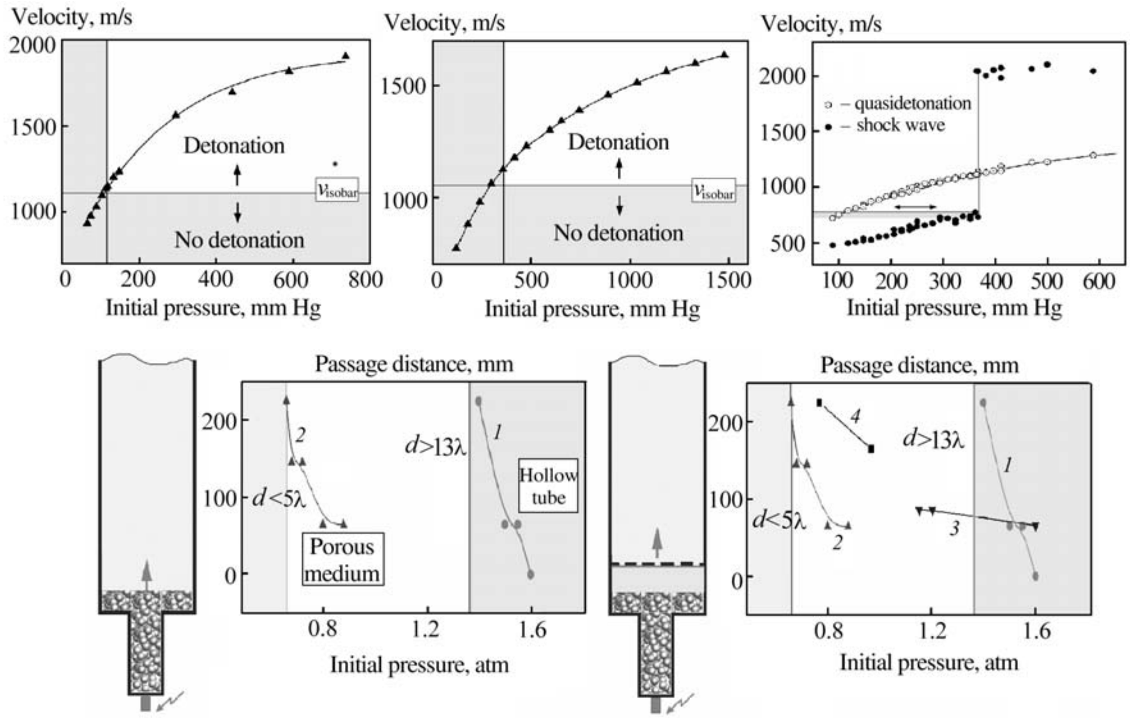

Fig. 7. Evolution of the detonation velocity for different pressures and scenarios of escape of detonation from a porous medium to a channel of constant cross section.

works were carried out with the participation of O. G. Penyazkov, K. L. Sevruk, P. N. Krivosheev, N. L. Evmenchikov, and many others (see [46–55, 68, 69].

8. Generation of nanoparticles in nonequilibrium flows. Shortly after the discovery of fullerenes (C60) by the group of Smalley, Kroto, and Curl in 1985, for which these scientists were awarded the Nobel Prize in chemistry in 1996 [72], and multilayer carbon nanotubes by Ijiima in 1991 [73],[4] investigations of the means of commercial production of different nanomaterials by gasdynamic methods were began under the guidance of Academician S. A. Zhdanok at the A. V. Luikov Heat and Mass Transfer Institute of the National Academy of Sciences of Belarus [74]. By then, one already knew of the methods of production of carbon nanomaterials in an electric arc, in laser ablation of graphite, in the process of chemical gas-phase deposition, and others [75–77]. New methods of production of carbon nanomaterials in a low-temperature plasma have been proposed in the works of A. V. Krauklis and associates. The original method of production of multiwall carbon nanotubes and nanofibers in decomposition of hydrocarbons in an atmospheric-pressure, high-voltage discharge has been described in [78]. In this work, it has been shown that the formation of carbon nanomaterials on treatment of a methane–air mixture by the plasma of an atmospheric-pressure, high-voltage discharge occurs on the metal surface and is similar to the processes of catalytic decomposition of hydrocarbons by the mechanism of a carbide cycle. The influence of the additional magnetic field on the processes of production of carbon nanomaterials in an atmospheric-pressure, high-voltage discharge has been investigated in [79]. It has been shown that the superposition of a magnetic field leads to a 10–30% increase in the yield of a carbon nanomaterial. In this work, it was assumed that the atomic-carbon source can be the reaction involving vibrationally highly excited CO molecules:

$$\mathrm{CO}(v) + \mathrm{CO}(w) \Leftrightarrow \mathrm{CO}_2 + \mathrm{C}\,, \quad E(v) + E(w) \geq 5.5\ \mathrm{eV}\,. \tag{5}$$

[4]In Gibson's work (J. A. E. Gibson. Early nanotubes? Nature. 1992. Vol. 359. P. 369) it is stated that nanotubes were observed as early as 1953.

