CONTRIBUTION OF R.I.SOLOUKHIN IN THE INVESTIGATION OF FLOWS WITH CHEMICAL RECONSTITUTIONS

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After graduating from the Physical Faculty of the Moscow State University in 1953, Rem Ivanovich Soloukhin worked as a laboratory assistant and an engineer at the Energy Institute (ENIN) of the USSR Academy of Sciences until December 1958.

The first two papers of Prof. Soloukhin were published in 1957 in the Proceedings of the IVth Conference of young scientists of ENIN. One of these papers described the development of two variants of the structure of barium-titanate-based piezoelectric transducers, analysis of their resolution, and application to record the values and profiles of pressur2es arising due to bubble oscillations in the case of an underwater explosion. An unusual technique was used to record long-time signals: photographing of the oscillograph screen onto a moving film.

The second paper was supervised by Prof. Predvoditelev and dealt with studying gas detonation in a shock tube by the Schlieren method, which seems to be applied to this object for the first time in research practice. The most important result of these experiments was identification of an inhomogeneous structure of the detonation wave in the so-called “non-spin” mixtures and breaks of the leading front of spin detonation. This paper was published almost simultaneously with the more known papers of the team headed by B.V.Voitsekhovskii who applied filming with compensation of image velocity and that of another team headed by Ya.K.Troshin who found inhomogeneities by the soot tracking technique. Actually, these papers inspired extensive investigations on interpretation of the detonation-front structure in gases and changed the concepts of this structure.

These two papers served as a basis for the Soloukhin’s candidate’s thesis (equal to Ph.D. thesis), which was approved in December 1957.

The next paper published in Doklady Akademii Nauk (publications of the USSR Academy of Sciences) in 1958 (with S.G.Zaitsev as a co-author) described the pioneering application of the schlieren method together with high-speed scanning of the image and piezoelectric transducers to studying the ignition of a hydrogen-oxygen mixture adiabatically heated by a shock wave. Owing to the well-tested technique and high quality of the photographs, these experiments demonstrated a record-beating accuracy in measuring the ignition delay (±2%).

Another result of this work was the discovery of an inhomogeneous (hot-spot) character of ignition behind the uniform shock wave and the explanation of the deflagration-to-detonation transition on the basis of formation of shock waves due to overlapping of hot spots.
Prof. Soloukhin’s activities of this early period were summarized in three papers. One of them was published in July 1959 in Uspekhi Fizicheskikh Nauk and justified wide-range application of the shock-tube method for studying properties of gases, relaxation processes, chemical reactions, and spectroscopic research at high parameters behind shock waves.

The second paper (presented together with T.V. Bazhenova in August 1959 at the 7^{th} International Symposium on Combustion) and the third paper (published in the collection of scientific papers dealing with power engineering problems in 1959) demonstrate all advantages of the method reached at that time in combination with pressure measurement by piezoelectric transducers despite their comparatively low resolution (~10 μs) and large size (their height and diameter were approximately 10 mm). These papers again confirmed the existence of an inhomogeneous structure of the detonation wave in “non-spin” mixtures.
Prof. Soloukhin’s interests were not confined to processes in gases only: in 1959, he published two papers (one of them in co-authorship with T.V.Bazhenova) dealing with evolution of a gas bubble due to an underwater electric discharge and formation of shock waves in this process. This paper seems to

be the first one to study the kinematics of the boundary of the bubble arising owing to an underwater discharge and to demonstrate the conformance and applicability limits of theoretical models available at that time. Like all previous and later experiments of Prof. Soloukhin, these tests were characterized by an extremely high quality, being at the edge of impossible for the current moment.

In December 1958, Prof. Soloukhin was appointed the head of laboratory at the Moscow Physico-Technical Institute (MFTI) and then worked at the Institute of Hydrodynamics of the Siberian Division of the USSR Academy of Sciences (IGIL) since June 1959 till October 1967. This period of his activities is associated with a number of important results obtained by Prof. Soloukhin in the field of gas dynamics of reactive flows, mechanics of liquids with gas bubbles, technique of application of optical methods, measurement of pulsed pressures and temperatures of the gas in fast processes, etc. Under direct or indirect influence of Prof. Soloukhin, these techniques were improved and implemented into experimental research.

