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110 YEARS OF EXPERIMENTS ON SHOCK TUBES

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A brief account of the history of development of shock tubes throughout the world, the USSR, and Belarus is given. The principle of operation of a shock tube and some results for high-temperature gasdynamics obtained on shock tubes in the past years are shown. In these studies, the role of Rem Ivanovich Soloukhin is noted as a pioneer of experiments on shock tubes at the G. M. Krzhizhanovskii Institute of Power Engineering (1953–1958), the Siberian Branch of the Academy of Sciences of the USSR (from 1959), and in Belarus (from 1976).

Keywords: *shock tube, shock wave, experiment, optical diagnostics, gasdynamic lasers, plasma, high-temperature gasdynamics, nanoparticle generation, detonation, laser spectrograph.*

First Steps of Shock Tube Engineering. Interest in studying high-temperature gasdynamics on shock tubes has still not weaked in more than a hundred years. This is explained by the simplicity and reliability of shock tubes, which were invented about 110 years ago. The use of shock tubes allows one, with the aid of simple technical devices, to vary the temperature and pressure of the working gas over a wide parametric range and conduct investigations of high-temperature processes for various gases. The first shock tube was constructed by Paul Vieille[1] while studying combustion and detonation in tubes in 1899 [1, 2].

This discovery was brought about by experiments of the French physicists Mallard, Le Chatelier, Berthelot,[2] and Vieille himself, who as early as 1881 detected the deflagration–detonation transition in the flame propagation in tubes filled with a combustible mixture. Thus, a more complex phenomenon — the merging of a shock wave with a combustion wave and the formation of the detonation front — had been detected even earlier than they learned how to generate a shock wave in neutral gases. The diameter of the first shock tube was 22 mm, the channel length was 6 m, and the length of the measuring section was 271 mm. Cellophane, paper, and metal foil were used as the diaphragm materials. The most reproducible were experiments with cellophane diaphragms, which at 0.11 and 0.29 mm thicknesses broke at pressures in the high-pressure channel of 27 and 16 atm, respectively. In the low-pressure channel there was air at atmospheric pressure. Here a shock wave was recorded with a Mach number of about two. Shortly afterward, basing himself on Hugoniot's[3] studies [3, 4] and investigating pneumatic brake systems of railroad coaches, the Austrian scientitist Kobes developed the theory of origination of a shock wave [5]. Kobes' work prompted Hubert Schardin[4] to construct a 10 m long shock tube in 1932 [6]. Most importantly, by that time Cranz and Schardin had already developed an optical system that allowed recording fast processes while modeled on a shock tube and visualizing invisible shock waves [7].

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[1]Paul Marie Eugène Vieille (1854–1934), French engineer, graduate of the Polytechnic School, inventor of smokeless powder (1884), founder of the Central Laboratory of Powders in Salpetres, Paris ("Laboratoire Central des Poudres et Salpêres", et Paris). The invited Paul Vieille Lecture is delivered at International Symposia on Shock Waves (ISSW) (see below).

[2]Francois Ernest Mallard (1833–1894), Henri Louis Le Chatelier (1850–1936), and Marcellin Pierre Eugène Berthelot (1827–1907), French Physicists-engineers, pioneers of the investigation of gas detonation.

[3]Pierre-Henri Hugoniot (1851–1887), French engineer, graduate of the Polytechnic School, specialist in marine artillery.

[4]Hubert Reinhold Hermann Schardin (1902–1965), German ballistics engineer, developer of optical diagnostic methods and systems of photographic recordings of fast processes. He was the first director of the German-French Research Institute in Saint Louis and the founder and leader of the Fraunhofer Research Institute of Dynamics of Fast Processes (Fraunhofer-Instituts für Kurzzeitdynamik) and the Ernst Mach Institute in Freiburg.

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Studies of the British scientists Payman and Shepherd [8–13] concerning detonation processes in tubes in connection with the problem of explosion danger in UK mines also led to designing a "pure" shock tube, in which a shock wave is initiated on breaking of the diaphragm separating neutral gases in high- and low-pressure channels [13]. In these works, diagrams made of thin sheet copper were used. In the 1940s, British experience enabled U.S. and Canadian scientists to construct a whole series of shock tubes and to begin investigations of hypersonic gasdynamics using them [14–29]. By the early 50s, shock tubes were successfully employed at several universities and governmental laboratories (such as Princeton, Michigan, Toronto, Cornell, Lehigh, Johns Hopkins, NASA, NOL, and other institutions; see the fundamental manual [14] and reports of 1943–1950 cited in it). Pioneers in mastering shock tube engineering in the North American continent were Walker Bleakney[5] and his colleagues at Princeton University [15, 16, 18], Raymond Emrich at Lehigh University [27–29], Irvine Glas in Toronto [14, 22], Otto Laporte[6] [25], Abraham Taub[7], Abraham Hertzberg[8] [17], and many others. At the same time, works on shock tubes were continued in Europe, where, specifically, in 1952 B. D. Henshall defended a doctoral dissertation on the same topic at Bristol University (Great Britain) [30] and shock tubes were constructed in France[9] and in Germany, where shock tube engineering continued to develop under the guidance of H. Schardin [31], as well as in Japan [32], Israel [33], the Republic of South Africa, Romania, and other countries. The Bristol shock tube [30] came to be the first and most probably the only one made analogously with rosewood wind tunnels. The First Symposium on Shock Tubes held under the auspices of the U.S. Air Force and Navy in Boston in 1957 may be considered as the completion of the first step of the development of shock tube engineering. Beginning 1967, the Symposium became international and has been held every two years for as long as 50 years (see below).

R. I. Soloukhin's First Experiments on Shock Tubes. Four years short of the First Symposium on Shock Tubes, in 1953 in works on the development and use of shock tubes, a student of the Department of Molecular Phys-

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[5]Walker Bleakney (1901–1992), American physicist, pioneer of the development of shock tube engineering in the U.S., under whose guidance shock waves were investigated in the U.S. during World War II. Bleakney is called the "inventor" of the shock tube engineering in the U.S. In 1941, under Bleakney's guidance, a proving ground was set up based at Princeton University for studying the destructive effect of shock waves. In studying the Mach reflection of a shock wave, for dynamic calibration of pressure pickups Bleakney used a copper cylinder with a breaking diaphragm which separated gases with different pressures. After a discussion with theoretician A. Taub (see below), Bleakney realized that he had manufactured a shock tube. His first shock tube was 3 inches in diameter. Subsequent shock tubes at Princeton had larger diameters and were fitted out with optical windows. Using an interferometer, Bleakney followed the twisting of compression waves and the formation of shock waves. In 1959, W. Bleakney was voted into the National Academy of Sciences of the USA and 1963, into the American Academy of Arts and Sciences.

[6]Otto Laporte (1902–1971), American physicist, specialist in quantum mechanics, propagation of electromagnetic waves, spectroscopy, and gasdynamics. The American Physical Society instituted the annual Otto Laporte Award. In 1973, the invited Otto Laporte lecture was established at the International Symposia on Shock Waves (ISSW) (see below) for studies in the field of shock waves. The first Otto Laporte lecture was delivered by R. I. Soloukhin at ISSW 15 held in the U.S.

[7]Abraham Haskel Taub (1911–1999), American physicist and mathematician, specialist in differential geometry, general relativity theory, and applied mathematics. From 1942 he worked at Princeton with Walker Bleakney. With the aid of a shock tube he studied destructive effects of explosive shock waves on structures. He developed the theory of shock tubes in the U.S. Together with von Neumann he "discovered" the Mach reflection behind a shock wave. In 1946, for his defense-related works Abraham Taub received the Presidential Certificate of Merit.