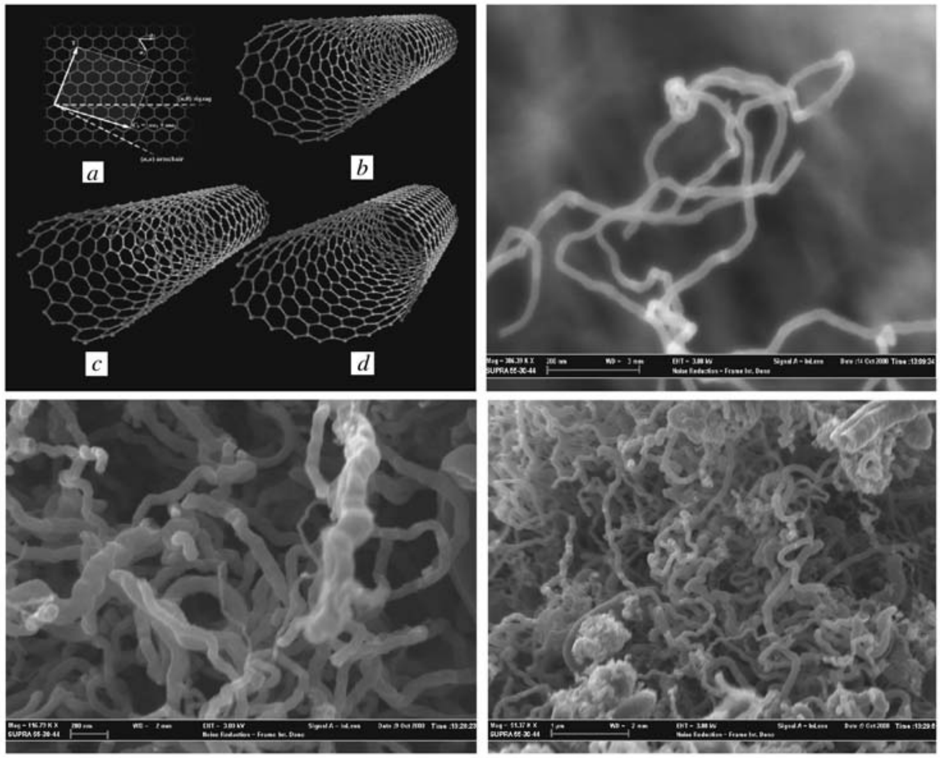

Fig. 8. Nanotube structure [a) structure of the nanotube surface, b and d) chiralities (0.10) (b), (7, 10) (c), and (10, 10) (d)] and samples of nanostructures obtained at the Heat and Mass Transfer Institute of the National Academy of Sciences of Belarus [78–83].

In [80, 81], a 30-kW dc plasmatron with a hollow copper anode and a copper cathode with a hafnium insert was used. A propane–butane mixture with air was fed to the plasmachemical reactor. The yield of carbon nanomaterial was 100 g/h for an average structuring of the material of 40%. The analysis has shown that the carbon nanomaterial contains fibers with a characteristic diameter of 300 nm or higher and multiwall carbon nanotubes of diameter 50–70 nm with a length of up to 1 μm. Optimization of the unit made it possible to increase the yield of the carbon nanomaterial to 150 g/h with a structuring of the material of up to 50% [81]. In [82, 83], ordered nanosize structures were produced by plasmachemical synthesis on a catalytic substrate at a reduced temperature (200^{o}C). In these works, the carbon-containing mixture was activated by the plasma of a pulsed barrier discharge at atmospheric pressure. In [83], it has been shown that bush-like masses of loosely packed carbon nanotubes of equal diameter (of the order of 60 nm) are formed on the surface of a nickel substrate by the activating action of a glow-discharge plasma. The tube length is relatively small, but individual nanotubes may be as long as 300 nm. The photographs of the characteristic nanotubes produced at the A. V. Luikov Heat and Mass Transfer Institute illustrate possible nanotube structures, too (Fig. 8). Theoretical issues of formation of a nanofiber from a nanodroplet have been considered in [84]; an attempt to analyze the statistical properties of nanostructures based on an analysis of speckle fields formed as a result of the scattering of probing coherent radiation on nanofibers has been made in [85].

