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"QURILISHDA YASHIL IQTISODIYOT, SUV VA ATROF-MUHITNI ASRASH TENDENSIYALARI, EKOLOGIK MUAMMOLAR VA INNOVATSION YECHIMLAR" MAVZUSIDAGI RESPUBLIKA MIQYOSIDAGI ILMIY-AMALIY KONFERENSIYA

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Structural analysis of disperse systems and energy-efficient rheological modeling in hydrotransport processes

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Abstract: This article provides a comprehensive overview of the modern theoretical foundations, classification, physicochemical and rheological properties, as well as the electrokinetic and kinetic characteristics of disperse systems, including the mechanisms of their formation and stabilization. The role of disperse systems in hydrotransport, along with the impact of their interaction with polymer composites on pressure dynamics, is analyzed based on international scientific research. The article covers both theoretical and practical approaches aimed at enhancing the significance of disperse systems in construction, mining, environmental protection, the food industry, and the oil and gas sectors.

Keywords: Dispersing systems, pipe cleaning and materials strength, hydrotransport systems.

1. Introduction

Disperse systems are complex physicochemical structures widely used in modern chemistry, hydraulics, construction materials science, food technology, pharmaceuticals, and many other fields. At the core of any colloid chemistry or nanomaterials technology lie disperse systems. The role of disperse systems in hydrotransport is particularly significant in terms of increasing the efficiency of industrial pipelines and reducing resistance that forms on their internal surfaces. All disperse systems share certain common characteristics.

Disperse systems are physicochemical systems in which one substance is evenly distributed (dispersed) within another. These systems consist of two main components:

Dispersed phase – the substance distributed in the form of small particles within another substance;

Dispersion medium – the primary substance that contains the dispersed phase.

In colloid chemistry, the classification of systems is based on several key characteristics of colloidal systems. All colloidal systems are classified according to the following features:

a) The size and fineness of the dispersed phase particles (degree of dispersion);

b) The physical (aggregate) state of the disperse system;

c) The interactions between the dispersed phase and the dispersion medium.

Based on the particle size of the dispersed phase, disperse systems are categorized accordingly.

A specific formula is used to measure dispersity.

$$D=1/a, \tag{1}$$

Here, D represents the dispersity, and a denotes the transverse dimension of a dispersed phase particle. For example, in the case of a spherical particle, a is taken as the diameter, while for a cubic particle, a corresponds to the edge length of the cube.

The smaller the particle size, the greater the degree of dispersion in the system. The specific surface area (S_{sol}) is determined by the ratio of the total surface area S of the particles to the unit volume V (or sometimes the mass) of the dispersed phase:

$$S_{sol}=S/V,(m^{-1}) \tag{2}$$

$$S^{sol}=S/m,\ (m^2/kg) \tag{3}$$

To express dispersity, formula (3) is commonly used. For disperse systems, the specific surface area typically ranges from 10 to 10^6 m²/kg. If S_{sol} does not exceed 10^3 m²/kg, a coarse disperse system is formed. This category includes suspensions, emulsions, and powders. For colloidal and aerosol systems, a value of S_{sol} greater than 10^4 m²/kg is considered typical. According to the size of the dispersed phase particles, disperse systems are classified as follows:

1. Coarse Disperse Systems

Particle size: >1000 nm. Appearance: Particles are visible to the naked eye or through an optical microscope.

Example: Muddy water (solid particles dispersed in water).

2. Colloidal Systems

Particle size: 1–1000 nm. Appearance: Particles are very small but can be observed using specialized techniques.

Example: Milk (liquid fat particles dispersed in water).

3. Molecular Disperse Systems

Particle size: <1 nm

Appearance: Particles are uniformly distributed at the molecular level. Example: Salt dissolved in water.

V. Ostwald proposed classifying disperse systems based on their aggregate states. Depending on the aggregate states of the dispersed phase and the dispersion medium, disperse systems can be divided into nine different types.

2. Object and method of study

Disperse systems possess properties such as degree of dispersion, specific surface area, density, viscosity, particle size distribution, and stability. These characteristics, especially in colloidal systems, determine their stability. Rheologically, disperse systems often exhibit non-Newtonian behavior, meaning their viscosity depends on the applied shear stress.

