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ELECTRORHEOLOGY: FROM ITS BEGINNING TO THE PRESENT

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The development of world studies in the field of electrorheology — the division of hydromechanics of liquid structuring in external electric fields — has been considered from the historical aspect. The significant contribution and the key role of the Belarusian school of scientists founded by A. V. Luikov have been noted.

Introduction. Systematic rheophysical investigations were started in Belarus in the early 60s of the 20th century under the guidance of Academician Aleksei Vasilievich Luikov. Initially they were carried out in the laboratory of thermo- and aerodynamics (the head of the laboratory was Corresponding Member of the Academy of Sciences of Belarus B. M. Smolskii) by a small team headed by senior scientific worker Z. P. Shul'man. In this period, investigations were carried out on heat and mass transfer in liquids whose behavior does not obey the laws of classical hydrodynamics. Results of the theoretical study of heat and mass transfer in non-Newtonian liquids were published in the book "Boundary Layer of Non-Newtonian Liquids" by Z. P. Shul'man and B. M. Berkovskii (Minsk, Nauka i Tekhnika Press, 1966). In January 1969 an independent laboratory was set up, which was first headed by Academician Luikov. Under his direct guidance, theoretical and experimental investigations of hydromechanics of water solutions of polymers and water dispersions (N. N. Pokryvailo) were initiated, specific features of flow over various-geometry objects (B. I. Puris) and thermal physical properties of rheological systems (L. N. Novichenok) were studied, and physicomathematical modeling of flow and heat transfer of nonlinear viscoplastic liquids (Z. P. Shul'man) was accomplished (Fig. 1).

After defending a doctoral dissertation Z. P. Shul'man (1970) was entrusted with the heading of the laboratory. Owing to Z. P. Shul'man's enthusiasm and activity, under the direct scientific guidance of A. V. Luikov the collective of the laboratory (numbering 25–45 persons in various years) very rapidly set up a comprehensive experimental and theoretical study of the mechanical behavior and heat and mass transfer in complex flowing materials of a wide range, such as oils, drilling fluids, lubricants, construction mixtures (concretes and lime solutions), polymers, food masses (minced products, caramel and chocolate pastes, milk derivatives), etc. New trends in investigations also arose, which involved the investigation of transfer processes in liquids whose internal structure changes in external fields. A result of the comprehensive study of rheological properties, heat conduction, and convective transfer in flow in tubes and ducts of painwork materials was the publication of the book "Rheodynamics and Heat Transfer of Nonlinear Viscous Materials" by B. M. Smol'skii, Z. P. Shul'man, and V. M. Gorislavets (Minsk, Nauka i Tekhnika Press, 1970). In Z. P. Shul'man's monograph "Convective Heat and Mass of Rheologically Complex Liquids" (Moscow, Energiya Press, 1975), a systematic account is given of results of solving the problems of rheodynamics and heat and mass transfer for bodies in rotating flows, jets, and film flows.

These works formed the foundation for the basic directions of scientific investigations, which remain topical after the range of their problems was extended by pupils of A. V. Luikov and Z. P. Shul'man. These are:

the study of the viscoelastic behavior, plasticity, creep, normal stresses, thixotropic and relaxation parameters, and thermal physical characteristics (thermal conductivity, specific heat, and calorimetry) of various filled fluid media for optimizing their composition and searching new formulas and standardizing them for various branches of economy;

hydromechanics and heat transfer of nonlinear viscous liquids in flow in various-geometry tubes and channels, in film flow, and in flow over various-geometry objects;

the development and study of the hydromechanical behavior of smart materials — electro- and magnetorheological fluids, technologies of their application in hydromechanical devices (such as pump valves, pressure gener-

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Fig. 1. Academician A. V. Luikov discusses experimental results obtained on an aerodynamic test rig (1967). In the photograph, from left to right are senior scientific worker Z. P. Shul'man, director of the Heat and Mass Transfer Institute of the Belarusian Academy of Sciences A. V. Luikov, chief engineer R. G. Gorodkin, and engineer E. B. Kaberdina.

ators, and viscous friction dampers), connecting pieces, fixing equipment and processing devices, and heat-exchange, acoustic, and optical units with varied parameters;

biorheological investigations including the development of models of blood circulation in human and animal organisms based on rheological, cytometric, and biochemical measurements for oncological needs in examining photodynamic and hyperthermic therapy of tumors, for cardiovascular surgery, and for determining rheological characteristics of blood in order to estimate the influence of various pathologies to improve therapeutic methods.