[8]Abraham Hertzberg (1922–2003), American physicist, Professor in Aerophysics, inventor. In 1943 he received the diploma of the Polytechnic Institute in Virginia, worked on probation at Cornell University and from 1950 worked at the Cornell Aeronautical Laboratory. Abraham Hertzberg initiated works on high-power lasers in the U.S. From 1966 he worked at Washington University, Seattle.

[9]Specifically, at the French-German Research Institute in Saint Louis, at the Higher School of Mechanics and Aerodynamics of France in Poitiers under the guidance of Prof. N. P. Manson, at Orléans University under the guidance of Prof. J. Combourieur, a pupil of one of the pioneers of the detonation study in France Prof. P. Laffitte, and at Aix-en-Provence University (Marseilles) under the guidance of Prof. R. Brun.

ics[10] of the Physical Department of Moscow State University, Rem Ivanovich Soloukhin (1930–1988), who was sent for prediploma practice to the G. M. Krzhizhanovskii Institute of Power Engineering, the Laboratory of Combustion Physics,[11] began to actively participate. Under the guidance of T. V. Bazhenova, R. I. Soloukhin, and S. G. Zaitsev started dynamic calibration of the pressure pickup on the setup of O. A. Tsukhanova and G. D. Salamandra designed for studying detonation formation. At the same time, several students of Moscow State University and the Moscow Physics and Technology Institute, among them I. M. Naboko and L. G. Gvozdeva, carried out diploma works at the Laboratory. In the course of this study, a shock tube was independently invented in the USSR. Pressure pickups were calibrated using a shock wave in air that was generated in the tube ahead of the moving pistol. The pistol was set in motion by explosion of an oxygen–hydrogen mixture that took up the space behind the pistol, which was separated from it by a film diaphragm. At one time, they forgot to mount the pistol, but after explosion a distinct shock wave in air was produced, which, of course, was recorded on the photosweep. Thus, unlike the studies of Mallard et al. (see above), who certainly observed a shock wave when investigating detonation in tubes, in R. I. Soloukhin's experiment a shock wave was formed as a result of the breaking of a diaphragm separating high-pressure and low-pressure channels, as was also the case with experiments conducted by Paul Vieille [1, 2]. Shock-tube engineering, which was then being actively developed in the U.S., became known in the USSR later. The first symposia on shock tubes were held in the U.S. under the auspices of NATO under the conditions of secrecy, and shock-tube engineering was discovered in the USSR independently. The author of this discovery was a student, R. I. Soloukhin. The first of Soloukhin's works on shock tubes was published exactly in 1957 in the proceedings of the 4th Conference of Young Scientists of the Scientific-Research Institute of Power Engineering [34, 35]. Very symbolically, this conference was held in the same year as the First Symposium on Shock Tubes that was closed to Soviet scientists. In 1967, the regular Symposium on Shock Tubes received international status and was, for the first time, held beyond the U.S., in Freiburg (Germany). Immediately on completion of this Symposium, many participants decided to continue discussions on the problems of high-temperature gasdynamics, including those with the use of shock tubes, in a more "open" atmosphere with the participation of USSR specialists. Bruxelles was chosen as the location of the meeting.[12] Thus, the International Colloquium on the Gasdynamics of Explosions and Reactive Systems — ICOGERS[13] — was organized, which, starting in 1967, was held every two years, immediately following the International Symposium on Shock Tubes.[14] The organizers of the Colloquium were Prof. N. P. Manson (France), A. K. Oppenheim (the U.S.), and R. I. Soloukhin (the USSR)[15].

Development of Shock Tube Engineering in the USSR. In 1954, R. I. Soloukhin performed diploma work on the formation of a shock wave with an electric discharge in water. He filled the section designed for studying gas detonation with water and obtained high-quality Töpler patterns of a train of waves initiated by an electric discharge, and also followed the formation of a shock wave from them. Afterward these experiments were conducted in large reservoirs with measurement of the pressure field. These works were published much later [36].

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[10]The Chair of Molecular Physics was set up in 1931 and is one of the oldest at the Physical Department. Its founder and first head was Professor, Corresponding Member of the USSR Academy of Sciences (from 1939) Aleksandr Savvich Predvoditelev (1891–1973).

[11]This Laboratory was also headed by A. S. Predvoditelev.

[12]Bruxelles Free University (Université Libre de Bruxelles) founded in 1834.

[13]Now the Colloquium is called the International Colloquium on the Dynamics of Explosions and Reactive Systems and is held under the auspices of the International Institute of the same name. The second Colloquium took place in Novosibirsk and gathered many scientists from the USSR, who by that time had mastered shock-tube engineering. In subsequent years, two more Colloquia were held in the the USSR and CIS — the 8th in 1981 and the 22nd in 2009, both in Minsk.

[14]Now this Symposium is called the International Symposium on Shock Waves and is held under the auspices of the International Institute of Shock Waves. The last, 27th, Symposium took place in St. Petersburg in 2009.

[15]The triad of prominent scientists in the field of physics of combustion and explosion, detonation, and shock waves — N. P. Manson. A. K. Oppenheim, and R. I. Soloukhin — were called the three musketeers by colleagues, implying their constant readiness to start a scientific discussion and their ability to always find the simplest solution of complex scientific problems.

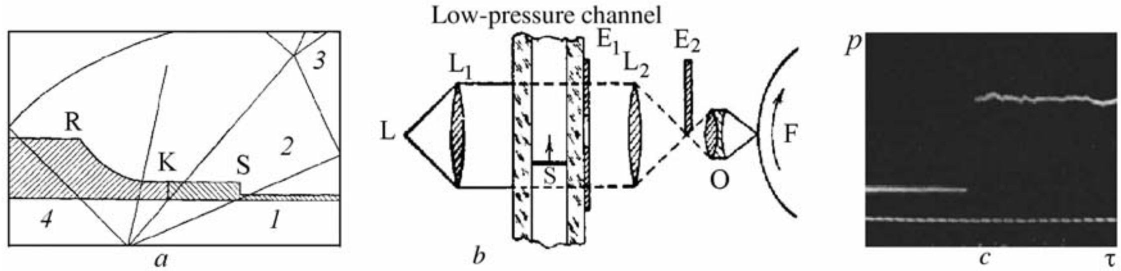

Fig. 1. Flow diagram in a shock tube (a): S, front of the shock wave; K, contact surface; R, rarefaction wave; 1) initial state of gas ahead of the shock wave in the low-pressure channel, 2) state of gas behind the incident shock wave, 3) state of gas in the high-pressure channel, 4) initial state of gas in the low-pressure channel. Soloukhin's original scheme of compensation of the shock wave movement [66] (b): L, light source; L_1 and L_2, collimator lenses; E_1 and E_2, screens; O, lens focusing the image into the film; F, moving film. Pressure oscillogram obtained using the sensor manufactured by R. I. Soloukhin (c).

By the late 50s, shock tube engineering was actively being developed in several scientific centers of the USSR. By this time, shock tubes successfully operated at Moscow State University [37–42], the G. M. Krzhizhanovskii Institute of Power Engineering, the Institute of High Temperatures of the USSR Academy of Sciences[16] [43–45], the N. N. Semyonov Institute of Chemical Physics [46, 47], the A. F. Ioffe Leningrad Physics and Engineering Institute [48], the Novosibirsk Science City (Akademgorodok) [49–51], and in other scientific centers [52–60]. In 1962, on the initiative of Academician G. I. Petrov,[17] the Laboratory of Kinetic Processes in Gases was set up at the Institute of Mechanics of Moscow State University; for many years it was headed by Soloukhin's friend and associate — Prof. S. A. Losev [38–42].

