STUDY OF THE RHEOLOGY OF GAS-LIQUID MIXTURES FOR DETERMINING HYDRAULIC LOSSES DURING THEIR FLOW IN THE REPAIR OF OIL AND GAS WELLS

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Abstract - The article is devoted to the study of the flow and structure of aerated liquids. The main methods for determining the rheological parameters of gas-liquid mixtures, the gas phase of which is nitrogen, are considered. This type of mixture is widely used in the oil and gas industry for current repair and overhaul of wells, when the formation pressure is less than the hydrostatic liquid column in the well. The mathematical model for calculating the hydraulic losses of a gas-liquid nitrided mixture, which consists of Newtonian media of water and gaseous nitrogen, is considered. It is noted that, despite the Newtonian properties of the media, the resulting nitrided liquid is described by the non-Newtonian model, namely the Bingham liquid model. The calculation of the determination of the liquid hydrostatic column at the well bottom during the flow of this type of mixture is presented. Functions for determining the coefficient of hydraulic losses and plastic viscosity of the mixture at a gas content less than 0.52 were obtained based on the obtained experimental data on the nitrided mixture flow through a coiled tubing pipe at different operating modes of the pumping and nitrogen units.

Keywords: Aerated medium, Non-Newtonian liquid, Bingham liquid model, Yield stress, Hydraulic losses, Hydrostatic pressure.

1. Introduction

The aerated liquids [1] and gas-liquid mixtures are increasingly being used in the oil and gas industry. The majority of oil and gas fields in Ukraine have depressed reservoir pressures. This prevents drilling, overhaul and well intensification work, since there is a constant absorption of working fluids, an increase in work time and damage to productive layers. One way to prevent absorption is to use water- or hydrocarbon-based blocking fluids. These fluids create a low-permeability surface on the well walls in productive horizons and prevent the penetration of the working fluid into the reservoir.

The disadvantage of this method is the need to eliminate the formed surface and restore the connection between the reservoir and the wellbore. This entails the use of additional chemical reagents - acids or organic hydrocarbon solvents [2-5]. The use of aerated fluids makes it possible to reduce depression on the reservoir, eliminate the absorption of the working fluid, and subsequently begin well development.

The main gas used to aerate working fluids is nitrogen – an inert, non-corrosive gas that does not cause harm to surface and downhole equipment.

Aerated, in this case nitride, liquids are used during drilling, well overhaul with abnormally low reservoir pressures, repairs using coiled tubing units in the well cleaning, normalizing well bottom, washing proppant after hydraulic fracturing or acid treatments.

2. Literature Review

The properties and rheological parameters of aerated media were studied by A. Bashir, A. Sharifi Haddad, R. Rafati [6], Berger, S.A., Talbot, L., and

Yao, L. S. [7], Azouz, I., Shah, S. N., Vinod, P. S., and Lord, D. L. [8].

Reidenbach et al. [9] carried out experiments with gas-liquid mixtures using nitrogen as the internal phase. The authors suggested that the Herschel-Bulkley model is the most suitable for describing the laminar flow of a gas-liquid mixture through pipes. It was found that replacing N_2 with CO_2 as the internal phase reproduced a similar laminar rheology. A modified scaling relation was used to describe compressibility in turbulent flow. A correlation has been determined for apparent viscosity, which is used as Newtonian viscosity in standard pressure difference calculations.

Sagyn Omirbekova et al. [10] considered the flow and rheological characteristics of gas-liquid mixtures in capillary tubes.

Blauer et al. [11] proposed using effective viscosity, density, average velocity and pipe diameter to calculate the Reynolds number and coefficient of friction for aerated liquids. The author found that the relationship between the Reynolds number and the friction coefficient for an aerated fluid is the same as for a single-phase fluid. He suggested that aerated fluids behave like a plastic Bingham fluid without slipping in a laminar flow area. The viscosity and yield stress of the aerated liquid were determined experimentally depending on the volumetric content of the gaseous component and are presented on Fig. 1 and Fig. 2.

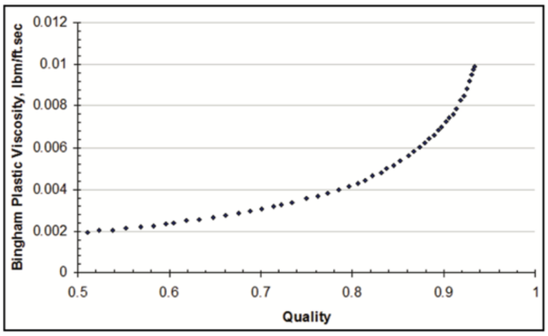

Figure 1: Dependence of the plastic viscosity of an aerated liquid on the volumetric gas content