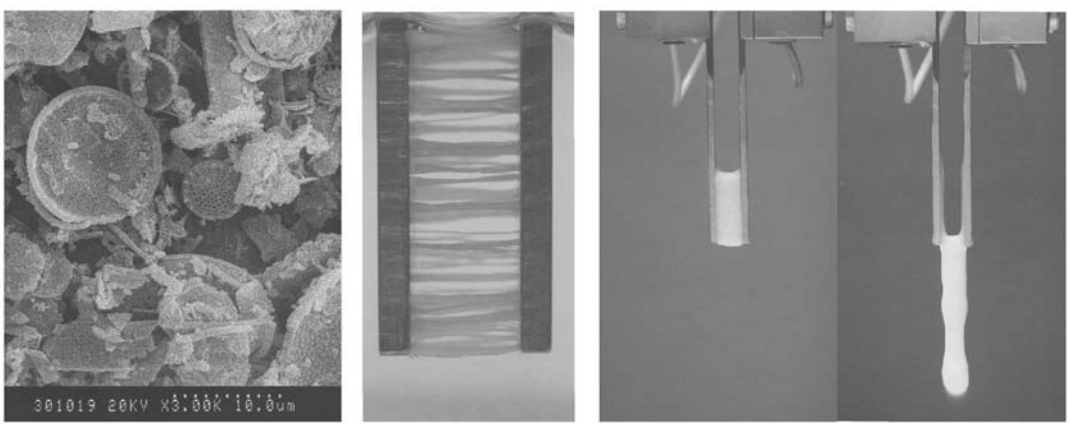
The Beginning of the Road. A special place among the directions of rheophysical studies is taken up by developing and studying electro- and magnetorheological liquids. A. V. Luikov first learned of unusual phenomena in liquids occurring by the action of external electric fields (supposedly in 1967) from a short paper in a scientific journal while being in the U.S. The effect of the electric field on the setting up of periodical structures in various liquids was known earlier. Thus, for example, while studying the structure of plastic lubricants in the electric field Yu. F. Deinega from the Institute of Colloid and Water Chemistry of the Ukrainian Academy of Sciences noted a change in their viscosity linked with the fact that a carcass of charged filler particles was attracted to one of the electrodes. In contradiction, the American paper stressed the use of dielectric fluids made up of uncharged particles and their strong structural response to the electrical pulse.

A. V. Luikov was enticed with the idea of a purposeful control of filled media using simple, low-power electric signals and with promising prospects for its practical application. By 1970, a team of researchers was formed that included workers of the laboratory of rheophysics and the design department SKB No. 7 — Z. P. Shul'man, R. G. Gorodkin, A. D. Matsepuro, and T. A. Demidenko, as well as V. A. Kuz'min, S. A. Demchuk, V. K. Kim, A. A. Gleb, and E. V. Korobko who had recently graduated from the Belarusian State University.

Results of first investigations of electrorheological suspensions were presented by A. V. Luikov at the conference on physicochemical mechanics of dispersive materials (Minsk, 1970) and at the conference Progress in Heat and Mass was Transfer (Paris, 1971). In 1972, the first ever book on electrorheology "Electrorheological Effect" was edited by Academician A. V. Luikov (Minsk, Nauka i Tekhnika Press, 1996). An outcome of the investigations was 80 author's and inventor's certificates. In all, 10 dissertations pertaining to electrorheology were defended, among them one doctoral. The first candidate's dissertation was defended by A. A. Kim.

