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Д.В. Сокольский атындағы «Жанармай,
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ИЗВЕСТИЯ

НАЦИОНАЛЬНОЙ АКАДЕМИИ НАУК
РЕСПУБЛИКИ КАЗАХСТАН
АО «Институт топлива, катализа и
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Қазақстан Республикасы Ұлттық ғылым академиясы "ҚР ҰҒА Хабарлары. Химия және технология сериясы" ғылыми журналының Web of Science-тің жаңаланған нұсқасы Emerging Sources Citation Index-те индекстелуге қабылданғанын хабарлайды. Бұл индекстелу барысында Clarivate Analytics компаниясы журналды одан әрі the Science Citation Index Expanded, the Social Sciences Citation Index және the Arts & Humanities Citation Index-ке қабылдау мәселесін қарастыруда. Webof Science зерттеушілер, авторлар, баспашылар мен мекемелерге контент тереңдігі мен сапасын ұсынады. ҚР ҰҒА Хабарлары. Химия және технология сериясы Emerging Sources Citation Index-ке енуі біздің қоғамдастық үшін ең өзекті және беделді химиялық ғылымдар бойынша контентке адалдығымызды білдіреді.

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S.R. Rasulov, G.R. Mustafayeva

Azerbaijan State Oil and Industry University, Baku, Azerbaijan Republic.
E-mail: rasulovsakit@gmail.com, gulsen190777@gmail.com

HYDRODYNAMIC FEATURES OF SUSPENSIONS AND EMULSIONS FLOWS.

Abstract. This scientific article is devoted to the problems associated with the flow of suspensions and emulsions and some simplifications of the real picture of the flow of a polydisperse medium are made. It is also stipulated that differential equations characterizing the motion of suspensions and emulsions should take into account the fundamental discontinuity of the medium and the physicochemical processes of heat and mass transfer occurring in it. Taking into account all these factors, a general equation for multiphase systems is proposed with certain simplifications that do not change.

The behavior of particles in two-phase systems, their concentration, collision and coagulation are considered. As a result, it was concluded that there is a multifactorial interaction and mutual influence of both phases in a dispersed flow. A differential equation of motion of a single i-th spherical particle in suspension was proposed, and an equation describing the drag force of a solid spherical particles. Equations of conservation of mass and momentum are presented for one-dimensional laminar motion of two incompressible phases in a gravity field with the same pressure in the phases.

Having studied the parameters of the flow of fine particles in a turbulent gas flow, some assumptions were made. It was found that the pulsating motion of particles, performed by them during one period of gas pulsations, can be represented as a change in the pulsating gas velocity in time. The parameter of entrainment of particles by a pulsating medium is an important characteristic in determining the transport coefficients in a turbulent flow.

It is concluded that the presence of various kinds of particles in the liquid complicates the problem of solving hydromechanical problems in turbulent and laminar flow, and the assumptions given in the work facilitate the study of this problem.

Key words: hydrodynamics, differential equation, suspensions, emulsions, dispersed phase, solid spherical particle, turbulent flow, pulsating motion.

In order for theoretical solution the problem of suspensions and emulsions flows, some simplifications of the real picture of the flow of a polydisperse medium with the presence different types particles and sizes were carried out, on the grounds that to study this problem it is necessary to combine hydromechanics, statistical mechanics, mechanics of continuous media, thermodynamics of irreversible processes, etc. [1-8] In addition, the systems of differential equations describing the general cases of motion of suspensions and emulsions must take into account the fundamental discontinuity of the medium and the physicochemical processes of heat and mass transfer occurring in it. In [2], the general equations of motion of multiphase systems, the equation of continuity and energy with a certain simplification of the flow scheme for that phase were proposed:

$$\frac{\partial \rho^{(k)}}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho^{(k)} U_j^{(k)}\right) = W^{(k)}$$

$$\rho^{(k)} \frac{dU_i^{(k)}}{dt} = \frac{\partial}{\partial x_j}\left[-P^{(k)}\delta_{ji} + \eta_m^{(k)}\Delta_{ji}^{(k)} + \eta_{m2}^{(k)}\Theta^{(k)}\delta ji\right] +$$

$$+\rho^{(k)} F_i^{(k)} - \left(U_i^{(k)} - U_{mi}\right) W^{(k)} + +\rho^{(k)} \sum\nolimits_{(p)} f^{(kp)} \left(U_i^{(p)} - U_i^{(k)}\right) \qquad (1)$$