Optical Diagnostics of Shock-Wave Processes. Starting with the first photograph of a shock wave ahead of a bullet flying at a supersonic speed, which was obtained by Ernst Mach[18] and Russian marine artilleryman Peter Salcher at Vienna University in 1887 [61], and with W. Bleakney's first interferograms of the formation of a shock wave, the optical diagnostics of shock-wave processes has always played a determinant role in experiments on shock tubes. This is especially clearly demonstrated by the work of R. I. Soloukhin, who used a wide range of optical diagnostic methods beginning with his very first studies. In 1995, Soloukhin enrolled in courses of postgraduate training and continued to work, at the G. M. Krzhizhanovskii Institute of Power Engineering, on the problem of detonation formation during the propagation of shock waves in a combustible gas mixture. In cooperation with T. V. Bazhenova and S. G. Zaitsev, he conducted pioneering experiments to study ignition of explosive and combustible mixtures in a shock tube [36, 37].

[16]In 1967, the Combustion Laboratory of the G. M. Krzhizhanovskii Institute of Power Engineering was transferred to the Institute of High Temperatures of the USSR Academy of Sciences, where on its basis the Laboratory (since 1975, the Department) of Physical Gasdynamics was set up. In 1994, the Department formed part of the Institute of Thermophysics of Extreme States of the Joint Institute of High Temperatures, Siberian Branch of the Russian Academy of Sciences.

[17]Georgiy Ivanovich Petrov (1912–1987), graduate of the Mechanical Mathematical Department of Moscow State University (1935). He worked in the laboratory of the Central Aerodynamic Institute headed by Academician S. A. Chaplygin. In 1944 he was transferred to the Scientific-Research Institute NII-1, where, while working under the scientific guidance of Academician M. V. Keldysh, he headed the department in which investigations of the deceleration of a supersonic flow in the entry divergent channels of ramjet engines and heat transfer and heat shielding of bodies moving in atmosphere at high supersonic speed are carried out. These studies were conducted in collaboration with workers of the S. P. Korolyov and S. A. Lavochkin Design Offices. Under the guidance of G. I. Petrov, a unique experimental base was set up at the NII-1, which provided data used by him and his pupils for developing methods of heat shielding of first domestic reusable spacecraft.

[18]Ernst Mach (1838–1916), Austrian physicist born in Moravia, was graduated from Vienna University in 1860 where, from 1895 to the end of his life, he was Professor of History of science.

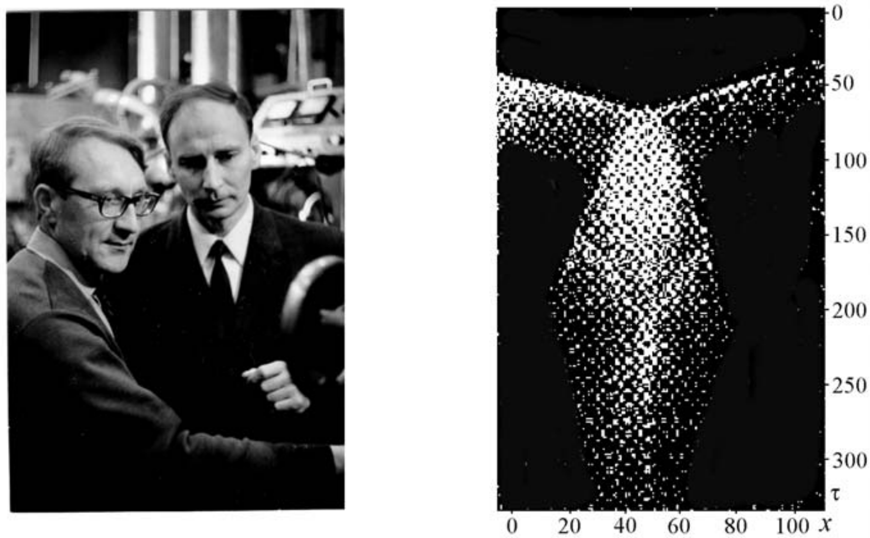

Fig. 2. On the left, newly elected Corresponding Member of the USSR Academy of Sciences, Rem Ivanovich Soloukhin shows to newly elected Academician of the USSR Academy of Sciences Roald Zinnarovich Sagdeev an electric-discharge shock tube at the Institute of Hydrodynamics, Siberian Branch of the USSR Academy of Sciences (1968); on the right, photograph of the collision of two shock waves with the same amplitudes moving at velocities of about 30 km/s [51].

The optical system of recording frame-by-frame images with reference to experiments on a shock tube was worked out by Cranz and Schardin as early as 1927 [7]. This system allows, one to obtain limiting velocities of frame sweeps while retaining a high representation quality; however, the number of frames in such systems is basically limited.

In order to obtain longer frame sweeps and continuous slit sweeps, Soloukhin used systems with film motion or optical sweeps with rotating mirrors (see Figs. 1–4). Rapidly rotating mirrors provide sweep velocities of up to 1–2 mln frames per second while retaining a high spatial resolution, which is determined by the recording medium [62–65]. Electrooptical sweep methods allow an appreciable decrease in the rate of the recorded processes; however, the spatial resolution here decreases [63]. He obtained sweeps and frame photographs of the Töpler pattern occurring on reflection of a shock wave from the end face of a tube and in the case of a half-wedge in flow behind a shock wave, in collision of shock waves, and many other results.

The operational principle of a shock tube is extremely simple (see Fig. 1). A shock wave is generated in a shock tube on disruption of an arbitrary breaking in the initial states of two gases separated by an impermeable partition. After the diaphragm breaking toward a lower-pressure gas, a shock wave propagates in the low-pressure channel and a rarefaction wave propagates in the "pushing" gas issuing from the high-pressure channel. The shock wave S is followed by a uniform flow of a compressed gas whose region in the low-pressure channel is separated from a flow of a cool pushing gas by the contact surface K. The region between S and K is effective, and it is used for studying processes in a high-temperature gas [66]. The gas parameters behind the front of a shock wave are determined by the Mach number $\mathrm{M} = U/c$ and parameters ahead of the front of a shock wave. For an ideal gas with a constant ratio of specific heats $\gamma = c_p/c_v$, the equations relating the jumps of parameters on a shock wave are of the form

$$\frac{\rho_2}{\rho_1} = \frac{(\gamma+1)\,\mathrm{M}^2}{(\gamma-1)\,\mathrm{M}^2+2}, \qquad \frac{p_2}{p_1} = \frac{2\gamma\,\mathrm{M}^2}{(\gamma+1)} - \frac{\gamma-1}{\gamma+1},$$

$$\frac{T_2}{T_1} = \frac{[2\gamma\,\mathrm{M}^2-(\gamma-1)][(\gamma-1)\,\mathrm{M}^2+2]}{(\gamma+1)^2\,\mathrm{M}^2}. \qquad (1)$$

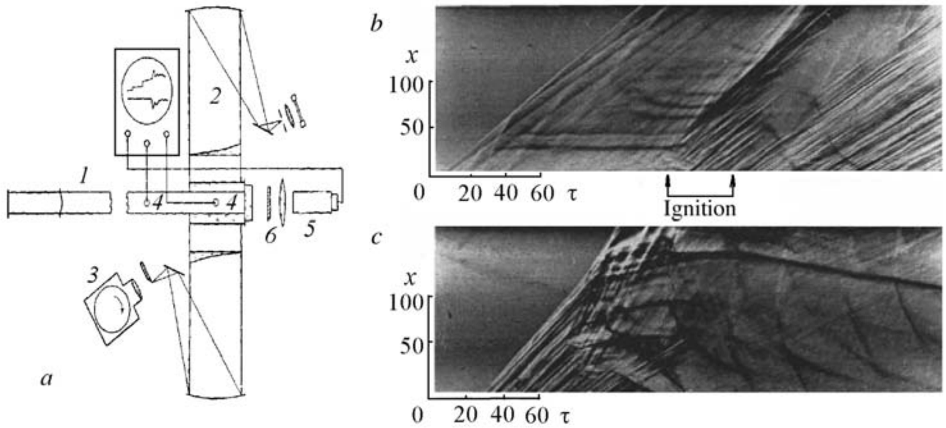

Fig. 3. R. I. Soloukhin's optical system for studying shock-wave and detonation processes (a): 1) shock tube; 2) shadow system; 3) photorecorder with rotating mirrors, 4) pressure pickups, 5) electron photorecorder, 6) light filter; (b) slit sweep of the schlieren pattern of ignition of the mixture of natural gas with oxygen behind the front of the shock wave (b); detonation formation in the same gas [66] (c).