Specifics, Difficulties, and Prospects of the Development of Electrorheology. The future development of most technologies involves not the rationalization, improvement, and modification of the traditional methods and equip-

Fig. 2. Presentation of the memorial medal to the Belarusian young scientist E. V. Korobko by W. Winslow, pioneer in the discovery of the rheological effect (Rayleigh, North Carolina, U.S.A).



a *b* *c*

Fig. 3. Photographs of: a) elementary structure of the ERL filler (× 3000), b) structure between electrodes in the passing light, and c) ERL in flow in a plane channel-capacitor (E = 1 kV/m and E = 0 kV/m).

ment but rather the working out and introduction of basically novel approaches that combine highly efficient methods of external action on the materials envisaging the use of properties of smart materials whose characteristics can range widely. Among these materials are electrically structured (electrorheological) liquids (ERLs) representing a class of flowing, roughly colloidal systems (dielectric particles of a solid phase in dielectric dispersive media) whose hydrodynamic specifics depends on the change in physical properties of a fluid as a result of structural transformations under the electric effect. Geometry, strength, and also energy, frequency, and other characteristics of the fields allow their use, in combination with ERLs, for automatic smooth programmed control of many current production operations.

The electric structure effect was first recorded in 1938 by the American engineer W. Winslow of Colorado Springs when studying purification of contaminated oils. The observed change in the shear viscosity and liquid flow in a plane channel-capacitor in the electric field was termed "the electroviscous effect" (Fig. 2). The investigated bridge-type structures were fairly strong and had a marked traction with electrodes (Fig. 3); therefore, an appreciable amount of energy was needed for setting up irreversible deformations and the developed flow in them.

Regardless of the clear prospects of flexible control of the flow of "electroviscous" liquids, in subsequent 10–15 years they had not found any significant application. This had to do with the small increase in the electrical viscosity and with sedimentation and temperature instability of the first formulas of ERLs.

In the 60s of the past century, the electroviscous effect was studied more actively in Great Britain on orders of the Ministry of Defense, and also in the United States of America. In these years, the role of water and electrolytes in forming stable quartz-based ERLs was studied in detail, and it was shown that introducing acids into liquids changed the electroviscosity by 100 times or more, while data obtained previously by W. Winslow indicated only a tenfold change. This discovery fostered wordwide developments aimed at implementing potential applications of the effect.

In the late 60s and early 70s, the Heat and Mass Transfer Institute of the Belarusian Academy of Sciences developed formulas of suspensions of hydrated silicon oxides (natural and synthesized) in nonpolar dielectrics. Consideration was given to the potential of using finely dispersed particles of silicas of various modifications, oxides and hydroxides of various elements (including metals), salts, polymers, and ferroelectrics as a disperse phase of electrorheological liquids. Rheological parameters (effective viscosity and yield) of ERLs were measured as functions of concentration of the filler particles, strength of a constant or alternating (various-frequency) electric field, and temperature. Hydrodynamics and heat transfer in flow in plane and coaxial cylindrical channels was studied. Furthermore, electrophysical properties of ERLs were ascertained over wide frequency and temperature ranges, and also the electric conductivity of ERLs was determined as a function of strength of the electric field and temperature. The influence of moisture binding and of the amount of moisture on absorbent particles of rheological, electrophysical, and thermophysical properties of ERLs was studied. The results showed that the considered effect is electrorheological in nature, since it is linked not only with the viscosity variation but also with the origination and increase of the liquid plasticity. Thus, the term "electrorheological" was introduced in the world literature, and the relevant field of knowledge was called electrorheology.

Advances made in this period are mostly associated with the engagement, in the solution of problems, of various specialists (specialists-rheologists were not trained at any Belarusian universities) — physicists, chemists, mechanical engineers, specialists in hydraulics, and electricians — and with a skillful combination of the creative potential of experienced workers of the laboratory of rheophysics and the enthusiasm and inquisitiveness of newcomers who graduated from the Department of Thermophysics of the Belarusian State University headed by Academician A. V. Luikov. Owing to the first publications abroad, Belarusian scholars established scientific relations with the then world center of electrorheological studied — Sheffield University — and with other research teams in Liverpool and Cranfield in the Great Britain.