$P^{(k)}$ – partial static pressure of the component k, η_m – viscosity of the liquid phase in the mixture, $\eta_{m2} = \zeta_m - \frac{2}{3}\eta_m, \zeta_m$ – second viscosity, $\Delta_{ji}^{(k)} = \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}$ – shear strain rate, $\Theta^{(k)} = \frac{\partial U_k}{\partial x_k}$ – elongation strain rate, δ_{ji}-thickness of deposits, $W^{(k)}$ – formation rate of component k per unit volume, $\rho^{(k)}$ – is the concentration of the k - th phase, the $x_j - j$ – th axis of the coordinate system, $f^{(kp)}$ – the time constant of the process of exchange of momentum between the set of particles k and p, $U_j^{(k)}$ – which are the velocities of that particle in the direction. $F_i^{(k)}$ – i-th the component of the external force acting on a unit mass of the liquid and defined as:

$$F_i^{(k)} = \frac{1}{2}\frac{\rho_c}{\rho_d{}^{(k)}}\frac{d}{dt}\left(U_i - U_i^{(k)}\right) + \frac{9}{2\sqrt{\pi}a_r}\frac{\rho_c}{\rho_d{}^{(k)}}\, x$$

$$x\sqrt{\frac{\eta}{\rho^{(k)}}}\int_0^t \left[\frac{d}{d\tau}\left(U_i - U_i^{(k)}\right)\right](t-\tau)^{-1/2}d\tau$$

where $\rho^{(k)}$- is the density of the k-th phase, t- is the considered moment of time, ρ_c and ρ_d is the density of the medium and the particle, a-is the particle diameter, τ – is the shear stress.

The significant assumptions and simplifications made do not change the formal and complex nature of equation (1). In order to simplify these equations, you can use them for two-phase systems, in which many phenomena can be neglected. The processes of collision, coagulation and fragmentation play an important role here. It should be noted that with an increase in the concentration of particles, suspensions and emulsions belong to viscoplastic fluids and obey the laws of flow of non-Newtonian fluids [9-14]. This is determined by the value of the viscosity, which is due to the transverse shear and the interaction of particles and the carrier phase. As a result, we conclude that a complex multifactorial interaction and mutual influence of both phases, significantly changing the intensity of interphase exchange, is possible in a dispersed flow.

The movement of particles of the same type and size in a turbulent flow is the simplest case of the movement of a turbulent mixture formed by the carrier and dispersed phases. Proceeding from this, equation (1) is the differential equation of motion of a single spherical particle in a turbulized medium, considered by Basset, Boussinesq and Oseen, and is represented in the form [15,16]

$$\frac{\pi}{6}a^3\rho_d\frac{du_{di}}{dt} = 3\pi\eta_c a(V_i - u_{di}) - \frac{\pi}{6}a^3(\rho_d - \rho_c)\frac{dV_i}{dt} -$$

$$-\frac{1}{2}\frac{\pi}{6}a^3\rho_c\left(\frac{dV_i}{dt} - \frac{du_{di}}{dt}\right) +$$

$$+\frac{3}{2}a^2\sqrt{\pi\rho\eta_c}\int_{t_0}^{t}\frac{dV_i/dt' - du_{di}/dt'}{\sqrt{t-t'}}dt' + F_e\,, \qquad (2)$$

where V_i and u_{di} – is the velocity of the medium and the particle, respectively, considered in the i -th direction, F_e-is the external force. On the right side of the equation, the first term is represented by the force of resistance to the motion of the particle, the second term characterizes the pressure gradient in the liquid that surrounds the solid particle, the third term shows the force accelerating the particles relative to the liquid. The fourth term takes into account the possibility of flow deviation from the steady state (Basset force). The terms containing the pressure gradient attached to the mass and the Basset force are significant if the density of the fluid is of the same order of magnitude or greater than the density of the solid particle.

