# Preface

Practically all fluids in our everyday surroundings are to some degree disperse systems one of the following types: liquid-solid particles, liquid-gas particles, gas-liquid particles, liquid-liquid particles. They are called accordingly suspensions, liquid-gas and gas-liquid mixtures, emulsions and consist of continuous or carrying phase, which could be liquid or gaseous, and dispersed phase, which contains solid particles of different size and form, bubbles and droplets. The latter will be henceforward called simply particles, adding when needed words solid, liquid or gaseous.

Particle size changes in broad range from microscopic (submicron, micron) to macroscopic (millimeter, centimeter). Particles, which sizes do not exceed several microns, are called Brownian, since they are subjected to Brownian (thermal) motion. Small particles, which density slightly differs from that of surrounding medium, are called inertialess and passive when in addition their volume concentration is negligible small, so that they do not affect the motion of carrying flow. Increasing of particle size and (or) particle density relative the outer medium leads to rise of particle inertia, while buildup of volume concentration enhances particle-fluid and particle-particle interactions, formation of particle aggregates and in the presence of external oriented force field production of oriented particle structures. The latter exerts influence on rheological properties and sometimes causes the non-Newtonian behavior of the medium.

Particle shape may also be multiform. Sometimes it could be approached by form close to canonical: spherical, ellipsoidal with different ratio of semi axes (in limiting case oblate disk-shaped, prolate cigar-shaped) and cylindrical.

Prime interest in engineering applications attracts determination of properties of dispersive media, separation of multiphase multicomponent mixtures subjected to different force fields (gravitational, centrifugal, electrical, magnetic) and motion of dispersive media in tubes, channels and through porous medium. To solve these problems it is necessary to know behavior of separate particle as well as ensemble of particles.

One of the basic parameter affecting both properties and dynamic characteristics of medium is volume content (volume concentration) $\varphi$ of disperse phase. Disperse medium with $\varphi \ll 1$ are called dilute. For such a medium average spacing between particles is much more than the particle mean size and each particle in limiting case

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of infinite diluted solution, that is at $\varphi \to 0$, behaves as a single one, its motion is completely determined by external forces, including forces acting on particles from surrounding medium. To the latter belong regular (mean) viscous drag force and random force due to collisions of molecules of surrounding medium with the particle, which causes Brownian motion of the particle. Brownian motion is noticeable only for Brownian particles and does not substantially affect movement of larger particles. Random force arises besides by chaotic fluctuations of carrying fluid, when particle moves in turbulent flow.

Enhancement of $\varphi$ reduces the mean distance between particles and requires to take into account interactions between particles. The motion of particle subject to interaction forces is called hindered motion. Among interaction forces are distinguished hydrodynamic, molecular and electrostatic forces. The first one is characterized by long-range interaction and depends on hydrodynamic parameters, geometrical properties of particles (size, shape, orientation in space) and mutual arrangement of particles in space (configuration). Hydrodynamic forces are most pronounced when the distance between particle surfaces (clearance) is equal or less than particle linear size. The molecular interparticle force (Van der Waals attractive force) manifests itself distinctly only when the clearance between approaching particles becomes much less than the particle size. This force keeps particles together and promotes coagulation of rigid or coalescence of liquid and gaseous particles. Electrostatic force is repulsion force due to thin charged double layers on particle surfaces. This force prevents particle collisions and stabilizes dispersive medium. The range of action of electrostatic force is small compared with hydrodynamic force, and so it is short-range as well as molecular force. When particle volume concentration exceeds 10% the average interparticle spacing is not great and combined action of all mentioned forces can lead to formation of ordered structures of particles causing anisotropy of transport coefficients and non-Newtonian properties of dispersive system.

Great influence on particle behavior exert flow conditions of carrying phase. Particle in quiescent fluid settles under gravity with constant velocity called sedimentation velocity. At $\varphi \to 0$ this velocity is determined by Stokes formula for rigid spherical particle and Hadamar-Rybczynski formula for liquid one. Increasing of $\varphi$ leads to noticeable influence of surrounding particles on sedimentation velocity. If besides the particle size is enough small, the Brownian motion also affects the sedimentation velocity. Inhomogeneity of velocity distribution in laminar flow can also influence particle motion. Since the particle size is small compared to characteristic linear scale of the flow region, the flow in the vicinity of the particle could be considered as sheared. Such a flow induces translation and rotation particle motions, which with regard to interaction forces brings to mutual approach and further collision and coagulation of particles.

Particle motion in turbulent flow is more complicated problem, while particle random motion due to effects of chaotic turbulent fluctuations, which enhances collision frequencies, is superimposed on regular transport with mean velocity under the action of carrying medium and external forces. Hence the rate of particle coagulation increases and processes of heat and mass exchange become more intensive.

The size of particles and ratio of densities of particle and carrying medium determine the particle inertia. Dimensionless parameter that allows to distinguish inertial particle from inertialess one, is Stokes number St equal to the ratio of particle dynamic relaxation time to characteristic time of exposure to environmental factors on the particle. Inertialess particles ($St \ll 1$, small particles which density differs slightly from that of carrying medium) are fully involved in the movement of the carrying flow and its motion is on the whole determined by the characteristics of continuous phase. Inertial particles ($St \gg 1$, relative big particles which density considerably deviates from the density of carrying medium) are only partially involved in the motion of continuous phase. All this makes difficult to investigate dynamics of such particles, since it requires to take into account interparticle collisions (for high concentrated disperse medium this concerns inertialess particles too) and to recruit kinetic theory of gases.

Presence of enormous amount of particles in a unit volume of disperse medium, action of random fluctuations of environmental factors and inverse influence of random motion of particles on the surrounding medium makes impossible the description of dispersive medium behavior through deterministic method. The most fruitful and productive method is statistical method. This method examines not the behavior of each particle but the behavior of particle ensemble by means of probability distribution function (PDF), which, is able to describe the change of particle ensemble configuration in space-time with regard for particle relative motion under action of different forces. Statistical characteristics of PDF permit to determine the macroscopic properties of dispersive medium.

The content of the book stems from lecture courses given to students of Moscow State University of Oil and Gas. The aim of the book is to give foundation of statistical methods used in hydrodynamics of micro particles that is hydrodynamics of suspension, which contains suspended in fluid micro particles. The first two chapters provide an introduction to probability theory and microhydrodynamics. The theory of Brownian motion of micro particles taking into account particle-particle and particle-fluid interactions are described in chapter 3. The fourth chapter contains necessary information about turbulent flow and its statistical description. The motion of micro particles in turbulent flow forms the subject of chapter 5. Chapters 6 and 7 deals with interactions of inertialess and inertial particles.

It should be made a remark about the title of the book. The notion of microhydrodynamics was first introduced by G.K. Batchelor (see Batchelor G.K. Developments in Microhydrodynamics/In theoretical and applied Mechanics. Ed. W.T. Koiter. - Amsterdam: North Holland, 1976. P. 33-55) and was defined as a part of hydrodynamics, which studies the motion of particles in fluid under low Reynolds numbers. In the book this notion is extended not only to small but also to finite Reynolds numbers, in order to cover micro particle motion in turbulent flow. It seems that this naturally reflects the increasing interest to the topic of the book.

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