Works of Professor G. Block from the Cranfield School of Engineering who used water-free materials allowed viewing the electrorheological effect (ERE) as a complex phenomenon whose nature is specified by polarization and is largely determined by physicochemical characteristics of the ERL components. This required practical use of the advantages of purposeful experiments to study the mechanism of the effect and optimize the ERL properties.

To date, large state research centers and private companies of the leading world states, such as the U.S., the Great Britain, Japan, South Korea, France, Germany, and also Belarus, have developed separate quite efficient ERL formulas on which modern engineering applications are based.

Technological aspects of the use of electrorheological liquids are extremely diverse and numerous, since the electrorheological effect allows a simple and efficient connection of weak electric control signals with power hydraulic performing devices. The most significant distinctive features of such devices are the absence of moving elements, a low energy consumption, and operation speed (of 10^{-3} s).

According to specific features of the rheological behavior of ERLs dependent on the composition of the working fluid and the modes of electric and mechanical effects, all known engineering decisions can be classified into several main groups:

1. devices controlling transfer characteristics,
2. vibration-proofing devices,
3. fixation devices,
4. untraditional devices and technologies of ERL application based on physical characteristics of electrorheological liquids in the field of other physical characteristics of ERLs.

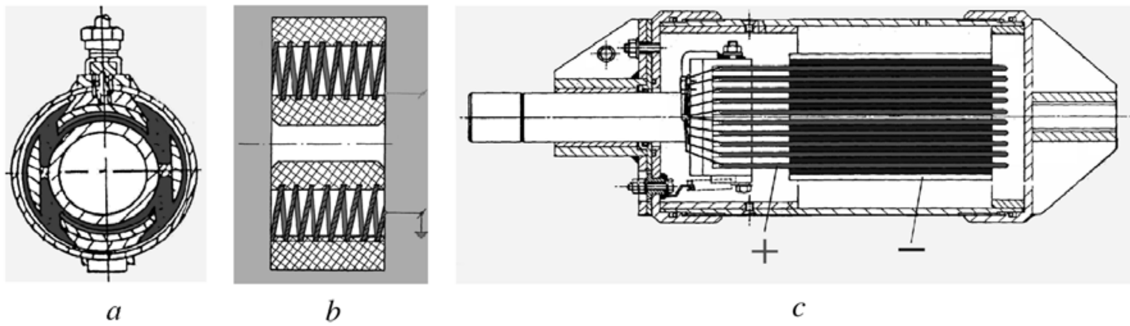


Fig. 4. Typical schematics of electrorheological continuous-flow valves for controllable hydraulic devices: a) torsion-type valve; b) helical valve, and c) plate valve.

Reviewing multitudinous publications on the practical use of the ERLs revealed several stages in its history marked sometimes by an upswing of the engineering activity and sometimes by a dwinding of interest of both individual researchers and engineers and of the market as a whole. As to the duration and extent of embracing the branches of economy, these stages correspond to our knowledge of the mechanism and features of the manifestation of the electrorheological effect. For this matter, science and practice alike "fed" each other while raising new tasks and focusing attention on some or other problems.

Thus, at the initial stage, the study of the mechanisms of flow in plane and coaxial cylindrical channels offered an opportunity for developing controlled hydraulic systems. In this period flow rate and head characteristics of Poiseulle flow were measured. The structural nature of the effect also prompted measurements of shear stresses as a function of shear rate in Coutte flow and a construction of the corresponding flow curves. These relations indicated a pseudoplastic behavior of ERLs in shear, i.e., a decrease in the viscosity with increasing shear rate, which lead to the development of complicated power-law, exponential nonlinear phenomenological rheological models. These models subsequently enabled engineers to calculate the characteristics of basic hydraulic elements such as ER valves and to design their improved compact versions in the form of plane, coaxial cylindrical, or helical electrodes (Fig. 4).

Shut-off units (throttles) of hydraulic systems, controlled shock absorbers, hydraulic pumps, brake pushers, hydraulic vibrators and other new-generation devices based on them were developed, which operated in the "open–closed" mode. Attempts to use valve pistons in tracking and damping systems and in generators of pressure oscillations of liquid, in which a change in the electric field and a corresponding variation in the liquid viscosity should follow the dynamic load, necessitated the study of temporal laws (kinetics) of the ERL response.

