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Hydrodynamic Model of De-Emulsification Processes of Layer' Fluids Flow

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Abstract— **Construction of multiphase fluid movement model is discussed. The classical equation of Navier-Stokes is used for the model description. The interaction water/oil emulsions with the surfactants, leading to decrease the number of emulsions in a stream at its movement upward is considered. The model allows to describe the movement of the water-oil stream taking into account its physical and chemical features.**

Keywords— ***hydrodynamics; oil emulsion; dispersion system; de-emulsification; physical-chemical features***

I. INTRODUCTION

During the extraction and field oil piping of watered oil in wells, as well as in devices of desalinization of oil as a result of sharp decompression and as a consequence degassing, high speed and intensive turbulent mixing the oil emulsions are formed. The main physical and chemical properties of oil emulsions: dispersion, viscosity, density, and resistance to breakage. The formation of emulsions of oil leads to a loss of oil during its production, transportation and preparation for treatment. Destruction of emulsions (de-emulsification) is one of the most important commercial processes for oil [1-3].

For the correct selection of oil dehydration method (de-emulsification) it is necessary to know the mechanism of formation of emulsions and their properties. The intensity of the formation of emulsions in a well depends on the method of oil production, which in turn is determined by the nature of the deposit, period of its operation and physical-chemical properties of the oil itself.

In a flowing mode, the largest mixing of oil and water occurs in the lifting pipes due to degassing of oil and gas mixture passing through the sockets. During the compressor extraction method the emulsions obtained are of extremely high stability due to oxidation of naphthenic acids forming compounds that are effective emulsifiers.

Oil emulsion, being dispersed systems, under certain conditions, have anomalous properties, i.e. are non-Newtonian fluids. As with all non-Newtonian fluid viscosity properties of oil emulsions are characterized by an apparent (effective) viscosity.

Depending on the physical-chemical properties of oil and water, as well as the conditions of formation of emulsion droplet size can be very diverse and range from 0.1 microns to a few tenths of a millimeter. The critical droplet size that may exist in the stream at a given thermodynamic regime are determined by the rate of joint motion of the water and oil, surface tension at the interface and the scale of the flow pulsations. In turbulent flow, zones occur due to irregularity of pulse, and the presence of velocity gradient variable at cross-sections of the pipeline, in which the existence of droplets of different diameters is possible. Small droplets, moving across sections of the pipeline and getting into the zone of lower velocity gradients and smaller-scale fluctuations, have a tendency to enlargement, while getting into the zones of high gradients and large scale fluctuations - have a tendency to fragmentation.

The presence of additional factors (heating, the introduction of de-emulsifiers, etc.) under certain hydrodynamic conditions can lead to phase separation of emulsion transported through pipelines. The stability of emulsions is largely dependent on the composition of the components in a protective shell, which is formed on the surface of the droplet.

The analysis shows that the main factors influencing to the efficiency of the separation of emulsions are:

- density of fluid comprising an emulsion;
- viscosity of liquids comprising an emulsion;
- the diameter of the dispersed phase of globules;
- acceleration of particles;
- the surface area of sedimentation.

II. PROBLEM FORMULATION

Identifying these factors and the nature of their influence can identify techniques to improve the separation of emulsions.

The present work is discussed by us as part of the general problem of modeling the processes of formation and destruction of globular particles that occur sequentially in the working bottom hole formation zone due to the dispersion of one phase to another and then the development of this process of lifting the pipes and finally in the preparation of emulsified primary fluid.

There have been many publications devoted to study of process of oil de-emulsification in recent years. However, the relatively small number of studies is devoted to the study of the rheological characteristics and features of the formation of emulsions depending on the content and composition of the aqueous phase in a wide temperature range. At the same time, there is great need for detailed data on the rheological properties of oil-water emulsions. The main difficulty in solving of these problems is related to insufficient knowledge of the features of the interfacial layer, depending on the conditions of formation of emulsions.