An ideal nanotube represents a graphite plane rolled into a cylinder, i.e., a surface made of regular hexagons at whose vertices there are carbon atoms. The results of such an operation is dependent on the angle of orientation of the graphite plane relative to the nanotube axis. The angle of orientation in turn assigns the chirality of the nanotube, which determines, in particular, its electric characteristics [81]. The nanotube chirality is denoted by a set of symbols (m, n) indicating the coordinates of a hexagon that, as a result of the rolling of the plane, should be coincident with the hexagon in the origin of coordinates. The indices of chirality of a single-layer nanotube (m, n) unambiguously determine its diameter D. Standing out among various possible directions of rolling of nanotubes are those for which bringing the hexagon (m, n) into coincidence with the origin of coordinates does not require its structural distortion.

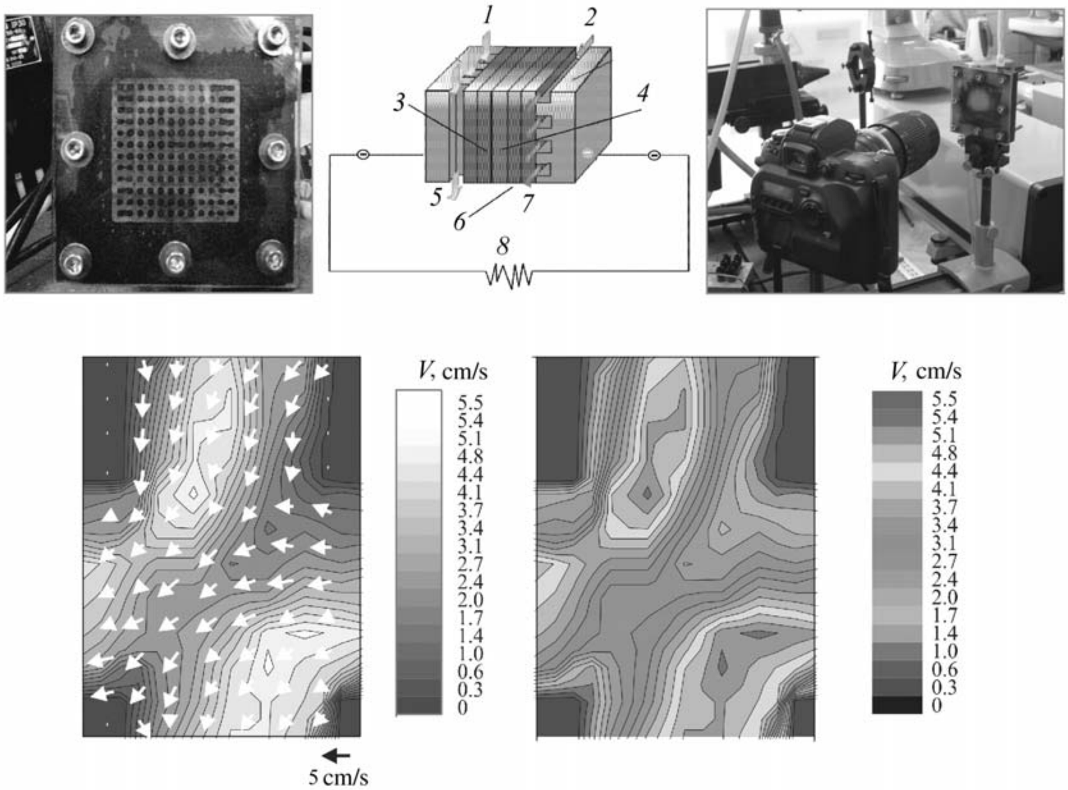

Fig. 9. Speckle photograph of the velocity field in the fuel-cell model [87]. Top: the photograph and geometry of the channels of the PEM-fuel-cell assembly (1) fuel (hydrogen) feed; 2) oxidant (air or oxygen) feed; 3) anode with a platinum catalyst inducing the decomposition of hydrogen into positively charged ions (protons) and electron; 4) PEM transmitting only positively charged ions; 5) water formed on the cathode as a result of the recombination of charged reaction products; 6) cathode; 7) yield of the unused oxidant; 8) load; on the right, photograph of the experiment. Bottom: velocity isolines in the highlighted fragment in black and white representation (left) and in quasi-color (right).

The technology of nanotube production is rather difficult; therefore, high-grade nanotubes are an expensive material at present: one gram costs several hundred U.S. dollars. The A. V. Luikov Heat and Mass Transfer Institute of the National Academy of Sciences of Belarus is the largest patent holder on methods for producing nanotubes and is implementing commercial projects on manufacturing units for production of carbon nanomaterials. A. V. Krauklis, V. F. Buyakov, S. P. Fisenko, and many others are taking an active part in these projects.