More detailed comprehensive rheological studies using vibroviscometric measurements carried out at the Heat and Mass Transfer Institute, National Academy of Sciences of Belarus, and experimental data for trixotropy and creep revealed a viscoelastic behavior of ERLs at small strains. Furthermore, they showed that the prehistory, according to which the ERL underwent a certain mechanical shear over a certain time, needs to be taken into account. Even a simplified idea of the structuring kinetics and the influencing factors made it possible to explain the specific features of the behavior of damping ERLs in absorbers of various oscillatory systems and the shift of resonance curves on their amplitude-frequency characteristics and to develop basic principles of their control.

At that time (in the 70–80s of the past century), in the development of traditional hydrodynamic applications, U.K. scientists and engineers (B. Bullof and J. Stangroom) made a significant contribution to designing new structures of clutches with ERLs whose state instantaneously changed from a flowing to a quasi-solid one. The most successful examples of using a quasi-solid mode of the ERL operation are works on designing fixing devices, carried out in Belarus. These are appliances of the type of cramps-coverings with electrorheological elements for fixing pliable objects (for example, large-diameter tubes) during mechanical treatment, various clamps for parts of any materials (including magnetic and perforated ones) that are both plane and of intricate shape (turbine blades), and electrorheological clutches in the form of a robot's "hand" for moving the parts and setting them in position. We implemented the same principle in vibrotests of electronics articles (Fig. 5).

In the past two decades, the works of researchers were directed mostly at studying the nature of EREs, the reasons behind the structuring in the electric field, and the factors determining it and at setting up adequate physical