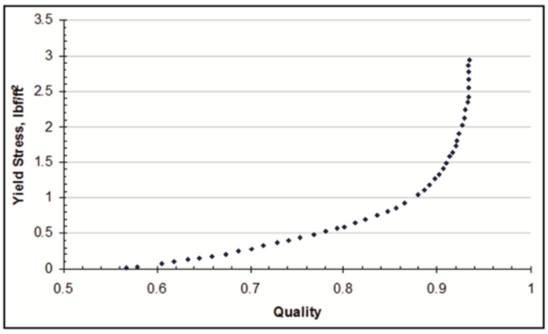

Figure 2: Dependence of the yield stress of an aerated liquid on the volumetric gas content

For further research and detailed flow study, can be used the modern technologies [12, 13], taking into account the peculiarities of the multiphase medium [14].

3. Goal of the Work

The main goal of the work is to study the rheology of gas-liquid mixtures, determine the hydraulic losses during flow through coiled tubing pipes, and the pressure of the aerated liquid column on the well bottom.

4. Materials and Methods

This work considers the flow of a mixture of water with the density of 1000 kg/m^3 and nitrogen gas a flowing through a coiled tubing pipe with an internal diameter of 31.7 mm. The pressure loss along the length of a pipe with a length of L = 4730 m was experimentally determined for various operating parameters - flow rate of nitrogen and pumping units. The experimental results are shown in Table 1, the scheme of installation is shown in Fig. 3.

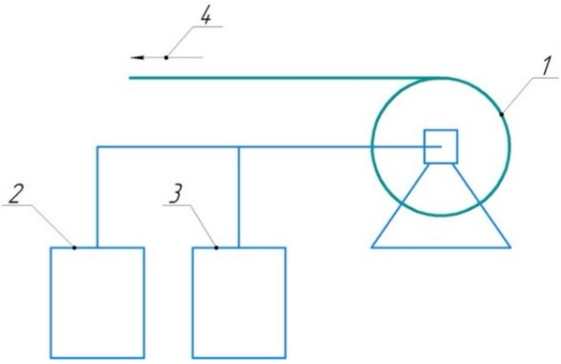

Figure 3: Installation for determining hydraulic losses during the flow of a nitrided mixture: 1 – drum with coiled tubing pipe, 2 – pumping unit, 3 – nitrogen unit, 4 – outlet of nitrided liquid to the atmosphere

Table 1. Mode parameters of nitrided fluid flow and hydraulic losses during the experiment

Flow rate of the nitrogen unit, m^3/min	Flow rate of the pump, l/min	Inlet pressure, atm
10	80	155.3
10	100	198.1
15	100	220.7
15	150	342.9
20	120	292.3
20	150	373.3
30	200	591.7

The flow values of the pumping unit and nitrogen unit, as well as pressures, were determined using special devices - flow and pressure sensors with a measurement error of 0.5%.

To determine hydraulic losses, it is necessary to calculate the following values:

1. Total volume of aerated liquid. Defined as the total volume of liquid and nitrogen per unit time. In this case, the volumetric component of nitrogen is calculated depending on thermobaric conditions.
2. Volume fractions of gaseous and liquid phases.
3. Nitrogen density as a function of pressure and temperature.
4. Density of the gas-liquid mixture.
5. The flow velocity of the mixture through the pipe.
6. Effective viscosity, Reynolds number, hydraulic losses and hydraulic losses coefficient.

The above parameters and hydraulic losses were calculated not for the entire pipe as a whole, but in sections of 10 m in length. For more accurate calculations, the pipe length can be divided into shorter sections. This is necessary to take into account the parameters of nitrogen - the gaseous phase – since its parameters constantly change depending on the pressure, which will differ in each section of the pipe due to the compressibility.

During the experiment, the flow rates in each mode were fixed and measured in m³/min for the nitrogen unit and l/min for the pumping unit. The liquid is considered as an incompressible medium and its volume is constantly fixed. The volume of nitrogen is calculated based on the pressure and temperature at each pipe section.

At a certain inlet temperature and pressure, the nitrogen flow rate in a certain pipe section in m³ is:

$$V_{N_2} = \frac{Q_{N_2} \cdot P_0 (273.2 + t)}{273.2 \cdot P}, \tag{1}$$

where Q_{N2} – volume of nitrogen pumped per unit time, m³/min; P_0 – pressure normal conditions, P_0=0.1 MPa; t – nitrogen temperature at the pipe inlet, C; P – pressure at the pipe inlet, MPa.

The total unit flow rate of the mixture in a certain section of the pipe is:

$$V_\Sigma = V_{N_2} + V_F, \tag{2}$$

where V_F – volume of liquid component in the mixture, m³.