The results of this short-time activities at MFTI were a paper in Doklady Akademii Nauk (April 1959) published in co-authorship with the authors of this presentation (apparently, the first student who prepared his diploma under Prof. Soloukhin's supervision) and a brief communication "On a divergent spin detonation wave" published at the end of 1959 in Izvestiya Akademii Nauk. The first paper offered a final confirmation of the acoustic nature of the spin detonation tail, which was the hypothesis put forward by N.Manson back in 1947, and the second paper proved for the first time that the structure with transverse waves and its size are determined and "self-sustained" regardless of the existence of the bounding walls.

After Prof. Soloukhin moved to Novosibirsk in 1959, the first paper he published dealt with a topic that was not typical of his research, namely, detonation of gunpowders. This work performed under Prof. Soloukhin's guidance on the direct instruction of academician M.A.Lavrentyev; the problem was to verify the proposal put forward in 1944 by N.Sytyi who suggested to use substandard powders as a standard high explosive (HE) for surface blasting. This work was performed by V.V.Mitrofanov and the author of the present paper. Owing to the technique developed in joint discussions, more than 150 types of black and white (smokeless) powders were tested within a very short time, and the expediency of Sytyi's assumption was confirmed. A consequence of these activities was a very big benefit of the national economy, namely, much less expensive elimination of dozens of thousands of tons of various gunpowders left after the World War II. Substandard powders were used as a standard HE in daylight surface blasting, in particular, in constructing a dam in Medeo.

Simultaneously, Prof. Soloukhin put much effort in organizing his laboratory, selecting engineering personnel, and providing shock tubes and all necessary equipment. Already in the first issue of the newly founded Journal of Applied Mechanics and Technical Physics (JAMT) in May-June 1960, he published a paper on acetylene detonation, where the activation energy of acetylene decomposition behind a shock wave (1100-1300 K) was measured for the first time. In the next issue (JAMT, No. 2, July-August 1960), Prof. Soloukhin supplemented the technique used by photometric measurements and published the results obtained for mixtures based on carbon oxide and ethyl alcohol. These experiments were performed on test facilities of the new laboratory.

In the monograph "Some methods of studying fast processes" published in 1960 in co-authorship with T.V.Bazhenova, S.G.Zaitsev, I.M.Naboko, et al., Prof. Sololukhin continued promoting and improving experimental techniques. In 1961 (Pribory I Tekhnika Eksperimenta, No. 3), he described a modified structure of a piezoelectric transducer (a cylinder 13 mm in diameter and 11 mm high) with an acoustic wave-guide filled by beeswax suppressing acoustic waves in the wave-guide. In measuring the wave reflected from the wall, he suggested that the pressure profile during the time of compression-wave passage over the transducer body should be reconstructed by means of signal differentiation.

It should be noted that many fine experimental techniques mastered and improved by young scientists of IGIL, even by those who were not researchers in Prof. Soloukhin's laboratory, were implemented and developed under his indirect but undoubted influence. In particular, this structure of the transducer inspired the author of this presentation to develop a technology for manufacturing small-sized piezoelectric transducers. Their diameter was reduced to 1 mm, and their time resolution reached 0.7 μs in the transient wave (D~1700 m/s) and less than 0.1 μs in the reflected wave. These transducers were used to measure the pressure field in spin detonation. Another example is the use of the schlieren technique to prove the existence of a pre-compression front ahead of the transverse wave, predicted by B.V.Voitsekhovskii. By means of a simple setup and proper inclination of the detonation tube, photographs with positions of shock fronts could be made by the method of complete compensation. These photographs revealed that the flows behind the leading front and the transverse wave join in two triple points. The photographs made it possible to measure the angle between the leading front and the gas flow, which allowed pioneering calculations and construction of a spin-detonation flow pattern that satisfied conservation laws. The paper "On divergent wave of spin detonation" inspired obtaining and investigating of converging detonation.

A natural continuation of research related to studying the electric discharge in water was two aspects in investigating the behavior of bubbles under compression. First of all, experiments performed with participation of V.K.Kedrinskii gave an answer to the question about the character (adiabatic or isothermal) of compression of the gas in the bubble (Doklady Akademii Nauk, 1961, Vol. 136, No. 2). To register the increase in temperature, the bubble was filled by explosive gas mixtures C_2H_2+O_2 or $2H_2$+O_2, and the fact of their ignition was used as a criterion of the gas temperature of the compressed bubble. These experiments offered an explanation to initiation of liquid HEs, which was observed under a comparatively weak shock-wave action. The dynamics of asymmetric compression of the bubble with formation of a cumulative jet was studied for the first time in experiments with an inert gas (JAMT, 1961, No.1, published together with V.K.Kedrinskii as a co-author).