Among the most well-known rheological models is the Bingham model (flow after yield stress), which states that a certain threshold shear stress (τ_0) must be exceeded before the fluid begins to flow:

$$\tau=\tau_0+\mu p\cdot du/dy \tag{4}$$

Examples: oil, concrete mixtures, thick clay.

Pseudo-plastic (shear-thinning) fluids exhibit a decrease in viscosity with increasing shear rate. Examples include polymer solutions, paints, and muddy suspensions. Their mathematical model (Ostwald–de Waele law) is given by:

$$\tau=K\cdot(du/dy)^n,\ n<1 \tag{5}$$

Dilatant (shear-thickening) fluids show an increase in viscosity as the shear rate increases.

Examples include concentrated starch solutions.

They are described by the Ostwald–de Waele model with n>1. Transporting disperse systems through industrial pipelines (hydrotransport) is widely used in construction, oil and gas, chemical, and mining industries. To improve their efficiency, polymer additives are introduced into the dispersion medium. This:

Reduces internal friction;

Decreases pressure loss;

Saves energy;

Extends the service life of pipelines.

Currently, a number of scientists and researchers worldwide are conducting scientific studies on the hydrotransport of dispersed systems and the influence of polymer compositions on pressure in pipelines. Among them are:

Professor Donald G. Baird, Virginia Tech Institute and State University (USA). Research on “Polymer rheology and processing, polymer compositions, and their flow properties.”

Dr. Jianfeng Wu, Xi’an Jiaotong University (China). Research on “Hydrodynamics of dispersed systems, friction reduction by polymer additives, and turbulence control.”

Professor Georgios C. Georgiou, Cyprus University (Cyprus). Research on “Rheology and hydrodynamics of polymer solutions, friction reduction by polymer additives, and improvement of energy efficiency.”

Dr. Maria Antonietta Aiello, Salento University (Italy). Research on “Polymer compositions and their application in construction materials, enhancing the strength and durability of hydrotransport pipelines.”

Professor Suresh G. Advani, University of Delaware (USA). Research on “Polymer compositions processing technologies, rheology, and behavior in hydrotransport processes.”

Professor Vladimir V. Makarov, Moscow State University of Civil Engineering (Russia). Research on “Friction reduction in hydrotransport systems with polymer additives, rheological properties of dispersed systems.”

Professor Anatoliy P. Grishin, Belarus National Technical University (Belarus). Research on “Application of polymer compositions in hydrotransport pipelines, corrosion protection of pipelines.”

Professor Nikolay I. Lebedev, Saint Petersburg State Technological Institute (Russia). Research on “Rheology of dispersed systems and efficiency improvement of hydrotransport processes with polymer additives.”

Professor Yevgeniy S. Petrov, Kyiv National University of Construction and Architecture (Ukraine). Research on “Application of polymer coatings in hydrotransport systems, reduction of pressure losses in pipelines.”

Professor Shinichi Koyama, Tokyo Institute of Technology (Japan). Research on “Friction reduction and energy efficiency improvement in hydrotransport systems using polymer additives.”

Professor Jong-Ho Kim, Seoul National University (South Korea). Research on “Improving corrosion resistance and extending service life of hydrotransport pipelines using polymer compositions.”

Professor Rashid A. Karimov, Baku State University (Azerbaijan). Research on “Application of polymer compositions in hydrotransport pipelines, corrosion protection of pipelines.”

These scientists and researchers conduct important studies in this field. Naturally, in our country there are also many scientists who conduct significant scientific research in this area. The development of colloid chemistry in Uzbekistan is associated with the research and practical achievements of Uzbek chemists such as K.S. Akhmedov, Kh.U. Usmonov, M.A. Asqarov, and their students. Regarding improving hydrotransport of dispersed systems in pressure pipelines, scientific studies have been carried out by Yu.G. Abrosimov, Hoang Zan Bin, A.H. Mirzajanzada, N.M. Lebedev, K. Sellin, I.L. Povkh, Na Tiong Lin, M.I. Valiyev, J.W. Hoyt, M.P. Tulin, I.I. Yeroshkina, F.I. Frankl, G.I. Barenblatt, V.M. Makkaveyev, M.M. Gareyev, I.I. Levi, Kh. Rauz, Yu.A. Buyevich, A.N. Krayko, S. Sou, G. Uoilis, A. Fortye, D.F. Fayzullaev, Kh.A. Rakhmatulin, K.Sh. Latipov, S.I. Kril, A.A. Shakirov, I. Khujayev, S. Khudaykulov, I.E. Makhmudov, Kh. Ilkhomov, A.I. Umarov, S.S. Negmatov, A.G. Jalilov, T.A. Atakuziyev, A.S. Ibadullayev, Kh.E. Yunusov, E.U. Teshabayeva, A.R. Babayev, and other scientists. They introduced methods to improve efficiency and maintain particle balance in dispersed systems used in construction and mining industries, including the physical-chemical properties, concentration, machinery and apparatus involved in hydrotransport under pressure.