To visualize such flows, Soloukhin used original schlieren methods, interferometry, and spectroscopy. Figure 1c shows an optical scheme of photographic recording of processes behind a shock wave with the wave motion compensated for by the photofilm movement. While still a young scientist, R. I. Soloukhin not only proposed this scheme but also personally manufactured a photorecorder that allowed "stopping" a shock wave. As recognition of his experimental artistry, the International Colloquium on the Dynamics of Explosions and Reactive systems that was held in the U.S. in 1989 instituted the international award for the best experimental work "Gold Hands of Soloukhin."

In 1958, Soloukhin began working at the Moscow Physics and Technology Institute at the chair headed by Academician M. A. Lavrentiev.[19] At this chair the main body of the future Novosibirsk Akademgorodok is formed. In 1959, among the first team of young scientists, together with Academician M. A. Lavrentiev, he moved for work to Akademgorodok, then under construction, where at the Institute of Hydrodynamics, Siberian Branch of the USSR Academy of Sciences, he continued and developed the scientific trend started at the G. M. Krzhizhanovskii Institute of Power Engineering. Figure 2 illustrates the picture of the interaction of high-intensity shock waves obtained on an electric-discharge shock tube, on which shock waves with velocities of up to 40 km/s can be produced [51]. On the schlieren photograph of the combustion–detonation transition (Fig. 3) it is seen that, ahead of the flame front, a flow arises in the form of a compression wave with a clearly defined leading front. In this work of Soloukhin published in 1964, the mechanism of detonation formation in a homogeneous gas mixture of acetylene and oxygen was disclosed, which consisted of the fact that behind a shock wave there form ignition centers from which the flame front propagates at a normal combustion rate. Ahead of the flame front, compression waves originate whose interaction initiates a volume explosion and a detonation wave which catches up with the primary shock wave (see [66]).

Pioneering investigations of the mechanism of high-temperature exothermic reactions were carried out by R. I. Soloukhin and V. V. Voevodskii in recording the period of induction of ignition. The use of a highly sensitive interferometer combined with a system of photographic sweep enabled Soloukhin to observe insignificant density disturbances in the induction period in high-temperature ignition of ammonia (see Fig. 4).

Experiments with a shock tube demonstrated its unique capabilities as a physical tool in studying complex gasdynamic processes. From the outset of his scientific work up to his final days, Rem Ivanovich remained an active adherent and propagandist of employing shock tubes for a wide range of physical studies.

[19] Mikhail Sergeevich Lavrentiev (1900–1980), mathematician and physicist, founder of the Siberian Branch of the USSR Academy of Sciences and Novosibirsk Science City (Akademgorodok), Academician (from 1946) and Vice President (1957–1975) of the USSR Academy of Sciences.

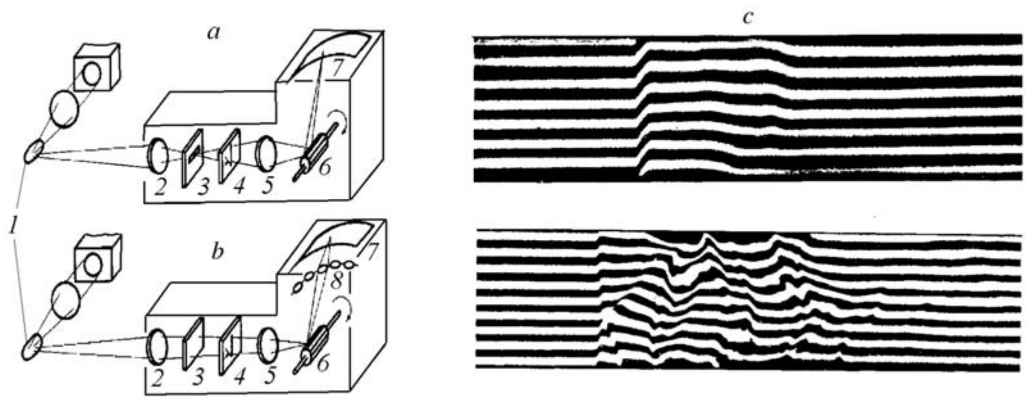

Fig. 4. Mechanical systems with rotating mirrors for "sweeps" of the images of fast processes in continuous (a) and "framing" (b) modes: 1) investigated object, 2) imaging lens, 3) slit or mask, 4) shutter, 5) receiving lens, 6) rotating mirrors, 7) 8) microlenses for forming frames; interferograms-sweeps of the ignition of ammonium behind the shock wave (c).

In the early 1960s, the development of shock-tube engineering was summarized in several fundamental reviews and monographs [40, 42, 59, 60, 66–73], among them R. I. Soloukhin's studies [66–68, 71]. He unified the results of studying shock and detonation waves in the monograph "Shock Waves and Detonation in Gases" [66], which was published in 1963. In 1965, the monograph was translated and republished in the U.S. This monograph became widely known and has deserved its prestige among specialists. Along with the works "Shock Tubes in High-Temperature Chemical Physics" by A. G. Gaydon and I. R. Hurle [72] and "Physics of Shock Waves and High-Temperature Phenomena in Gases" by Ya. B. Zeldovich and Yu. P. Raizer [73], R. I. Soloukhin's monograph came to be a manual in all of the world's laboratories that used shock tubes for physicochemical investigations.

A beautiful physical phenomenon that is important in the aspect of application — spinning detonation — attracted the young scientist, and Rem Ivanovich began to investigate the loop and acoustic phenomena attending spinning detonation and also studied multifront waves using shock tubes. After accomplishing a cycle of fundamental studied at the Institute of Hydrodynamics, Siberian Branch of the USSR Academy of Sciences, in 1965 Rem Ivanovich (together with B. V. Voitsekhovskii, Yu. K. Troshin, and K. I. Shchelkin[20]) was awarded the Lenin Prize for investigations of detonation in gases.