Early 1960s saw the interest in the development of practical schemes of detonation combustion of propellants, which was associated, in particular, with the problem of scramjet design. In their attempts to ensure a steady supersonic process in active fuel-air mixtures, experimenters encountered insurmountable difficulties. Prof. Soloukhin suggested the use of a quasi-steady pulsed mode with a detached shock wave arising on a blunt obstacle. Using a shock tube for generating a supersonic flow, he brilliantly implemented his idea and studied the main features of the phenomenon. At the end of his publication (JAMT, 1961, No. 5), Prof. Soloukhin indicated that this method of generating a pulsed mode of supersonic combustion is not the only possible one and that formation of pulsations can be caused by a change in concentration of the mixture, which was an idea surpassing some of more recent works.

Prof. Soloukhin continued to expand the range of techniques used for studying gas-dynamic processes in chemically reacting media. In 1962 (JAMT, No. 2), he published the results of spectroscopic investigations (by the method of inversion of spectral lines) of gas temperature in detonation of acetylene-oxygen mixtures and obtained the first reliable experimental data that could be compared with calculations.

In his Doctor's thesis (September 1962) defended by Prof. Soloukhin when he was not yet 33 years old (which is not the usual thing for an experimenter), he made up an intermediate summary of his previous activities. He continued promoting and justifying the method of shock waves and the use of the most advanced equipment as an effective means of studying various fast processes in gases and other media; he also reported results of investigating nonequilibrium processes and spontaneous ignition in shock waves, deflagration-to-detonation transition, etc.

In 1963, Prof. Soloukhin published two papers where he generalized the results of studying processes in shock and detonation waves and reviewed the development of appropriate methods. These were the paper in Uspekhi Fizicheskikh Nauk (1963, Vol. 50, No. 4) and the monograph "Shock Waves and Detonation in Gases" (Fizmatgiz, 1963). These publications demonstrated the achievements of science in this field and served as an example and a starting point for new investigations; the book itself is a good tutorial for students.

Prof. Soloukhin continued to work on experimental techniques, demonstrating remarkable ingenuity. In his brief communication (JAMT, 1963, No. 6), he suggested using wave reflection from a flat obstacle to eliminate the influence of the near-wall region of the flow behind the shock wave in studying the nonequilibrium state of the gas (in particular, CO_2) in a shock tube (Fig. 11). As a result, he obtained a flow region suitable for one-dimensional probing, which was free from near-wall disturbances.

In their brief but fundamental paper (Doklady Akademii Nauk, 1964, Vol. 154, No. 6), R.I.Soloukhin and V.V.Voevodskii considered possible chemical-kinetic mechanisms of evolution of reactions behind the shock-wave front. Participation of the reaction of hydrogen and excited molecular oxygen (almost with a zero activation energy, which is important) in chain branching was obtained and justified for the first time. This reaction sustains combustion in the vicinity of the low-temperature limit. Thus, an explanation was found to significant disagreement between the theoretical assumptions and experimental data obtained by Prof. Soloukhin previously in this range of temperatures, where a change in the character of spontaneous ignition behind shock waves was registered. Significance of this paper goes outside the framework of observations in a particular hydrogen-oxygen mixture, because participation of vibrationally excited molecules in reactions behind the shock wave and their influence on the kinetics of initial stages of the reaction can be manifested in other reactions as well.

Exhaustion (diffraction) of a detonation wave from a tube into a certain volume was considered in the paper published together with V.V.Mitrofanov (Doklady Akademii Nauk, 1964, Vol. 159, No. 5), where the theoretical estimate of the wave-decay condition was experimentally verified on the basis of high-quality photographs made with an open shutter, scanning, and individual frames of the phenomenon. This estimate was commonly accepted for conventional mixtures by other researchers: for the detonation to leave the tube and enter the volume, the tube should contain 13 or more transverse waves in one direction.

Prof. Soloukhin continued to improve experimental techniques. In the first issue of a new journal (Combustion, Explosion, and Shock Waves, CESW, 1965, No. 1), which was founded with direct participation of Prof. Soloukhin who was the Deputy Editor-in-Chief, he suggested a modification of the schlieren technique to be used for quantitative measurements of the density jump in the shock wave. The method ensured the measurement accuracy within 5-10% and offered, in some cases, an alternative for interferometry, which requires fine equipment difficult in exploitation.