Electrokinetic phenomena in dispersed systems — such as electrophoresis, electroosmosis, sedimentation potential, and streaming potential — depend on the motion of charged particles in the system.

Brownian motion, diffusion, osmosis, and sedimentation represent the kinetic movements of particles. If Brownian motion is related to the thermal movement of medium molecules, then particles of the dispersed phase are also subject to thermal motion. This implies that the dispersed phase — the collection of particles, gases, and solutions — must obey the statistical laws of molecular-kinetic theory. Einstein and Smoluchowski developed this theory, basing it on the law of diffusion, because the randomness of Brownian motion is necessary to equalize the concentration of the dispersed phase in all dispersive media.

The Einstein-Smoluchowski equations mathematically describe particle motion and diffusion:

$$\frac{R*T}{6*\pi*\eta*N_A} \tag{6}$$

N_a – Avogadro number (Avogadro soni), R – Universal gas constant (Umumiy gaz konstantasi), T – Temperature, Kelvin (Harorat, K), η – Viscosity of the dispersion medium, N·s/m² (Dispers muhitning yopishqoqligi), r – Radius (size) of the diffusing particle, meters (Diffuziya qilayotgan zarrachaning oʻlchami, m).

The application of molecular-kinetic laws, statistical laws, and entropy laws to solutions allows them to be viewed simultaneously as systems possessing the properties of heterogeneous-dispersed systems and true solutions. At the same time, colloidal solutions (lyosols) must also obey the laws of osmotic pressure. Osmosis is the one-way diffusion of substances through semipermeable membranes from a solution with a higher concentration to a solution with a lower concentration. For lyosols, the osmotic pressure, P_{osm}, is calculated according to the van’t Hoff equation.

$$P_{OCM}=\frac{C_v*R*T}{N_A} \tag{7}$$

R is the universal gas constant; T is the absolute temperature; C_v is the partial concentration (the number of colloidal particles per unit volume). From the equation, it can be understood that the osmotic pressure P_{osm} increases with the increase in the number of colloidal particles in a given volume, even if the mass of the dispersed phase remains constant (with increasing dispersity). For two identical lyosols with different partial concentrations, the change in osmotic pressure is directly proportional to their partial concentrations. The osmotic pressure in colloidal solutions is much smaller compared to true solutions because the particle concentration in true solutions is higher than in colloidal solutions (sols). The characteristic property of suspensions, emulsions, powders, and aerosols is the tendency of dispersed phase particles to settle or rise.

The process of settling of dispersed phase particles is called sedimentation, while the rising of particles is known as reverse sedimentation (flotation). Each particle in the system is subjected to gravitational force and Archimedes' force. These forces act constantly but in opposite directions. The resultant force causing sedimentation is calculated as follows:

$$F= 4/3\ \pi r^2(p-p_0)g \tag{8}$$

F — gravitational force, kg·m/s^2(Newtons);r — radius of the dispersed phase particle, meters (m);ρ — density of the dispersed phase particle, kilograms per cubic meter (kg/m³);ρ_0 — density of the dispersion medium, kilograms per cubic meter (kg/m³); g — acceleration due to gravity,9.8 m/s^2;η — viscosity of the dispersion medium.. Equation for calculating the sedimentation velocity of a particle

$$V_{sub}=\frac{2g*(p-p_0)*r^2}{9*\eta} \tag{9}$$

The equation shows that the constant sedimentation velocity of a particle is proportional to the square of its radius, proportional to the difference in densities between the dispersion medium and the dispersed phase, and inversely proportional to the viscosity of the medium. If $\rho > \rho_0$, the particle settles down; if $\rho < \rho_0$, the particle rises, which is typical for gases and most liquid emulsions, where the reverse sedimentation phenomenon occurs. The sedimentation of particles occurs in suspensions, aerosols, and emulsions according to this law.