Volume fractions of gaseous and liquid phases in a gas-liquid mixture:

$$\varphi_{N_2} = \frac{V_{N_2}}{V_\Sigma}, \tag{3}$$

$$\varphi_F = \frac{V_F}{V_\Sigma}. \tag{4}$$

Nitrogen density in kg/m³ as a function of pressure and temperature is:

$$\rho_{N_2} = \frac{101300 \cdot P \cdot M}{R(273.2 + t)}, \tag{5}$$

where M – molar mass of gas (for nitrogen M = 0.028 kg/mol); R – universal gas constant (R = 8.31 J/(C·mol) (J/(K·mol))).

Density of the gas-liquid mixture, kg/m³:

$$\rho_{GLM} = \rho_{N_2} \cdot \varphi_{N_2} \cdot \rho_F \cdot \varphi_F. \tag{6}$$

Next, to consider the calculation of the parameters necessary to determine the Reynolds number: the velocity and the effective viscosity of mixture movement in the pipe section.

The velocity of mixture movement in the pipe section is, m/sec:

$$v = \frac{V_\Sigma}{F}, \tag{7}$$

where F – pipe cross-section area, m².

The next step is to determine the rheological parameters of the aerated liquid at various values of the gas component content.

If consider water and nitrogen gas separately, each of them is Newtonian media. But when they are mixed, the resulting nitrided liquid acquires specific structure and is described by the Bingham non-Newtonian fluid model [15]. The main rheological parameters of this model are dynamic yield stress τ_y and plastic viscosity μ_p [16, 17]. These values make it possible to determine the effective viscosity for further calculation of the Reynolds number, the hydraulic loss coefficient and the hydraulic losses along the length of the pipe and in the annular space.

According to Blauer et al. the equation for determining the effective viscosity μ_e has the form:

$$\mu_e = \mu_p + \frac{g \cdot \tau_y \cdot D}{6v}, \tag{8}$$

where μ_e – effective viscosity of aerated liquid, lbm/ft·s; μ_p – plastic viscosity of an aerated liquid, determined from the graphs in the Figure 1, lbf/ft·sec; g – gravity acceleration (g = 32.2 ft/sec^2); τ_y – yield stress determined from the graphs in Fig. 2; D – hydraulic diameter (pipe internal diameter); v – mixture flow velocity through the pipe, ft/s.

This function uses US units. During calculations, additional coefficients will be used to convert to the SI system.

To calculate the plastic viscosity at a volumetric gas content >0.52, an approximation was carried out and the most acceptable function was selected. This function is a cubic polynomial, which gives the smallest discrepancy with the graph (Fig. 1) (It would be good to give the Pearson correlation coefficient that in the programs for approximation shown R^2):

$$\mu_p = 0.2531\varphi_{N_2}^3 - 0.4953\varphi_{N_2}^2 + 0.3263\varphi_{N_2} - 0.0695. \tag{9}$$

In the case when the volumetric gas content is less than 0.52, this polynomial does not give satisfactory final results, the calculated plastic value is less than 0 (Fig. 4).

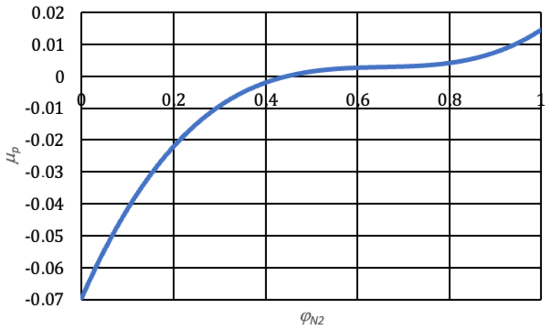

Figure 4: Illustration of the resulting cubic polynomial for determining plastic viscosity as a function of gas content

At known actual data along the pipe length, solving the inverse task, the refined function was defined for calculating plastic viscosity at the volumetric gas content that less than 0.52.

$$\mu_p = \mu_F \cdot \left(\frac{1}{1 + 4.5\varphi_{N_2}{}^{\varphi_{N_2}}}\right), \tag{10}$$

where μ_F – dynamic viscosity of liquid in the studied gas-liquid mixture.

Approximating the graph in Figure 2, to determine the yield stress τ_y:

1. When volumetric gas content is less than 0.52 τ_y=0.
2. When volumetric gas content is more than 0.52:

$$\tau_y = e^{-8.6171+10.0962\cdot\varphi_{N_2}} \tag{11}$$

Reynolds number:

$$Re = \frac{v \cdot D \cdot \rho_{GLM}}{\mu_e}. \tag{12}$$

Coefficient λ at $Re \le 2340$:

$$\lambda = \frac{64}{Re}, \tag{13}$$

at $Re > 2340$ experimentally for gas-liquid mixtures, the gas phase of which is nitrogen, this coefficient is corrected by the authors of this work and takes the following form:

$$\lambda = \frac{0.3}{Re^{0.225}}. \tag{14}$$

Hydraulic pressure losses are determined by the following expression:

$$\Delta P = \lambda \frac{L \cdot \rho_{GLM} \cdot v^2}{d \cdot 2}. \tag{15}$$

The result of all the above equations and functions is the determination of hydraulic losses along the pipe length during the flow of a gas-liquid mixture.