Analysis of pre-existing approaches to modeling this process has shown that existing models were originally intended only to show some general patterns of development of a complex system, but not reflected the hydrodynamics of the flow formation zone in the well and the process conditions. In this context, the purpose of this paper is development of the model of multiphase fluid movement of water-based hydrodynamic flow for a more detailed study of the process of calculation and analysis. There are essential requirements of unification to the equations of the model both in content and in applied numerical methods, which will facilitate the computational experiment.

The model must contain the equation:

a) the main dispersion (carrier) phase which is emulsified fluid;
b) a dispersed phase, which takes into account the interaction of globular particles and de-emulsifier;
c) the heat balance.

III. PROBLEM SOLUTION

Such a model can be derived from the Navier-Stokes equations [4] for an incompressible environment, written in the traditional system of "velocity - pressure."

Let's consider the most general case of motion of a multiphase fluid in an arbitrary three-dimensional volume of the computational domain in the system of rectangular coordinates (x_1, x_2, x_3).

The model of the dispersed environment of emulsified fluid phase. The classical Navier-Stokes equations (in the velocity-pressure domain) for the incompressible environment allows to consider convective as well as diffusive transfer and for three components of the velocity vector U using the effective viscosity $\nu_{ef} = \nu_{mol} + \nu_{turb}$, where ν_{mol} is molecular viscosity and ν_{turb} is turbulent viscosity, thus molecular and turbulent viscosity is presented as:

$$\frac{\partial u}{\partial t} + \sum_{i=1}^{3} u_i \frac{\partial u}{\partial x_i} = \sum_{i=1}^{3} \frac{\partial}{\partial x_i}\left(\nu_{эфф} \frac{\partial u}{\partial x_i}\right) - \frac{1}{\rho}\frac{\partial P}{\partial x_i} + F_j \qquad (1)$$

$$j = 1, 2, 3,$$

where $F_1 = F_2 = 0$, $F_3 = bg(T - \widetilde{T})$; ρ is the density of the base fluid; P is a pressure, b is a thermal coefficient of volumetric expansion of the base fluid, T is the temperature [K] and $\widetilde{T}$ is the temperature corresponding to a given value of $\rho = \rho()$, $g = 9{,}81$ m/s^2.

Not taken into account are:

a) the Coriolis acceleration due to insignificance, and

b) the effect of the globular phase on the base phase velocity.

The equation of incompressibility is added to Eq. (1):

$$\sum_{i=1}^{3} \frac{\partial u_i}{\partial x_i} = 0, \quad i = 1, 2, 3. \qquad (2)$$

In all equations the molecular are and turbulent viscosity of the dispersion phase flow [м^2/s] is defined as

$$\upsilon_{mol} = \frac{\mu_{mol}}{\rho} = const;$$

$$\upsilon_{turb} = \frac{\mu_{turb}}{\rho} = const,$$

where

$$\mu_{mol} = \mu_{mol_0}(1 + a_{11}T + a_{21}T^2)^{-1},$$

$$\mu_{turb} = \mu_{turb_0}(1 + a_{12}T + a_{22}T^2)^{-1}$$

are the dynamic and turbulent viscosity respectively, as a function of temperature [kg·m^{-1}·s^{-1}], where a_{i1}, a_{i2} – are constants, defined for each type of oil fluid, $\rho = F_1(T)$ [kg/m^3].

Combining the equation for the temperature T [K] of the flow and Eq. (1):

$$\frac{\partial T}{\partial t} + \sum_{i=1}^{3} u_i \frac{\partial T}{\partial x_i} = \sum_{i=1}^{3} \frac{\partial}{\partial x_i}\left(\left(\frac{\lambda_o}{c \cdot \rho} + \alpha_T \nu_{турб}\right)\frac{\partial T}{\partial x_i}\right) + \frac{\Delta H}{c \cdot \rho} + K_T \qquad (3)$$