Under the condition $\rho_c << \rho_d$, equation (2) is greatly simplified. This condition characterizes the flow of gas and liquid suspensions (for example, aerosols) and does not apply to the flow of emulsions (liquid-liquid systems), etc. Large sizes of a single drop or a single bubble during flow in a flow cause deformations and deviations from a spherical shape, this makes the movement non-uniform or creates non-uniform distribution of surface (capillary) forces. With the loss of the spherical shape of particles, the picture of their hydrodynamic flow around them, the drag coefficient, which affects the coefficient of mass and heat transfer, changes [17-20].

Let us determine the drag force for a spherical solid particle in suspension, if the law of its velocity variation with time is given $V = V(t)$. The drag force of a solid spherical particle can be determined from the expression

$$F_T = 2\pi\rho_c\, a^3\left[\frac{1}{3}\frac{dV}{dt} + \frac{3\nu_c}{a^2}V + \frac{3}{a}\sqrt{\frac{\nu_c}{\pi}}\int_{-\infty}^{t}\frac{dV}{dt}\frac{d\tau}{\sqrt{t-\tau}}\right] \quad (3)$$

where $\nu_c -$ is the kinematic viscosity of the medium

If the particle moves uniformly according to the law $V = \alpha\, t$, $\alpha -$ where is the acceleration of the particle, then from the above equation we obtain

$$F_T = 2\pi\rho_c\, a^3\alpha\left[\frac{1}{3} + \frac{3\nu_c}{a^2}t + \frac{6}{a}\sqrt{\frac{\nu_c\, t}{\pi}}\right]$$

With uniform motion of a particle with velocity V_0 , we have the expression

$$F_T = 6\pi\rho_c\nu_c\, aV_0\left(1 + \frac{a}{\sqrt{\pi\nu_c\, t}}\right)$$

which, at $t \to \infty$, approaches the value determined by Stokes' law

$$F_T = 6\pi\rho_c\nu_c\, aV_0$$

With one-dimensional laminar motion of two incompressible phases in a gravity field with the same pressure in the phases and monodisperse composition, the particle of equilibrium of motion can be represented in the following form:

a) mass conservation equation

$$\frac{\partial\rho_d\varphi}{\partial t} + \frac{\partial\rho_d\varphi U_d}{\partial x} = 0$$

$$\frac{\partial\rho_c(1-\varphi)}{\partial t} + \frac{\partial\rho_c(1-\varphi)U_c}{\partial x} = 0$$

b) the momentum conservation equation

$$\rho_d\varphi\left(\frac{\partial U_d}{\partial t} + U_d\frac{\partial U_d}{\partial x}\right) = -\varphi\frac{\partial P}{\partial x} - \rho_d\varphi g$$

$$\rho_c(1-\varphi)\left(\frac{\partial U_c}{\partial t} + U_c\frac{\partial U_c}{\partial x}\right) = -(1-\varphi)\frac{\partial P}{\partial x} - \rho_c(1-\varphi)g$$

where U_d and U_c- are the velocity of movement of particles and the flow medium, respectively, φ – the phase shift angle of the particle motion in the medium, determined by the inertness of the particles, due to which the particle is involved in the movement of the medium with some delay, g -is the acceleration of gravity.