First Experiments with Shock Tubes in Minsk. The first shock tube was brought to Minsk from Novosibirsk and put into operation in October 1976. The first experiments to study ignition behind a shock wave in Minsk

[20]Kirill Ivanovich Shchelkin (1911–1968), Trice Hero of Socialist Labor, Corresponding Member of the USSR Academy of Sciences, Doctor in Physical and Mathematical Sciences, Winner of the Lenin Prize and Three State Prizes. In 1932, he began working as a laboratory assistant at the Institute of Chemical Physics in Leningrad. In 1938, Shchelkin defended a candidate's dissertation. In 1943, the Institute moved to Moscow, where Kirill Ivanovich continued to work on his doctoral dissertation "Fast Combustion and Spinning Detonation of Gases" and already in November 1946 he publicly defended it. Kirill Ivanovich received his doctorate in physical and mathematical sciences and thereafter the title of professor. In 1947, Shchelkin was sent to work at the design office KB-11 as the deputy chief designer and scientific adviser. In the KB-11 he led works on gasdynamic development and physical investigations within the framework of the Soviet atomic project. For his participation in the creation of the first nuclear bomb, in 1949 Shchelkin was given the title of Hero of Socialist Labor and awarded with the State Prize. In 1951, for designing and testing new types of a nuclear weapon Shchelkin was awarded with the second Star of Hero of Socialist Labor and with State Prize. And there was new work ahead — the creation of a hydrogen bomb. For creating the domestic thermonuclear weapon, in 1953 Shchelkin was elected Corresponding Member of the USSR Academy of Sciences and awarded with the Third Star of Hero of Socialist Labor and a State Prize. In 1955, Kirill Ivanovich was transferred to the NII-1011 (the All-Union Scientific-Research Institute of Technical Physics) as the chief designer and scientific adviser. He was awarded with four Lenin Orders, an Order of the Red Banner of Labor (1953), and an Order of the Red Star.

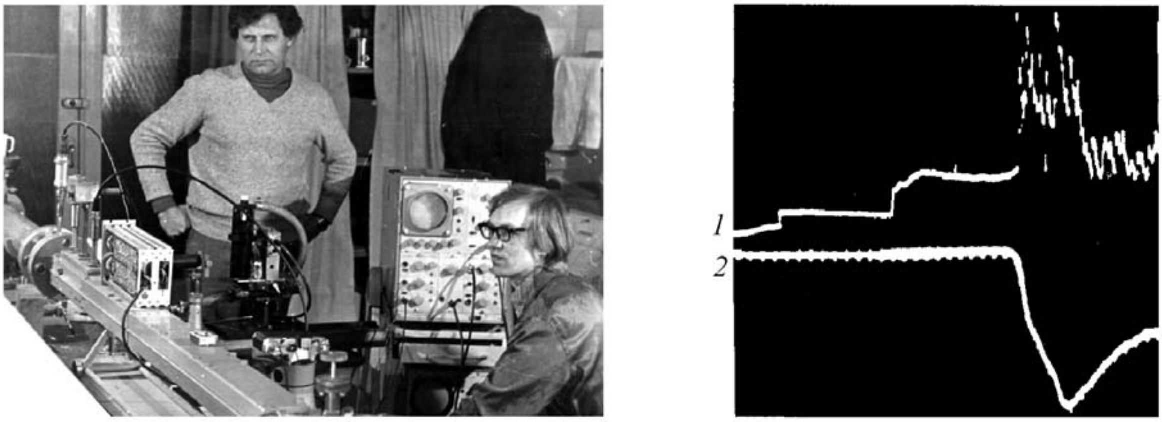

Fig. 5. On the left are Christian Brochet (France) and Nikita Fomin during first "shoots" of the shock tube UT-1 in Minsk (1976); on the right is the recording of pressure (1) and luminosity (2) on propane ignition behind the front of the reflected shock wave [74, 75].

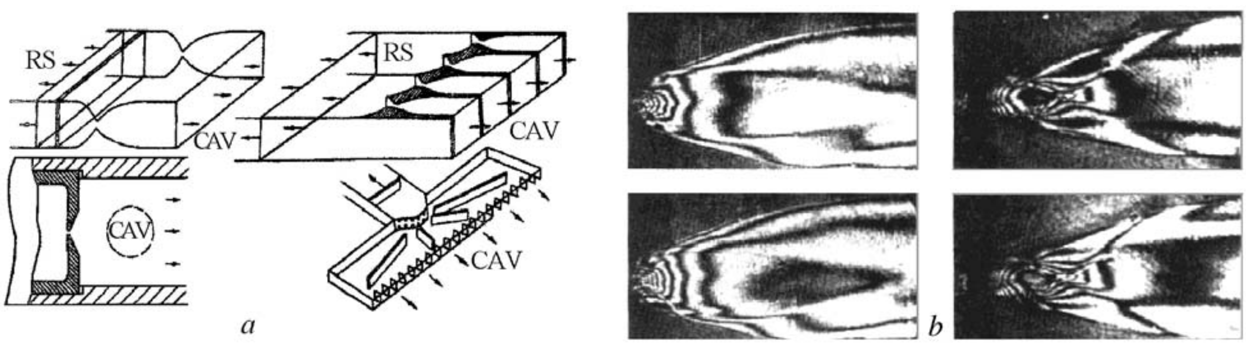

Fig. 6. Illustration of basic techniques of using the shock-tube engineering to produce inversion and generation of laser radiation on gas-flow laser systems (a): RS, reflected shock wave; CAV, laser resonator; (b), interferograms of starting a supersonic nozzle of the mixing gasdynamic laser for various flow regimes [85].

were conducted with the participation of renowned specialists in shock tubes — French scientists C. Brochet, J. Brossard, G. Dupre, and C. Paillard [74–78] (see Figs. 5–7). The shock tube constructed in Novosibirsk in 1960 is still used at the Laboratory of Chemical Fluid Dynamics of the A. V. Luikov Heat and Mass Transfer Institute. Channels in this tube are brass superhigh-frequency waveguides with a 50 × 50 mm rectangular cross section made in the form of seamless tube segments. The wall thickness of these channels is about 1 mm; therefore, for operation at elevated pressures a channel bracing in the form of a removable steel "jacket" is used. Such waveguides provide high purity of the inside surface, and the external reinforcement of the channel precludes the excitation and propagation, over the walls, of mechanical disturbances affecting pressure recordings by piezoprobes.

Shortly afterward, one of the pioneers of the development of shock-tube engineering in the U.S. — Prof. Raymond Emrich — arrived in Minsk; Soloukhin had become friends with Emrich as far back as his one-year stay in Novosibirsk in 1971–1972 [77]. In Minsk, Prof. Emrich participated in investigations of the processes of aerosol mixing in producing inversion in gasdynamic lasers (see below) [78]. At this time, the A. V. Luikov Heat and Mass Transfer Institute of the BSSR Academy of Sciences was actively cooperating with the Institute of Physics of the BSSR Academy of Sciences, specifically, with departments headed by L. I. Kiselevskiy and V. S. Burakov, and carried out joint investigations of the kinetics of high-temperature self-ignition with scientific centers in Orléans and Poitiers, the Department of Aerospace Investigations of the Moscow Physics and Technology Institute, and the Baltic State Technical University (Voenmekh) and began works on the kinetics of relaxation processes with Moscow State University,

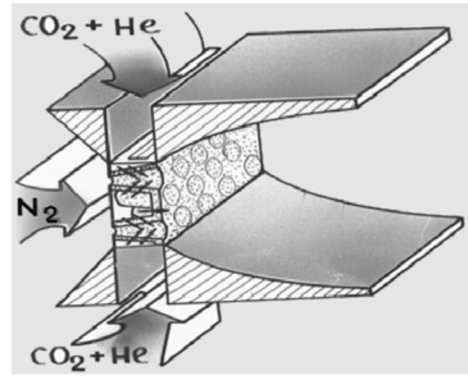

Fig. 7. On the left, Academician R. I. Soloukhin, graduate student S. A. Labuda, and Candidate of Physical and Mathematical Sciences N. A. Fomin are engaged in modeling a gasdynamic laser on the UT-1 (1979), and on the right is the unit of honeycomb structure for a gasdynamic laser made of a porous material [86].

the N. N. Semyonov Institute of Chemical Physics of the USSR Academy of Sciences, and the Department of Chemical Physics of the Moscow Physics and Technology Institute [79–81].