9. Hydrogen power engineering and other topical problems of physical gasdynamics. Hydrogen power engineering is a developing branch of power engineering, which is based on utilization of hydrogen as an environmentally clean heat-transfer agent for accumulation, transportation, and consumption of energy by people, transport infrastructure, and various productions. Hydrogen has been selected as the most widespread element on the Earth's surface and in space, the combustion heat of hydrogen is the highest, and the product of combustion in oxygen is water, which is returned to the process of hydrogen power engineering again. Hydrogen power engineering is a multidisciplinary science and its progress is determined by the development of many of the above trends in today's physical gasdynamics. In Byelorussia, the pioneering investigations on obtaining hydrogen and oxygen from water using the energy of nuclear reactors were initiated by Academician of the BSSR Academy of Sciences A. K. Krasin in 1971–1972 at the Laboratory of Hydrogen Power Engineering at the Institute of Atomic Power Engineering of the BSSR Academy of Sciences. In 1977, on R. I. Soloukhin's initiative, this Laboratory under the guidance of Corresponding Member of the BSSR

Academy of Sciences L. I. Kolykhan, moved to the A. V. Luikov Heat and Mass Transfer Institute of the BSSR Academy of Sciences. Since 2003, these investigations at the Institute have considerably been extended within the framework of the State programs "Vodorod" under the supervision of Academician S. A. Zhdanok [86].

Doctors of Sciences I. G. Gurevich, V. G. Minkina, and K. V. Dobrego, Candidates of Sciences N. B. Bazylev, S. A. Filatov, S. I. Shabunya, Yu. M. Dmitrenko, A. N. Migun, and many others are taking an active part in these works [50, 53–55, 87].

Figure 9 shows results of investigations of the flow field in a fuel cell, which have been obtained by the method of digital laser speckle photography. These experiments were conducted together with the Laboratory of Thermal Processes of the Higher National School of France on Mechanics and Aerodynamics (Ecole Nationale Supérieure de Mécanique et d'Aérotechnique) in Poitiers. From these data, the vorticity field was calculated in each cell of flow. An analysis shows that vorticity is mainly generated in wall flows. Despite the fact that the integral of vorticity over the field is generally small, the intensity of positive vortices in the highlighted fragment is appreciably higher. The evolution of this quantity with flow is a convenient parameter characterizing the flow structure and allowing detailed comparisons to the results of numerical simulation of operating regimes in a PEM (photon-exchange-membrane) fuel cell. The developed software makes it possible to reconstruct up to 250,000 velocity vectors in a two-dimensional 20 $\times$ 30 mm flow region in photographing with optical magnification $M = 1$, which ensures a spatial resolution of about 100 μm. The dimension of the region under study can be diminished and spatial resolution can be improved 10–100 times using the corresponding microoptics and optical magnification. The use of tomographic techniques of reconstruction of such combined flows for obtaining three-dimensional fields is the objective of subsequent investigations.

Conclusions. Analyzing the development of R. I. Soloukhin's works at the A. V. Luikov Heat and Mass Transfer Institute of the National Academy of Sciences of Belarus, we cannot but point to the high level of works on computational physical gasdynamics at the Laboratories of Turbulence, Mathematical Modeling, Radiation Gas Dynamics, and some others. In addition to the above-noted specialists in radiation gasdynamics — F. B. Yurevich, G. S. Romanov, V. V. Kondrashov, M. N. Rolin, and E. F. Nogotov — that high level is being maintained today by V. A. Babenko, A. D. Chornyi, S. I. Shabunya, V. V. Martynenko, K. L. Stepanov, Yu. A. Stankevich, F. N. Borovik, and A. S. Smetannikov (see [17, 18, 19–21, 87–90]). A number of other promising lines of investigations at both the Heat and Mass Transfer Institute and partner organizations, initiated by R. I. Soloukhin, have been analyzed in collected papers [91] devoted to his 75th birth anniversary.

The authors express their thanks to Academicians S. A. Astapchik, V. S. Burakov, and O. G. Martynenko, Corresponding Members of the National Academy of Sciences of Belarus V. A. Borodulya, V. L. Dragun, N. V. Pavlyukevich, and S. A. Chizhik, Professor S. P. Fisenko, Doctors of Sciences P. P. Khramtsov and K. V. Dobrego, and Candidates of Sciences A. V. Krauklis, S. I. Shabunya, I. F. Buyakov, K. L. Stepanov, and S. A. Filatov for useful discussions, assistance in the work, and valuable recommendations.

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