where $\lambda_0 = F_2(t)$ [J·m^{-1}·s^{-1}·K^{-1}], and $c = F_3(t)$ [J·kg^{-1}·K^{-1}] are the coefficients of thermal conductivity and specific heat of the base flow, respectively; α_T is an auxiliary coefficient that equals zero in the simplest case, ΔH - is the local volumetric energy flow entering the medium during the absorption of diffusion radiation (discussed below). The auxiliary coefficient α_T helps to determine the coefficient of the diffusion term (in this case, thermal) as a linear function of the turbulent viscosity. This gives the researcher the opportunity to consider the additional effects associated with turbulence, and thus refine the model. Similar auxiliary coefficients will be introduced in other equations. The value of α_T can be deduced from the definition of the turbulent Prandtl number

$$\mathrm{Pr}_{turb} = (\upsilon_{turb} \cdot \rho \cdot c) / \lambda_{turb},$$

and correspondingly

$$\alpha_T = 1/\mathrm{Pr}_{turb}.$$

We will formulate the part of the model describing the processes occurring in the dispersed phase. It consists of heavier particles with significant velocities for which the condition (6) does not hold. It consists of globular particles with significant own velocity, which can be affected by the size of the globules - influence on the Reynolds number of conditions for the formation of particles, the density distributions of which are known, as well as a small amount of de-emulsifier.

The density of globular particles may be either higher or lower than the density of the main phase. Depending on the state of development of the field in the reservoir fluid globular particles can be both water and oil.

In these conditions it is necessary to take into account the forces of gravity and flow resistance. Given the lack of inter-phase transitions we make the following assumptions:

a) neglect the random interactions of globular particles with each other and accept that changes in the number (concentration) of globular particles occurs only through interaction with the de-emulsifier;

b) ignore the effect of pressure gradient, inertia forces and other forces in the globular particles;

c) globule phase is considered one-component, considering some of averaged spherical particles;

d) the density of the phases due to the slight difference is not considered the same and treat them with the introduction of changes in the multiphase environment de-emulsifier and the chemisorption of a globule;

e) the change in volume of the multiphase medium after the destruction of the globules are not taken into account.

However, one must take into account the forces of gravity and the resistance to flow.

Taking into account the forces acting on the globule in the flow of the fluid emulsified [3, 5]:

$$F_p = W + F_{drag} + F_{adh} + F_{lift} + F_{fr} \qquad (4)$$

where F_p is the resultant force; W is the weight of the particle; F_{drag} is the flow pressure (drag force); F_{adh} is the force of adhesion; F_{lift} is the lifting force and F_{fr} is the frictional force on the particle surface.

Pressure created as a result of oil flowing past globular particles causes them to move. The magnitude of the pressure on the particle can be calculated by equation [6]:

$$F_{дав} = cSp\,\bar{u}^2/2$$

where c is the drag resistance coefficient of the particle; ρ is the density, [kg/m^3]; S is the cross sectional area of the particle, m^2; $\bar{u}$ is the mean velocity of the fluid, [m/s].

Neglecting the various forces acting on, the actual shape of the particles and other factors the force of adhesion [5], can be expressed with the correlation:

$$F_{ад} = h_\omega\, r / 8\pi z_0^2$$

where h_ω is the Lifshitz-Planck constant, J; z_0 is the gap between the particle and the plane in which the adhesion forces reach the maximum; r is the radius of the particle, m.

A non-uniform flow velocity of the particles can cause circulation along the contour of the globular particles, and if a particle pressure increases, and on the particle - decreases, thanks to a force acting on the particle from the bottom up.

$$F = P_p \cdot S$$

where P_p is the pressure of the flow, N/m^2. A force $dF_1 = P_1 S$ acts on the particle from above, while $dF_2 = P_{p2}$ acts from below, where P_{p1} and P_{p2} are pressures acting on the particle from above and below, respectively. Then:

$$F = \left|dF_1\right| - \left|dF_2\right| = \left|P_{p1} - P_{p2}\right| S .$$

Thus, the lifting force is mainly determined by the velocity gradient over the cross section of flow. The increase in the velocity gradient $i = \frac{dv}{dy}$ leads to an increase in the lifting force. The frictional force between the particle and the plane surface (of the given volume) can be written as follows:

$$F_{fr} = k(P + F_{adh})$$

where k is the friction coefficient.