Modeling and Diagnostics of High-Power Gasdynamic Lasers on Shock Tubes. While still in Novosibirsk, in the early 1970s, Soloukhin was enticed with the idea of designing high-power gasdynamic lasers in which inversion of the population of molecular levels is produced solely by thermal techniques [82]. Gasdynamic lasers are high-power converters of thermal energy directly into the energy of coherent light emission. On the basis of ideas and principles of the indicated systems proposed under the guidance of Academicians N. G. Basov and A. M. Prokhorov at the P. N. Lebedev Institute of Physics of the USSR Academy of Sciences, under the leadership of R. I. Soloukhin gasdynamic lasers which employed purely thermal methods of excitation of the active medium using shock tubes were constructed. In these studies, shock tubes proved to be a simple and extremely convenient means of modeling complex physical gasdynamic phenomena with a rapid adiabatic expansion of a relaxing high-temperature gas heated in a shock tube [83–85] (see Figs. 6 and 7).

The investigations of gasdynamic lasers started in Novosibirsk were continued in Minsk. Special attention was given to the so-called mixing (mixed flow) gasdynamic lasers, i.e. devices with selective thermal excitation only of gas — the carrier of vibrational energy — followed by a rapid mixing of exciting and radiating gases under the conditions of supersonic flow. In gasdynamic lasers of this type, the efficiency of energy transformation and the optical quality of the working medium in the laser resonator were markedly improved. Figure 7 shows a schematic of the nozzle unit of honeycomb structure designed at the Heat and Mass Transfer Institute of the National Academy of Sciences of Belarus in cooperation with the Baltic State Technical University in St. Petersburg under the guidance of Prof. A. S. Boreisho and with the Institute of Powder Metallurgy in Minsk under the guidance of P. A. Vityaz',[21] then Candidate of Technical Sciences [86]. Following our works, gasdynamic mixed flow lasers were investigated at ONERA (France)[22] under the guidance of J.-P. Taran and at the U.S. Boeing Corporation under the guidance of Dr. F. Cassady. In the 1980s, based on the results of investigations of various laser systems, dissertations were defended by workers of the Heat and Mass Transfer Institute N. A. Fomin, S. A. Zhdanok, O. V. Achasov (1954–2002) and S. M. Khizhnyak, S. A. Labuda, A. V. Krauklis, P. P. Samtsov, and D. S. Ragozin. O. G. Penyazkov wrote a prediploma work on the laser spectrograph designed by the Soloukhin–Yakobi optical scheme [87].

In the very beginning of his work at the Heat and Mass Transfer Institute, S. A. Zhdanok predicted the possibility of producing super-equilibrium ionization in a vibrational nonequilibrium gas, and experiments on shock tubes verify the existence of a new physical phenomenon — an increase in the electron density in the cooling of a vibra-

[21]At the present time, Academician P. A. Vityaz' is First Deputy Chairman of the Presidium of the National Academy of Sciences of Belarus.
[22]ONERA is the French Aerospace Center.

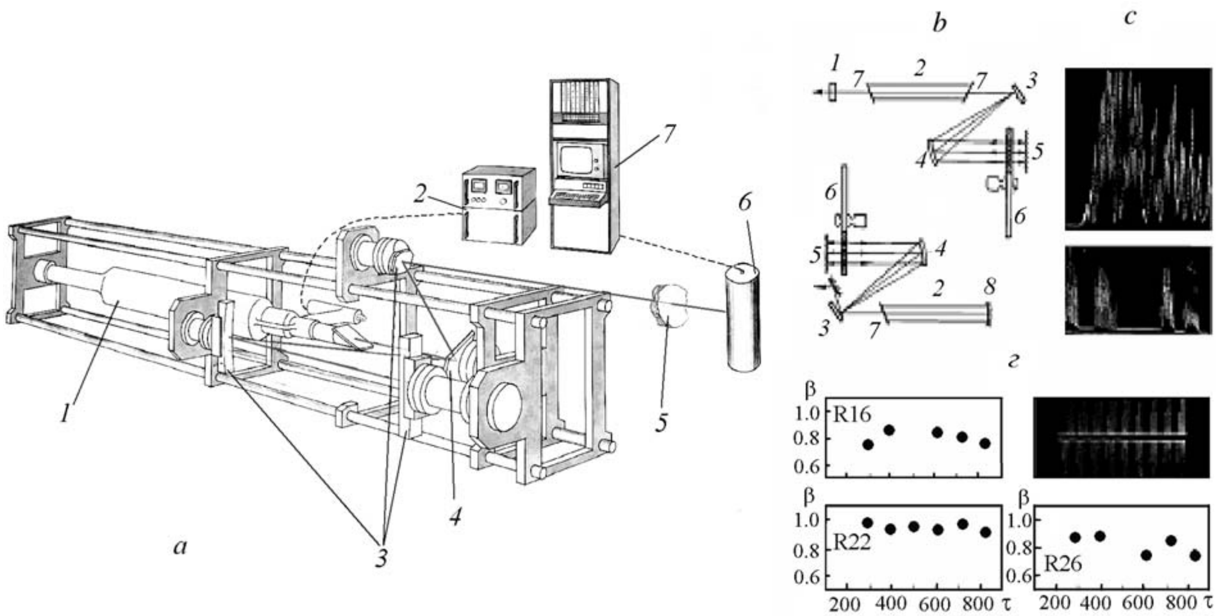

Fig. 8. Diagnostic assembly based on the Soloukhin–Yakobi laser spectrograph (a): 1) soldered-off electric discharge tube with the active laser medium, 2) feed unit, 3) mirrors of the resonator of the laser spectrograph; 4) diffraction grating, 5) investigated medium, 6) IR detector, 7) system of information collection and processing; optical schemes of the laser spectrograph (b): 1) semi-transparent mirror, 2) soldered-off electric discharge tube with the active medium of the laser, 3) diffraction grating, 4) parabolic mirrors, 5) plane-parallel mirrors, 6) rotating disk with slits, 7) transparent crystal positioned at the Brewster angle, 8) confocal mirror of the resonator; (c) oscillograms of the laser spectrograph generation on molecules CO_2 and CO; (d) results of measuring vibrational temperatures in modeling mixing hydrodynamic lasers using shock tubes at the Heat and Mass Transfer Institute, National Academy of Sciences of Belarus [79, 87]; R16, R22, and R26 are generation lines of the laser spectrograph on a molecule CO_2. β, m^{-1}; τ, μs.

tional nonequilibrium gas [83, 84]. Shortly thereafter, the discovery was verified on a shock tube of Prof. I. Mashtovsky (Socialist Czechoslovak Republic), and at the Heat and Mass Transfer Institute superequilibrium ionization was immediately used for an additional pumping, by an electric discharge, of the active medium of the gasdynamic mixed flow laser.

Soloukhin–Yakobi Laser Spectrograph. To describe nonequilibrium molecular distributions in the gasdynamic laser, in addition to the thermodynamic temperature T it is necessary to introduce the so-called vibrational temperatures T_{vi}, which, in fact, define the magnitude of inverse population of the active medium of the gasdynamic laser and determine the possible power of generation of laser radiation. These temperatures can be determined experimentally using diagnostic lasers with a tunable generation spectrum. In 1973, R. I. Soloukhin and Yu. A. Yakobi proposed a convenient scheme of a laser spectrograph as applied to experiments on shock tubes. The specific feature of the Soloukhin–Yakobi laser spectrograph is cylindrical mirrors placed such that all spectral lines go back to the diffraction grating which resolves the laser generation spectrum in space (see Figs. 8–10). This optical scheme provides a very rapid tuning of the generation spectrum, which is why such laser spectrographs are used with success in experiments on shock tubes [80].