Dispersion: The breakdown of large substances into smaller ones (e.g., colloidal mills, ultrasound).

Condensation: The aggregation of molecules, atoms, or ions to form colloidal particles. Since small particles have high surface energy, stabilizers such as ions, surfactants, or polyelectrolytes are used to stabilize them.

Dispersed systems are characterized by two main types of stability:

Sedimentation (kinetic) stability – the particles do not settle.

Aggregative stability – particles do not stick to each other.

Coagulation – the process where particles aggregate to form large clusters;

Peptization – the reverse process, where aggregated particles break apart.

3. Research results and discussion

Various researchers have attempted to explain experimental results in different ways and proposed several theories. However, each of them had certain limitations, neglecting many important factors, and therefore could not provide a fully substantiated explanation. Developing a single, comprehensive theory for the stability of dispersed systems turned out to be a complex task. Today, the scientific community widely accepts a theory that simultaneously takes into account the electrostatic repulsive forces between particles and the intermolecular attractive forces. This theory is especially effective in practice for lyophobic dispersed systems, i.e., systems where the adsorption stability factor plays a minor role.

This theory was first developed by Soviet scientists B.V. Derjaguin and L.D. Landau during 1937–1941. Later, it was independently advanced in 1948 by Dutch scientists E. Verwey and J.T.G. Overbeek. The theory is called the DLVO theory, named after the initials of its main authors.

The theory studies how Van der Waals attractive forces and electrostatic repulsive forces (interactions between the double electric layers) work together. According to Derjaguin, if particles are separated by a liquid, when they approach each other, a “disjoining pressure” arises. This pressure governs the interaction between particles based on the balance of attractive and repulsive forces. In other words, this pressure either facilitates the establishment of interaction between particles (positive pressure) or, conversely, their aggregation into coagulation (negative pressure). Experiments have confirmed the existence of this disjoining pressure. This phenomenon can be viewed as the difference between the hydrostatic pressures on the particle surface and in the surrounding liquid, explained by the difference in the energy state of liquid molecules in the free volume close to and far from the particles. The total interaction energy between two particles is expressed as follows:

$$U=U_e+U_m \tag{10}$$

Here, U_e is the repulsive energy, and U_m is the attractive energy. In this formula, the first term represents the repulsive energy arising from electrostatic effects, while the second term corresponds to the attractive energy caused by Van der Waals forces. According to the DLVO theory, these interactions determine the behavior of dispersed systems. Their stability or the rate of coagulation depends on the magnitude and direction of the total potential energy between the particles. The positive repulsive energy $U_e(h)$ decreases exponentially with increasing distance h, whereas the negative attractive energy $U_m(h)$ is inversely proportional to the square of the distance. The existence of this minimum is associated with the phenomenon of thixotropy, i.e., the ability of many sols to revert to gels. At intermediate distances, the maximum value represents the potential barrier that prevents particle aggregation. These interaction forces can act over distances of hundreds of nanometers, with the highest energy values reaching approximately 10^{-2} J/m² or greater on the particle surface. The increase in the potential barrier occurs due to a small increase in the surface potential φ_δ of the particles. In practice, it has been observed that when $\varphi_0 \approx 30$mV, a barrier forms that ensures the aggregative stability of the dispersed system. The coagulation threshold depends directly on the detection time, observation methods (light scattering, rheological properties, etc.), and the concentration of the sol, so experimental conditions must always be clearly specified.

Hidden and visible coagulation stages are distinguished. Initially, particles grow in size, which is unclear even to the naked eye (hidden coagulation), and later the particle size becomes visible, transitioning hidden coagulation into visible coagulation. The coagulation strength of an electrolyte varies significantly depending on its charge and interaction with ions of opposite charge. Experiments show that as the charge of ions increases, coagulation begins even at low ion concentrations. This phenomenon is known as the Schulze-Hardy rule. The DLVO theory allows the calculation of the critical concentration of the electrolyte, beyond which the coagulation process becomes irreversible. This concentration is known as the coagulation threshold.