Then, the equations for the components of the velocity vector of the globular phase u_p:

$$\frac{\partial u_{qj}}{\partial t} + \sum_{i=1}^{3} u_i \frac{\partial u_{qj}}{\partial x_i} = \sum_{i=1}^{3} \frac{\partial}{\partial x_i}\left((v_{mol} + \alpha v_{turb})\frac{\partial u_{qj}}{\partial x_i}\right) - g_j + F_{pj}; \ (5)$$

where n_{pmol} is the "molecular" kinematic viscosity of the second phase (globular particles); α is an auxiliary coefficient; $g_1 = g_2 = 0,\ \ g_3 = g;$ F_{pj} is the flow resistance force of a spherical globular particle.

We introduce a model of the dispersed phase equations describing the motion of globular particles and de-emulsifier. Due to the small - about 1% of de-emulsifier content in the dispersed phase, it changes the equation to describe the individual is not appropriate. The globular particles are understood as particular size uniform particles. The equations of globular particle diffusion with concentrations C_j (or the globular density distribution in the given volume) are as follows:

$$\frac{\partial C_j}{\partial t} + \sum_{i=1}^{3} u_i^j \frac{\partial C_j}{\partial x_i} = \sum_{i=1}^{3} \frac{\partial}{\partial x_i}\left((D_{C_j} + \alpha_{C_j} v_{turb})\frac{\partial C_j}{\partial x_i}\right) + \frac{dC}{dt};$$

$$j = 1,2 \qquad (6)$$

where $u_1^j = u_1, u_2^j = u_2, u_3^j = u_3 + u_q$; u_q - velocity of the dispersed phase; D_{C_j} - the diffusion coefficient jth substance α_{C_j} - an auxiliary factor for the substance (it is possible to express the relation for the turbulent number of Schmidt S_{cturb} as $\alpha_{C_j} = 1/Sc_{turb}$); a member $dC_j \big/ dt$ determines the change in concentration of jth compounds as a result of chemisorption [mol/m^3].

Here, D_d^0 is the diffusion coefficient of the de-emulsifier; α_{C_d} is the auxiliary coefficient; M_d is the molar mass of the de-emulsifier.

The diffusion coefficients [m^2/s] for the globules are calculated by Einstein-Smoluchowski equation taking into account the correction factor:

$$D_{C_j} = k_B \tilde{T} / 6\pi\mu_{mol} r$$

where k_B is the Boltzmann constant.

Changes in the concentration of the globules and the de-emulsifier due to the chemisorption and reduced surface tension of the globule at the interface can be described by different equations, in particular, by the kinetic equation of chemisorption:

$$\frac{dC_q}{dt} = \frac{dC_d}{dt} = -\frac{k(T) \cdot C_q \cdot C_d}{1 + K_p(T) \cdot C_d} . \qquad (7)$$

Where $k(T) = k_0 \exp(-E/RT)$ is the reaction rate constant; k_0 is pre-exponential factor; $\rho(\tau)$ is the density distribution of the globules; C_q, C_d are respectively, the concentration of globular particles and de-emulsifier; $K_p(T)$ is the equilibrium constant de-emulsifier on interfacial adsorption surface of the globules; T is temperature of chemical absorption; E is an activation energy (in kcal/mol), R is an universal gas constant.

To ensure adequate determination of the concentration of the globular particles the different types of distributions, including normal, power series distribution, exponential distribution of globular particles are used. These distributions have only one maxi-mum, whereas in the real world can be present for at least two peaks (at the confluence of the smallest particles formed as a result of molecular diffusion in the merger and the growth of larger particles). In such cases, the sum of several distributions can be used.

In solving the problem in a particular setting input and boundary conditions to the system of equations of the model are formed depending on the type of problem being solved. For its numerical solution the various differential methods can be used, including the method of fractional steps with an implicit scheme [7].

IV. CONCLUSION

Application of the proposed mathematical model, which differs from previously known as in appearance, and the number of factors taken into account in it, will expand the class of problems, including consideration of individual characteristics of the oil medium and increase the efficiency of selection of the appropriate de-emulsifier.

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