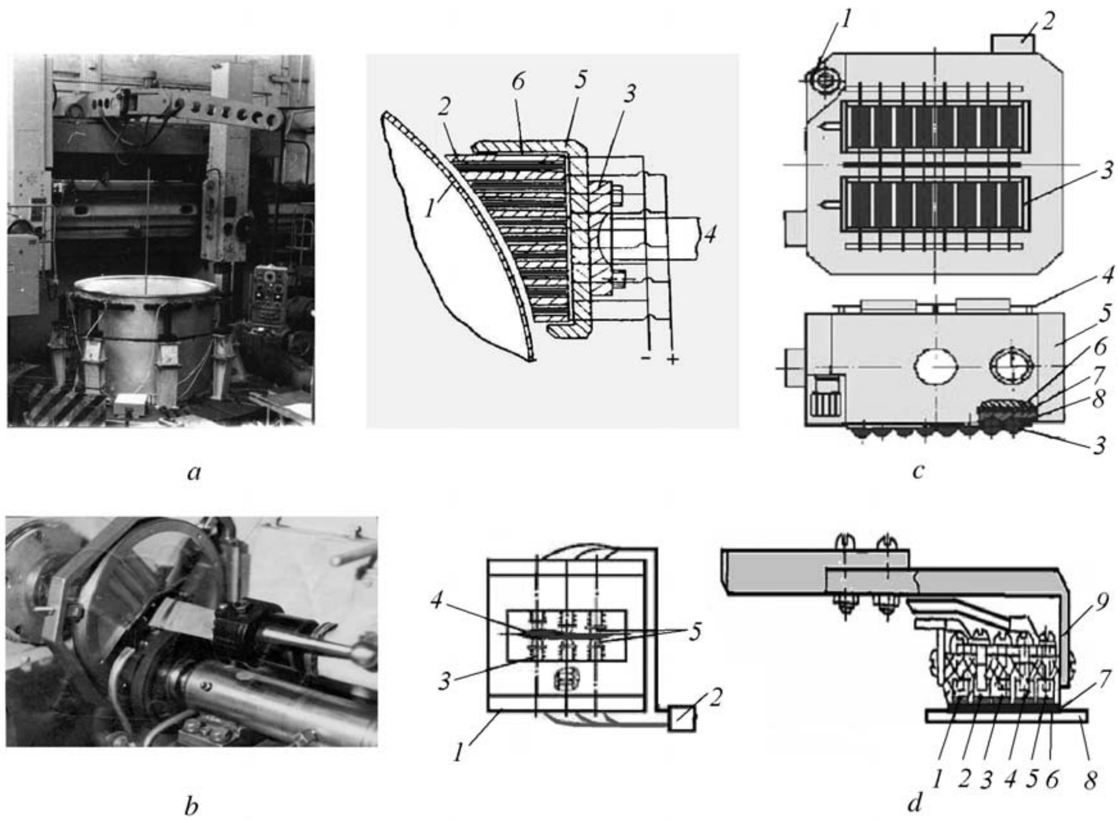


Fig. 5. Technological equipment for fixing: a) nonrigid frame plants, b) complex-profile articles (turbine blade) in mechanical treatment, c) for vibrotests of articles of the radioelectronic industry (capacitors), d) for carrying and installing details (robot's hand); a) 1, detail (D = 2 m); 2, ERL; 3, fastener; 4, stop; 5, frame; 6, electrodes; b) 1, supporting ring; 2) voltage source; 3, ERL; 4, treated blades; 5, stops; c) 1, terminal block; 2, electric shield; 3, capacitors; 4, capacitor leads; 5, frame; 6, insulator; 7, insert; 8, ERL; d) 1–5, electrodes; 6, semiconductor coating; 7, ERL; 8, part; 9, frame.

(structural and thermodynamic) models of the electrorheological effect on this basis. The acquired knowledge also made it possible to achieve noticeable success in improving the formulas of ERLs, specifically, based on fibers and nanocomposite materials. The electrorheological response was enhanced and the temperature range was broadened using methods of ash-gel synthesis of the ERL fillers. The properties of components of the already known ERLs were modified also by introducing additives, by physical or chemical treatment of the surface of particles of a solid phase, and by producing two-layer particles and composite fillers. Furthermore, basically new formulas were proposed, e.g, those of homogeneous type based on liquid crystals, which would allow restrictions imposed by the sedimentation factor to be removed. ERL formulas were developed that extended the range of application of the electrorheological effect. Thus, the invention of electrically sensitive polymer-bearing fast-drying ERL compositions (joint works of the Heat and Mass Transfer Institute and the Institute of General and Inorganic Chemistry, Academy of Sciences of Belarus) was the starting point of development of the technology of casting films with the parameters and structure formed by the electric field. Also, formulas of ERLs were created that are simultaneously sensitive to magnetic fields, which allows twofold control of the rheological response of liquids.

The origination of the ERLs with improved characteristics allowed inventors to come up with original proposals aimed at perfecting and designing mechanical devices, such as fishing rods, appliances for rehabilitation of convalescent persons, and seismometers. Possibilities were also widened of using ERLs also for chemical technologies, specifically, in comminution of a dispersive material by increasing viscosity in the gap between rubbing surfaces of colloid mills, batching of various liquid dispersive materials, filtration when vibrational electric precipitators are used, sedimentation, regulation of separation processes, and voltage control in gas cleaning.

In the 80–90s of the past century, the research interest extended not only to developing working fluids for a certain purpose — the utilization in vibration dampers and fixing devices — but also to studying other physical characteristics of electrorheological liquids, and as a result, several "untraditional" devices and technologies were developed, which were based on the electrostructural effect.

Specifically, workers of the laboratory of rheophysics studied thermophysical properties of ERLs in electric fields and measured thermal conductivity and thermal diffusivity. Their dependences on strength of the electric field was the basis for developing a differential method of determining thermal conductivity of media, where the tested medium and the reference medium are heated by equal heat fluxes and the temperature is recorded at several points. Here, in order to improve accuracy and make the procedure less tedious, the reference medium, which is an ERL, is acted on by a direct electric field while maintaining equal temperatures at the selected points equidistant from the sources of heat flux, the strength of the electric field is measured, and the sought thermal conductivity is determined from calibration curves. An experimental investigation of convective heat transfer of ERLs allowed determining the heat transfer coefficient as a function of strength of the electric field and recommending them for cooling objects with a high potential on their surface. The use of the electrorheological effect is also promising for controlling the thermal boundary layer and can serve as an efficient tool for studying the action of temperature fields and the characteristics of various heat exchangers.