Deryagin and Landau determined that the energy barrier between colloidal particles disappears when the coagulation threshold is reached. Thus, at high potentials, the rapid coagulation threshold is inversely proportional to the charge of the counterion, which correlates well with the Schulze-Hardy rule. At low potentials, the coagulation threshold on the particle surface is inversely proportional to the square of the counterion charge and also depends on the magnitude of the potential (i.e., if the system has a small barrier, coagulation slows down).

The slight deviation from the $z6$ dependence in the experimental relation with ion charge is explained by the increasing role of specific adsorption as ion charge increases. In this way, simplified forms of the DLVO theory help correctly describe the main laws of coagulation experimentally using electrolytes. According to DLVO theory, there are two extreme states in the coagulation process:

Neutralization coagulation, where stability loss occurs due to the loss (neutralization) of the charge of colloidal particles and reduction of their surface potential φ_0;

Concentration coagulation, where stability loss is not due to reduction of φ_0, but due to compression of the diffuse electrical double layer (DEDL or ITEQ).

According to DLVO theory, adding electrolyte to a dispersed system compresses the diffuse layer around particles, causing them to approach each other, and attractive forces dominate at this close range. Compression of the diffuse layer is related to the replacement of counterions by coagulating electrolyte ions. This compression occurs due to two factors: first, a decrease in potential through specific adsorption of the added electrolyte ions, and second, a reduction in thermal repulsion of counterions caused by increased ionic strength of the solution. Which mechanism dominates helps differentiate coagulation into neutralization and concentration types. Neutralization coagulation is more pronounced in systems where particles have low electrical potential. In this case, the added electrolyte ions specifically adsorb onto the particle surface, especially ions with the same charge as the counterions. They reside in the diffuse layer and significantly reduce the surface potential φ_0, while the neutralization of the φ_0 -potential occurs in the adsorption layer. If the charge of the ions exceeds φ_0, the particle surface may undergo charge reversal (overcharging). In neutralization coagulation, the absence of aggregative stability is typical between the minimum and maximum concentrations of the electrolyte. If the amount of electrolyte added exceeds a certain maximum limit, it can transfer the dispersed system into a second stability zone, where particles acquire a charge opposite to that in the first stability region. As the ion charge increases, the importance of specific adsorption grows; therefore, neutralization coagulation intensifies when electrolytes with multivalent ions are added. The effect of adsorption on stability and coagulation can be envisioned as a reduction in hydration or the formation of less dissociated compounds on the particle surface. In both cases, interaction with the environment decreases, surface tension increases, and as a result, the aggregative stability of the dispersed system is lost.

Dispersed systems are practically applied in the following fields:

Drinking and industrial water purification (coagulation);
Construction (concrete, clay);
Pharmaceuticals (emulsions, suspensions);
Food industry (oils, milk, sauces);
Cosmetics (creams, lotions);
Oil industry (drilling suspensions).

4. Conclusion

Dispersed systems are complex systems with not only theoretical but also significant practical importance, and their in-depth study is crucial in the context of modern scientific and technological progress. By thoroughly investigating their role in hydrotransport, as well as their rheological and physicochemical properties, industrial efficiency can be significantly improved. These systems can be further optimized based on polymer compositions and international experience. Hydrotransport of dispersed systems refers to the technology of transporting mixtures of solid and liquid substances through pipelines under various conditions. This technology finds broad application in many industries such as mining, chemical, oil and gas, construction, and utilities. Enhancing the efficiency of these systems improves not only technological processes but also substantially increases economic benefits. To boost the technological efficiency of hydrotransport, it is necessary to deeply analyze and optimally control the rheological properties of the mixtures, including viscosity, density, and particle size. Additionally, selecting and properly arranging equipment such as pumps, pipelines, and separators, as well as integrating modern automated control systems, greatly enhance overall performance. Implementing energy-efficient technologies, employing recycling circulation systems, using materials that reduce friction, and systematically organizing technical maintenance ensure the economic efficiency of hydrotransport systems. Moreover, reducing operational costs and material losses increases the profitability of the process.

Thus, by harmonizing technological and economic approaches in the hydrotransport of dispersed systems, maximal system efficiency can be achieved. This contributes to stabilizing production capacities, conserving resources, and improving environmental safety.

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