In the above equations, the true density of the material of the phases can change during movement due to changes in the compositions during phase transformations, which should be taken into account in the equations. The momentum conservation equation for steady-state uniform particle deposition has the form

$$-\varphi\frac{\partial P}{\partial x}+\rho_d\varphi g=0$$
$$-(1-\varphi)\frac{\partial P}{\partial x}+\rho_c(1-\varphi)g=0$$

Adding these equations taking into account the relation $\rho=\rho_d\varphi+\rho_c\left(1-\varphi\right)$,

$$\frac{\partial P}{\partial x}=\rho\varphi g$$

Having studied the flow parameters of fine particles in a turbulent gas flow, the following assumptions were made: a) the particle size is small in comparison with the scale of turbulent pulsations ($a<20$ *мкм*)and therefore each particle moves, remaining within the initial pulsating mole; b) the particles are spherical in shape and monodisperse; c) the hydrodynamic resistance of particles to the movement of a gaseous medium is described in the first approximation by Stokes' law; d) the concentration of particles in the flow is low and they do not impede the movement of each other, do not collide and do not coagulate. The pulsating motion of particles, performed by them during one period of gas pulsations, can be represented as a change in the pulsating gas velocity in time. Having considered the motion of a particle under the influence of the velocity of the medium, only in the longitudinal direction in the form of a monoharmonic function [15] we can write

$$u=\overline{u}+U'\sin\omega_E t$$

where ω_E- is the Lagrange frequency of the pulsations, $\overline{u}$ – the average value of the pulsation velocity, $U'-$ and the maximum amplitude of the pulsations

Then equation (2), for the Reynolds number $\mathrm{Re}_d<1$ and the mass of substances $m_d=\frac{1}{6}\pi a^3\rho_d$, will be represented in the form [21]

$$\frac{du_d}{dt}+au_d=a(\overline{u}+U'\sin\omega t) \quad (4)$$

The solution to this equation, under the initial conditions $t=0, u_d=0$, will be represented in the form

$$u_d=\overline{u}\left(1-\exp\left(-{}^{t}/_{\tau_p}\right)\right)+\mu_p^2\omega_E\tau_p\overline{u}\exp\left(-{}^{t}/_{\tau_p}\right)+$$
$$+\mu_p U'\sin(\omega_E t-\varphi) \quad (5)$$

where τ_p- is the relaxation time of particles, for Stokes particles, $\tau_p=\frac{1}{18}\frac{\rho_d}{\eta_c}a^2$, $\mu_p=1\big/\left(1+\omega_E^2\tau_d^2\right)^{1/2}$ – the degree of entrainment of particles by a pulsating medium. The parameter of entrainment of particles by a pulsating medium is an important characteristic in determining the transport coefficients in a turbulent flow.

Conclusions. In conclusion, it should be noted that the presence of particles of various kinds in the liquid complicates the problem solving of hydromechanics in turbulent and laminar flow. For this purpose, the paper contains assumptions that facilitate the study of this problem. A formula for determining the resistance force of a solid spherical fluid particle surrounding it is proposed.

С.Р. Расулов, Г.Р. Мустафаева

Әзірбайжан мемлекеттік мұнай және өнеркәсіп университеті, Баку, Әзірбайжан

СУСПЕНЗИЯ МЕН ЭМУЛЬСИЯЛАР АҒЫНЫНЫҢ ГИДРОДИНАМИКАЛЫҚ ЕРЕКШЕЛІКТЕРІ

Аннотация. Бұл ғылыми мақалада полидисперсті орта ағынының нақты көрінісін жеңілдету жүргізілген және суспензия мен эмульсиялар ағынымен байланысты мәселелерге арналған. Сондай-ақ, суспензиялар мен эмульсиялардың қозғалысындағы жылу және масса тасымалдаудың физика-химиялық процесстері, ортаның түбегейлі үзілістігін сипаттайтын дифференциалдық теңдеулерде ескеріліп қарастырылған. Осы факторлардың барлығын ескере отырып, теңдеудің формалды және күрделі сипатын өзгертпейтін белгілі бір оңайлатылған көп кезеңді жүйелердің жалпы теңдеуі ұсынылады.

Екі фазалы жүйелердегі бөлшектердің әрекеті, олардың концентрациясы, соқтығысуы және коагуляциясы қарастырылған. Нәтижесінде дисперсті ағында көп факторлы өзара әрекеттесу және екі фазаның өзара бір-біріне әсері бар екендігі көрсетілді. суспензиядағы сфералық бөлшек пен қатты сфералық бөлшектер кедергі күшін сипаттайтын теңдеу - Жеке алынған *i* қозғалысының дифференциалдық теңдеуі ұсынылды.

