Research of Upward Gas-Liquid Flows with Foam-Forming Surface-Active Substances in a Vertical Channel

N. G. Musakaev,[1, 2, a] S. L. Borodin,[1, 2] V. A. Ogay,[1] A. Yu. Yushkov,[1] and M. A. Vasilev[3]

[1] *Industrial University of Tyumen, Volodarskogo Str. 38, 625000, Tyumen, Russia*
[2] *Tyumen Branch of Khristianovich Institute of Theoretical and Applied Mechanics of SB RAS, Taymirskaya Str. 74, 625026, Tyumen, Russia*
[3] *University of Tyumen, Volodarskogo Str. 6, 625003, Tyumen, Russia*

[a] *Corresponding author: musakaev68@yandex.ru*

Abstract. In this work using experimental facility, which simulates a vertical section of a gas wellbore and allow us to creating foamed flows, experiments by research of steady gas-liquid flows with various types of aqueous solutions of surfactants have been carried out. Also a mathematical model is proposed that describes the upward flow of such mixtures in vertical channels.

INTRODUCTION

Currently, in a number of natural gas fields, there are problems associated with the accumulation of water at the wells bottom [1, 2]. This phenomenon is often caused by the fact that due to the extraction of gas from a reservoir, the reservoir pressure is significantly reduced. In this regard, water from aquifers can percolate to the gas-saturated reservoir part. Therefore, the volumetric water content in the wellbore gas-liquid flow increases. This leads to an increase in the density of the two-phase mixture and an increase in hydraulic resistance [3, 4]. Accordingly, the flow rate of the well decreases (with a constant bottomhole pressure), and with a large flow of water, the well may be shutdown.

For the stable operation of wells at a late stage of gas field development, various measures are used. One of the effective ways to struggle the accumulation of water in gas wells is the supply of foam concentrates based on surface-active substances (SAS) to the wells bottom. This technology has a relatively low volume of capital investments and high efficiency [5]. When SAS is fed to the well bottom, foam is formed, which leads to decrease in the density of the gas-liquid mixture and the coefficient of surface tension between the liquid and gas decreases. As a result, the critical gas velocity required to lift the fluid along the wellbore decreases, which allows the well to be operated without replacing the lifting string with a pipe of a smaller diameter and/or increasing the flow rate of the produced fluid. Since the technology of operation of gas wells with the use of SAS is becoming more and more spread, it is relevant to research the upward gas-liquid flows, which will make it possible to find the distributions of the main parameters along the well height for various operating modes.

Experimental studies of steady-state gas-liquid flows with various types of aqueous SAS solutions are presented in a number of works, for example [6, 7]. But these studies were carried out at atmospheric pressure, which can introduce a significant error in calculating the parameters of the gas-liquid flows in real production wells, because the pressure in such wells can reach values significantly exceeding 0.1 MPa [8]. Therefore, this work presents a technique for studying gas-liquid flows with SAS in a vertical channel at various pressures.

EXPERIMENT STATEMENT

From the considered complex problem, several simpler problems can be distinguished, the solution of which will make it possible to develop the required technique for studying gas-liquid flows with foaming surface-active substances:

– chemical analysis of the water used, selection of foaming SAS;

– measurement of the surface tension of aqueous solutions of selected foaming agents in order to determine the value of the critical concentration of micelles;

– conducting laboratory experiments on foaming solutions, determining the optimal concentrations of SAS in it;

– development of a unit (module) for synchronous flow cut-off in the upper section of the experimental stand tubing in order to determine the phase content in the gas-liquid mixture;

– experimental researches of steady gas-liquid flows with foaming agents.

Experimental researches of steady gas-liquid flows with foaming agents were carried out on the experimental stand simulating a section of a gas well bore (fig. 1).