The calculation algorithm is the following:

1. To divide the study area into sections. In this case, a 4730 m long pipe was divided into 473 sections of 10 m each.
2. In the inlet of the pipe, flow rate of the nitrogen unit and pumping unit, and nitrogen temperature are set.
3. The calculation is carried out using the method of successive approximations. First, to set the preliminary inlet pressure, which is the hydraulic loss along the length (it is equal to 1 atm).
4. To calculate the hydraulic losses in each pipe section in such a way that at the outlet from the previous section the parameters are the inlet ones to the next section. Then to sum up the hydraulic losses of each section and substitute the resulting value into step 3. To repeat the calculation until the difference between the previous and the next obtained value of hydraulic losses will be less than 0.01 atm.

Table 2 and Fig. 5 shows a comparison of actual hydraulic losses (Table 1) and those calculated using the algorithm and selected mathematical model.

Determining the value of the hydraulic losses of the nitrided liquid, which is the pressure at the pipe inlet, It is possible to calculate the pressure of the mixture column at the well bottom where the pipe is lowered, taking into account thermobaric conditions.

Table 2. Comparison of calculated and experimental values of hydraulic losses

Flow rate of nitrogen unit, m^3/min	Flow rate of pump, l/min	Inlet pressure, atm	Calculated hydraulic losses, atm
10	80	155.3	151.7
10	100	198.1	190.8
15	100	220.7	216.6
15	150	342.9	341.6
20	120	292.3	286.9
20	150	373.3	367.3
30	200	591.7	579.9

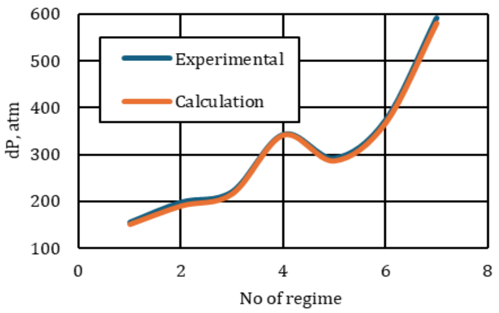

Figure 5: Comparison of experimental and calculated losses of nitrided liquid along the length of a coiled tubing pipe

The calculation is made as follows:

1. The pressure in the pipe is determined at the point where it enters the vertical section (into the well). This interval is divided into equal sections.

2. Based on the obtained pressure, the density of the nitrided liquid and the pressure difference in the first section are calculated:

$$\Delta P_i = \rho_i g h. \quad (16)$$

3. The resulting difference is summed with the inlet pressure $P_{ini} = P_{in1} + \Delta P_i$.

4. The calculation is repeated again, but the inlet pressure for determining the mixture density is P_{ini} and the resulting value. To calculate again the pressure increase and inlet pressure for the next section until the end of the pipe is reached.

5. The pressure of the nitrided liquid column will be the next:

$$P_{GLM} = P_{in1} + \Sigma \Delta P_i. \quad (17)$$

5. Conclusions

The properties of gas-liquid mixtures and their rheological parameters are considered. It was determined that the mixture of two Newtonian media (water and nitrogen gas) is described by the non-Newtonian Bingham fluid model.

Full-scale experiments were carried out to determine hydraulic losses during the flow of the water-nitrogen mixture through the coiled tubing pipe. This allowed to determine a function for calculating the plastic viscosity of the mixture, to clarify the coefficient of hydraulic losses, which will make it possible to more accurately calculate the pressures that need to be created for pumping the nitrided mixture in a certain mode of joint operation of the pumping and the nitrogen units.

The method of dividing the studied interval, determining the actual density, viscosity of gaseous nitrogen and gas-liquid nitrided mixture, step-by-step integration with successive approximations made it possible to obtain hydraulic loss values with an error of 2-3% relative to the experimental data.

As a result, the data obtained makes it possible to calculate the actual hydrostatic pressure at the well bottom and reduce the risk of fluid absorption.

The mathematical model presented in the work can be automated in order to simplify and speed up calculations, select operating modes of the pumping unit and nitrogen unit, taking into account the specific design and geological information of each specific well.

In the future, it is planned to study gas-liquid mixtures consisting of a liquid phase, which is a non-Newtonian liquid, described by various models, and a gaseous phase - nitrogen, air, natural gas, carbon dioxide.

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