Shock Tubes in Investigations of New Physical Processes and Phenomena. In the twenty-first century, shock tubes still play a deciding role in the investigations of new physical processes and phenomena (see, for example, [88–99] and papers in the current issue of IFZh). A strong impetus was imparted to the development of optical diagnostic methods by the advent of laser systems and their wide introduction in practice. Exactly the appearance of lasers

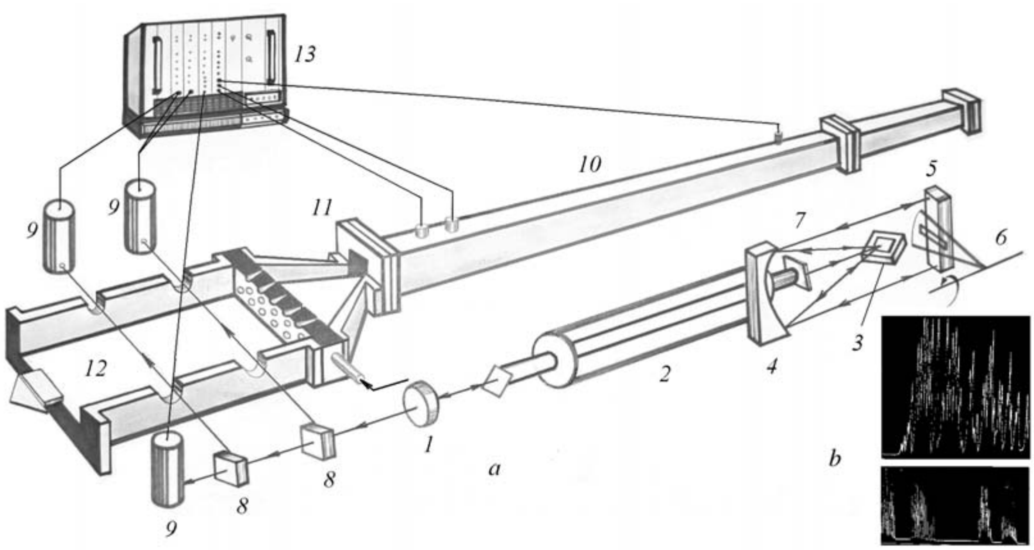

Fig. 9. Spectral measurements of the amplification coefficients at the entry to and exit from the resonator of the gasdynamic laser using the Soloukhin–Yakobi laser spectrograph (a): 1) semitransparent mirror, 2) soldered-off electric discharge tube with the active medium of the laser, 3) diffraction grating, 4) confocal mirror, 5) plane-parallel mirror, 6) rotating disk with slits, 7) transparent crystal placed at the Brewster angle, 8) guiding semitransparent mirrors of the resonator, 9) IR detectors, 10) shock tube, 11) expansion nozzle unit of the gasdynamic laser, 12) resonator of the gasdynamic laser, 13) system of information collection and processing; (b) generation spectra of the laser spectrograph on CO_2 and CO [87].

Fig. 10. On the left, Candidate of Physical and Mathematical Sciences Andrei Krauklis, Dr. in Physical and Mathematical Sciences Nikita Fomin, and Prof. Claude Paillard carry out the diagnostics of molecular states on the ShT-3 using the Soloukhin–Yakobi laser spectrograph (1988); on the right, the Soloukhin–Yakobi laser spectrograph in operation.

prompted the development of works on optical diagnostics using spectral analysis, the Doppler effect, and speckle fields generated in coherent radiation. The latter proved to be the most suited to conversion to digital systems of recording and processing of images which brought revolutionary changes in the possibilities of quantitative measurements and "passportization" of complex three-dimensional transients in many technological processes and devices of new technology.

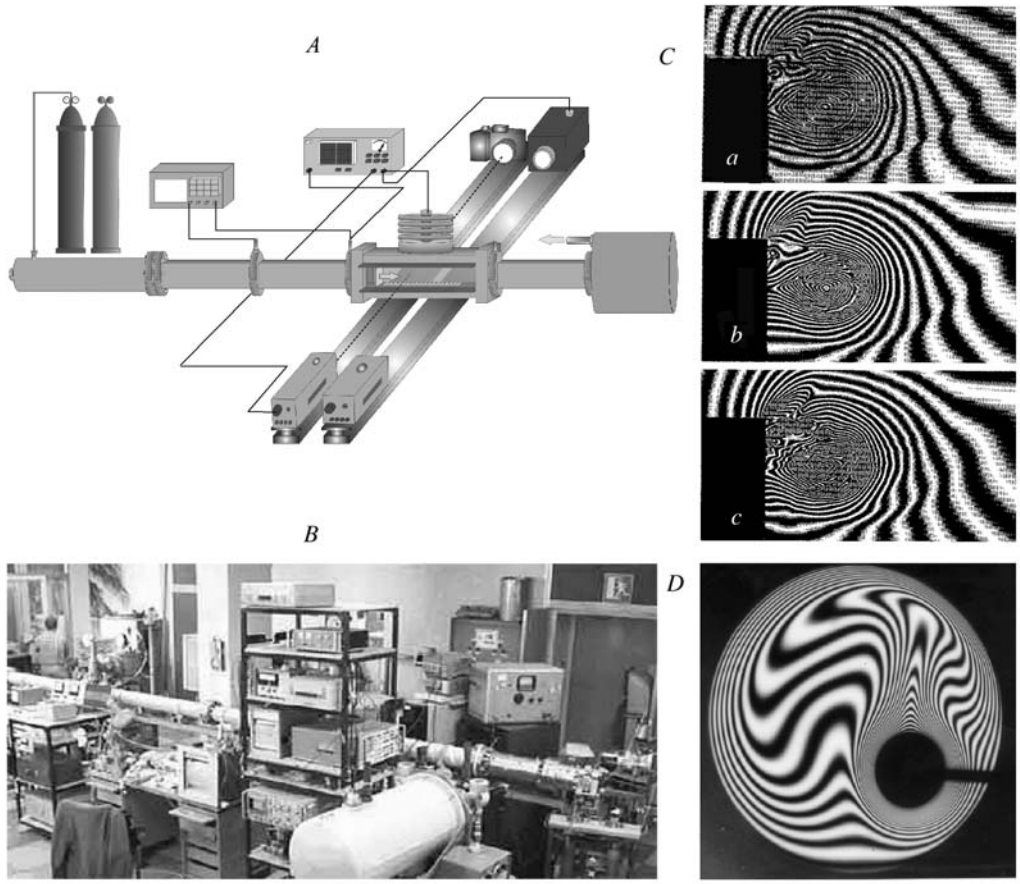

Fig. 11. Configuration of the shock tube of the Chair of Molecular Physics of the Physical Department of Moscow State University used for studying the structure of a shock wave during the interaction with plasma [93–95] (A); test bench of the Physical Gasdynamics Department of the Joint Institute of High Temperatures, Russian Academy of Sciences [45] (B); comparison of interferograms of the shock wave diffraction (a) with calculation with account for turbulence (b) and disregarding it (c), which was made at Tohoku University under the guidance of Prof. Takayama [96] (C); interferogram of convective flow obtained by Dr. in Physical and Mathematical Sciences P. P. Khramtsov [91] (D).