Бірдей қысыммен ауырлық күші өрісінде екі сығылмайтын фазалардың ламинарлық қозғалыс кезінде масса мен импульстің сақталу теңдеулері ұсынылған.

Турбулентті газ ағынындағы майдадисперсиялық бөлшектердің ағымының параметрлерін зерттей отырып кейбір болжамдар жасалды. Уақыт өте келе газдың пульсация жылдамдығының өзгеруі ретінде бір кезең ішінде газдың пульсациясы жасаған бөлшектердің пульсациялық қозғалысы деп ұсынылған. Импульсті ортамен бөлшектердің әуестену параметрі турбулентті ағындағы тасымалдану коэффициенттерін анықтауда маңызды сипаттама болып табылады.

Сұйықтықта әр түрлі бөлшектердің болуы турбулентті және ламинарлы ағым кезінде гидромеханика тапсырмаларын шешу мәселесін қиындатады, ал жұмыста келтірілген болжамдар, бұл тапсырманы зерттеуді жеңілдетеді.

Түйін сөздер: гидродинамика, дифференциалдық теңдеу, суспензиялар, эмульсиялар, дисперсті фаза, қатты сфералық бөлшек, турбулентті ағын, пульсациялық қозғалыс.

С.Р. Расулов, Г.Р. Мустафаева

Азербайджанский государственный университет нефти и промышленности, Баку, Азербайджан

ГИДРОДИНАМИЧЕСКИЕ ОСОБЕННОСТИ ТЕЧЕНИЯ СУСПЕНЗИЙ И ЭМУЛЬСИЙ

Аннотация. Данная научная статья посвящается проблемам, связанным с течением суспензий и эмульсий и проведены некоторые упрощения реальной картины течения полидисперсной среды. Также предусмотрено, что дифференциальные уравнения, характеризующие движение суспензий и эмульсий должны учитывать принципиальную разрывность среды и происходящие в ней физико-химические процессы переноса тепла и массы. Учитывая все эти факторы предложено общее уравнение многофазных систем с определенными упрощениями, которые не меняют формальный и сложный характер уравнения.

Рассмотрено поведение частиц в двухфазных системах, их концентрация, столкновение и коагуляция. В результате сделан вывод, что в дисперсном потоке существует многофакторное взаимодействие и взаимное влияние обеих фаз. Было предложено дифференциальное уравнение движения отдельно взятой *i*-той сферической частицы в суспензии, и, уравнение, описывающее силу сопротивления твердой сферической частицы.

Представлены уравнения сохранения массы и импульса при одномерном ламинарном движении двух несжимаемых фаз в поле силы тяжести с одинаковым давлением в фазах.

Изучив параметры течения тонкодисперсных частиц в турбулентном потоке газа, сделаны некоторые допущения. Установлено, что пульсационное движение частиц, совершаемое ими в течении одного периода пульсаций газа, можно представить как изменение пульсационной скорости газа во времени. Параметр увлечения частиц пульсирующей средой является важной характеристикой при определении коэффициентов переноса в турбулентном потоке.

Сделан вывод о том, что наличие в жидкости частиц разного рода осложняет проблему решения задач гидромеханики при турбулентном и ламинарном течении, а допущения, приведенные в работе, облегчают исследование данной задачи.

Ключевые слова: гидродинамика, дифференциальное уравнение, суспензии, эмульсии, дисперсная фаза, твердая сферическая частица, турбулентный поток, пульсационное движение.

Information about authors:

Rasulov Sakit Rauf, doctor of technical sciences, professor, head of the department, Azerbaijan State Oil and Industry University, Baku, Azerbaijan Republic; rasulovsakit@gmail.com; https://orcid.org/0000-0002-1548-3143;

Mustafayeva Gulsen Rasul, PhD in Engineering, docent, Azerbaijan State Oil and Industry University, Baku, Azerbaijan Republic; gulsen190777@gmail.com; https://orcid.org/0000-0001-7254-796X

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