An analogy observed in comparisons of the behavior of ignition of methane and hydrogen-oxygen mixtures behind the shock wave made it possible to justify the change in the character of chain branching with increasing temperature, as in the case of hydrogen, and to demonstrate that the activation energy of the governing reaction in the range of temperatures between 1250 and 2500 K behind the shock wave is 33 ± 1.7 kcal/mole. This paper (Doklady Akademii Nauk, 1965, Vol. 161, No. 3) published together with V.V.Voevodskii offered a completely new kinetic mechanism of high-temperature methane oxidation.

In the paper published in the journal Teplofizika Vysokikh Temperatur (1965, No. 9), Prof. Soloukhin turned to a magneto-hydrodynamic technique for measuring mass velocity and conductivity of the gas behind the detonation front, which was novel for him, and we can again see a clear formulation of the problem, analysis of errors, and cross checking of results. This study seems to be the first application of the method to gas detonation.

In this period, Prof. Soloukhin's interest starts to shift toward nonequilibrium processes in the plasma, which later (during his activities at the Institute of Theoretical and Applied Mechanics of the Siberian Division of the Russian Academy of Sciences) inspired him to develop a powerful gas-dynamic laser. A typical publication of this period is that dealing with electrode-free excitation of the discharge in argon with addition of hydrogen (JAMT, 1965). The electrode-free discharge was ensured by an induction coil onto which a capacitor was discharged. The boundaries of existence of the phenomenon were determined in the experiments, and various parameters were measured, such as velocity and temperature of the plasma (by three methods), etc. One of important results of this paper was recommendations on practical implementation of an electrode-free breakdown.

This work was partly performed on the basis of laboratories of the practicum in general physics of the Novosibirsk State University. Because of this fact, we cannot fail to mention one more aspect of Prof. Soloukhin's activities. Since the moment the university was founded in 1959, Prof. Soloukhin was its pro-rector in addition to his scientific working IGIL, was responsible for many issues of its organization, and was directly involved into the formation of the general physics course at the university. He delivered lectures, acted as a scientific and methodical supervisor, participated in the development and equipment for common physics practicum and in providing methodical tutorials for the educational process. These tutorials are still in wide use among students and lecturers. People who worked at the time at the General Physics Department still recall Prof. Soloukhin with great respect and warmth.

Prof. Soloukhin sought persistently for new applications for shock tubes. The latest works of the period under consideration include the study dealing with shock tubes used to apply thin silicon films and to study the properties of these films. A specific feature of this work on application of coatings was the fact that shock waves were used both for obtaining the coating material by means of uniform heating of a mixture of silicon tetrachloride with hydrogen and for accelerating silicon particles being released. To organize the process, a special system of supplying appropriate chemicals to the shock tube was developed, and methods of thickness measurement (within the range from less than 100 Å to 1800 Å) and micro-scale measurement of electrical conductivity of the coatings applied were mastered. The defect structure of the resultant films was examined by the method of electron paramagnetic resonance, which was comparatively new at that time.

The last publication that refers to the period under review (CESW, 1967, No. 3) offers the best description of the approach to the experiment, which was practiced by Prof. Soloukhin. To measure the oxygen recombination rate with the use of shock waves, he involved a wide range of measurement techniques: recording of pressures by piezoelectric transducers, conventional interferometry and interferometry by the zero-band method with frame-by-frame filming and scanning of the flow field, registration of density in the regime of bands counting with the use of a photoelectron multiplier, and registration of luminescence of atomic oxygen at the wavelength of 4600±800Å. Cross checking of results obtained by combining different methods made it possible to obtain the most reliable data on the oxygen recombination rate in the temperature range from 3000 to 4000 K.

In October 1967, Prof. Soloukhin moved to the Institute of Nuclear Physics of the Siberian Division of the Russian Academy of Sciences as Deputy Director. Apparently, this is the reason that his list of publications contains no papers published in 1968. Because of the limited volume of the presentation, this can be the "natural threshold" to terminate the narrative.

As we tried to make the review of scientific activities of Prof. Soloukhin as detailed as possible, we deliberately did not mention the monographs written by Prof. Soloukhin individually or with co-authors. There were four monographs published during this period (one of them was translated and published abroad); moreover, many tutorials for students were also published.
In this period of his life, Prof. Soloukhin manifested a tremendous capacity for work; he had enough time for all activities: science, teaching, establishing international relations, working with the journal, learning foreign languages, and sports. Everything he did was done with inherent pedantry in the good meaning, business approach, and punctuality.

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