Conversion to the digital system of recording of images of fast processes and the use of speckle technologies significantly improved the space and time resolution of optical diagnostics on shock tubes, which allowed one to determine the change in the Kolmogorov scale in the turbulence interaction with shock waves [88–91] and restructure three-dimensional distributions of shock wave processes by methods of restructuring tomography [92–94]. The works on speckle interferometry of fast processes begun when R. I. Soloukhin was alive are being continued at the Heat and Mass Transfer Institute. Based on these studies, candidate's dissertations were defended by G. N. Blinkov, D. É. Vitkin, E. I. Lavinskaya, and N. B. Bazylev, and the dissertation of O. V. Meleeva is on the way.

Figures 11 and 12 illustrate the current state of shock tubes on which Soloukhin worked in his time. On the shock tube of the Chair of Molecular Physics of the Physical Department of Moscow State University (Fig. 11), under the guidance of Prof. I. A. Znamenskaya works on the shock wave interaction with the plasma of a pulsed electric discharge are underway, which aim at controlling gasdynamic flows using plasma technologies [95–97]. This shock tube is fitted out with optical benches providing a two-aspect-angle probing of the considered processes. On the shock tube of the Joint Institute of High Temperatures of the Russian Academy of Sciences (Fig. 11), investigations are being carried out of unsteady gasdynamic processes in the interaction of strong shock waves with account for physi-

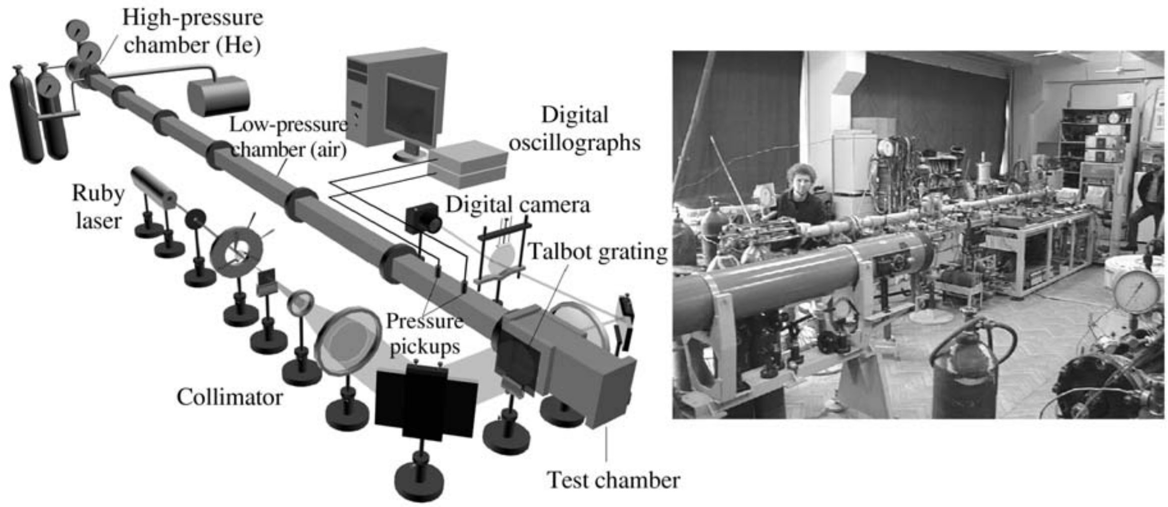

Fig. 12. On the left is an optical scheme of Talbot interferometry for measuring optical nonunformities in experiments on a shock tube; on the right, scientific worker Kirill Sevruk and Corresponding Member of the National Academy of Sciences of Belarus Oleg Penyazkov conduct experiments on the ShT-4 of the Laboratory of Physicochemical Fluid Dynamics, Heat and Mass Transfer Institute of the National Academy of Sciences of Belarus.

cochemical transformations in gases, optical diagnostics of the shock wave propagation in channels with a variable cross section is being performed, and the structure of pulsed supersonic flows and many other subjects are being considered (see [44, 45] and the current issue of IFZh).

On the right of Fig. 11 are experimental and computed interferograms of diffraction of a shock wave which demonstrate the high experimental and computational skill of workers of the Shock Wave Center at the University of the state of Tohoku (Japan), where shock wave processes are investigated under the guidance of President of the International Institute of Shock Waves Prof. Kazuoshi Takayama. As is seen from the interferograms, accounting for turbulence in computations improves the similarity of the experimental and computed flow pictures.

Figure 12 shows one of the shock tubes of the Heat and Mass Transfer Institute on which works are carried out under the guidance of O. G. Penyazkov, Corresponding Member of the National Academy of Sciences of Belarus. Here studies of high-temperature self-ignition in gases and heterogeneous media are being continued, works on Talbot interferometry are being carried out, and investigations of pulse detonation engines and the formation and dynamics of nanoparticles behind a shock wave are being conducted [98, 99]. The study [100] demonstrates the potentials of digital laser diagnostic methods, which were developed on shock tubes, as applied to biomedicine.

Acknowledgments. The author was introduced to shock-tube engineering by Rem Ivanovich Soloukhin in 1972 during his prediploma practice. In the subsequent 15 years, the author had the good luck to work under his benevolent and attentive scientific guidance. The author considers publications in coauthorship with R. I. Soloukhin [75, 77, 78, 80–87] as the best on the list of his scientific works. The author's first monograph published after the demise of Soloukhin [88] was dedicated to his memory. Therefore, the author considers it his duty to express his first gratitude to the teacher — R. I. Soloukhin — to whose memory this issue of IFZh is dedicated.

While working with R. I. Soloukhin, the author was fortunate to encounter and discuss problems of modeling and diagnostics on shock tubes with many coryphaei whose studies are cited in the current review. These are Professors D. Bershader, A. Hertzberg, R. Gullard, A. Oppenheim, E. Oran, S. S. Penner, R. Hanson, and *R. Emrich* (the USA); *J. Brossard*, Ch Brochet, *R. Brun*, *G. Dupre*, *J. Combourier*, *C. Paillard*, and J.-P. Taran (France); G. Wagner, *W. Mertzkirch*, Y. Kompenhans, P. Rot (Germany), *C. Greated* (the UK); P. Wolanski, P. Derfer, J. Staszek (Poland); *K. Takayama*, *K. Maeno* (Japan); G. Ben-Dor (Israel); J. Lee (Canada); T. V. Bazhenova, V. V. Golub, Ya. B. Zeldovich (1914–1987); I. A. Znamenskaya, V. K. Kedrenskii, *N. N. Kudryavtsev*, *S. S. Novikov*, V. A. Levin, S. A. Losev, B. E. Fortov, Yu. P. Raizer, A. K. Rebrov, M. E. Topchiyan, *V. M. Fomin* (Russia), and many others. The author prepared

joint publications with the authors whose names are given in italics, e.g. [75, 77–80]. I also express sincere gratitude to colleagues and associates with whom more than a thousand "shoots" on shock tubes were made. These are Academician S. A. Zhdanok, Corresponding Member of the National Academy of Sciences O. G. Penyazkov, Dr. of Technical Sciences O. V. Achasov (1954–2002), Candidates of Sciences S. A. Labuda, D. S. Ragozin, D. É. Vitkin, G. N. Blinkov, A. V. Krauklis, P. P. Samtsov, E. I. Lavinskaya, N. B. Bazylev, and engineer O. V. Meleeva.

NOTATION

c, speed of sound, m/s; M, Mach number; p, pressure, N/m^2; T, temperature, K; T_{vi}, vibrational temperature of the ith mode; U, velocity of the shock wave; β, amplification coefficient of the signal, m^{-1}; ν, vibrational mode; ρ, density, kg/m^3; τ, time, μs. Subscripts: 1, parameters ahead of the front of the shock wave; 2, parameters behind the shock wave.

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