Measurement of acoustic properties of ERLs in electric fields (such as supersonic velocity and absorptivity) allow proposing designs of controllable acoustic devices with readjustable parameters, such as hydrolocators, hydrophones, delay lines, filters, and lenses. ERLs were also used as matching interlayers, for example, for flaw detectors in controlling the strength for improving the quality of acoustic matchings of impedances of the materials of a transformer, contact medium, and controlled article. Similar practical applications are also possible in the area of the development of optical devices.

The use of ERL as the working fluid of dielectric engines made it possible to set up models operating at strengths of the electric field an order of magnitude smaller than when using homogeneous dielectric liquids.

Electrorheological liquids may not only be used in performing devices as transformers of electric energy into mechanical energy but may also serve as indicators and sensors in various technological processes. Thus, from the variation in electric conductivity it is possible to judge the change in parameters of the surrounding medium or an object, for example, of the level of vibration, temperature, and electric voltage.

From rheological characteristics that in the field uniquely depend on the concentration of the solid phase and the presence of water and other additives in an ERL, it is possible to determine the characteristics of a wide range of unknown materials using a comparative measuring procedure and special laboratory instruments such as viscosimeters.

Potentially, of significant interest is the possibility of controlling the surface tension and, therefore, the shape of a finite volume of liquid (droplets) and the spreading of an ERL layer discovered by workers of the Heat and Mass Transfer Institute, the National Academy of Sciences of Belarus. Recently it has also been proved experimentally that, on switching of the field, normal stresses arise in ERLs, whose role is important for the use of electrorheological lubricants in heavily loaded junctions, and the established dilatation phenomenon is important for developing micromechanical devices.

Having predicted the development of ingenious model structures of modern devices and the expansion of their functions, the accumulated new knowledge of the nature and mechanisms of manifestation of the electrorheological effect allows an optimistic forecast for electrorheological technologies. However, some difficulties that researchers, engineers and developers might encounter taking advantage of the merits of ERLs need to be noted (such as controllability, inexpensiveness, and accessibility) in designing devices of mass consumption. These are the limited stability of properties, a definite temperature range of activity, and special requirements on the level of the user's training.

By the estimates of experts, the predicted market for electrorheological liquids is very large. Potentially, they can replace 50% of liquids currently used for hydraulic systems and hydrodynamics, and this can yield a significant economic gain. Thus, in the U.S. alone, the sale of hydraulic pumps, drives, etc. provide an annual profit of 3.5 billion dollars, and for industrial robots it is up to 1 billion dollars. At the present time, large American, German, Chinese, and Japanese companies and universities work on applying electrorheological technologies to aviation, chemical, and medical industrial branches, general mechanical engineering, and the manufacture of control systems. Great interest in the ERL problems is shown by the automobile giants, such as Chrysler and Japanese Toyota and Bridgestone. They focus on applying the electrorheological technology to designing a stepless gearbox, controllable suspension, smooth couplings, brakes, and fuel supply systems. The Korean Samsung Electronics finances projects involving the problems of controlled vibration damping. Apart from the recognized directions of the practical use of the electrorheological effect, publications appeared on its utilization in microelectronics when developing chips (Hong Kong) and controllable micromechanical devices (Lithuania).

The ever-increasing theoretical and application significance of the electrorheological effect is manifested in the annual growth in the number of publications, its systematic listing of topics of the largest international conferences on power engineering, fluid mechanics, and advanced technologies, and also by the setting up (in 1989) and periodical (biennial) holding of international conferences on the ERE, the last of which took place in the summer of 2008 in Dresden and attracted the representatives of 26 countries.

The experience of the past half-century and analysis of the progress of world science and engineering in this period showed how rightful Academician A. V. Luikov was in realizing the importance and determining the principal directions of developing electrorheology. Through the efforts of the team of associates and pupils set up by A. V. Luikov and Z. P. Shul'man, there were developed and finely implemented remarkable capabilities of electrically controlled liquids as applied to modern technologies, which has allowed our state to occupy a prestigious position in the world scientific community over these decades.