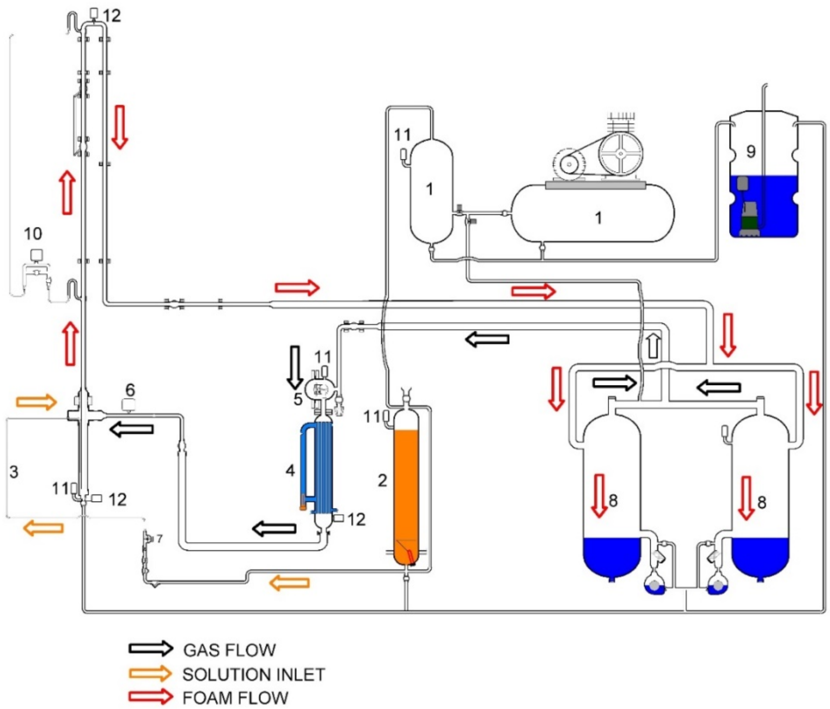

FIGURE 1. Experimental stand scheme: 1 – compressor with receiver, 2 – container with SAS solution, 3 – SAS solution supply line, 4 – air thermal stabilization system, 5 – centrifugal air blower, 6 – air flow meter, 7 – liquid flow meter, 8 – tanks for foam suppression, 9 – utilization tank, 10 – differential pressure meter, 11 – pressure sensor, 12 – temperature sensors.

The researches were carried out in the following sequence. Setting the experiment parameters: air flow rate, flow rate of the foaming agent solution, pressure and temperature in the tubing (vertical section of the pipeline 7 m long and 42 mm in inner diameter). When regulating the set pressure and temperature, the values of the pressure (11) and temperature (12) sensors located at the initial section of the tubing are used. Achievement of the corresponding pressure of the experiment, its maintenance was carried out by injecting air by a compressor (1) into its circulation loop and the foaming agent solution supply system (a container with a solution equipped with a thermal stabilization system (2) and a surfactant supply line (3)). The system of thermal stabilization of air (4) ensures the maintenance of its appropriate temperature during circulation. The required gas flow rate was set by automatically adjusting the power of the centrifugal blower (5). Before entering the lift column, the gas passes through the air flow meter; accordingly, the speed was recalculated under the thermobaric conditions of the experiment. The specified air flow rate was kept constant.

The supply of the foaming agent solution to the beginning of the lift column was carried out under the influence of the pressure difference between the system of its supply and the lift column bottom (in the system of supplying the solution, the pressure is always higher in comparison with the pressure of the experiment). Before being fed into the tubing, the liquid passes through a turbine flow meter (7), in which the volume of the incoming liquid is determined.

The stabilization of the gas-liquid flow was carried out, which was observed both visually (using a video camera) and according to the instruments readings. The flow rate of liquid and gas was stabilized and a constant value of the pressure drop was established. The pressure difference between the upper and lower parts of the tubing (the main measured value) was recorded using a pressure difference transducer (10), which is installed on a five-meter section of the tubing (to create conditions for measuring steady-state flow, the first measured point is located at a distance of two meters from the beginning of the tubing). Then, for at least 2 minutes, the flow parameters were recorded at a frequency of 1 time per 1 second, that is, at least 120 values of the measured parameters were recorded in each mode. Then, files with data on flow parameters were unloaded for further processing.

Based on the developed technique, experimental data were obtained on the parameters of stationary gas-liquid flows with different types of aqueous SAS solutions (type of surfactant and its concentration in solution), different pressure values (up to 1 MPa), different volumetric air flow rates (at a pressure of 1 MPa, the air flow rate in the pipeline with inner diameter of 42 mm up to 15 m s^{-1}).

To determine the content of phases in the gas-liquid flow, a section of the pipe with a length of 1 m in the upper part of the tubing was cut off. After cutting off the flow and flowing water and foam into the lower part of the section, the initial height of the liquid column H_l and the height of the foam column H_f. After the foam disintegrated, the height of the liquid column H_{lf} was measured.

Taking into account the measured values, the volumetric contents of the phases can be calculated as follows:

$$\alpha_l = \frac{H_l}{H_p}, \qquad \alpha_f = \frac{H_f}{H_p}, \qquad \alpha_{lf} = \frac{H_{lf} - H_l}{H_f},$$

$$\alpha_g = 1 - \alpha_l - \alpha_f, \qquad \alpha_{gf} = 1 - \alpha_{lf}.$$

Here H_p is the height of the cut-off section of the pipe; $\alpha_i \ (i = g, l, f)$ is the volumetric content of the i-th phase in the gas-liquid flow (g is gas, l is liquid, f is foam (foam film)); $\alpha_{if} \ (i = g, l)$ is the volumetric content of the i-th phase in the foam.

MATHEMATICAL MODEL

It is known that in order to be able to more accurately predict various scenarios and modes of gas well operation, it is necessary, inter alia, to combine experimental researches of upward gas-liquid flows in vertical channels with mathematical modeling of these processes [3, 4]. To do this, consider the following problem statement. Let a gas-liquid mixture move along the borehole of a vertical well with an inner radius r_w from the well bottom to head. The z axis is directed vertically upward, the well bottom corresponds to $z = 0$. At $z = 0$, the parameters of the two-phase flow (pressure, temperature, volumetric flow rate of the injected liquid foaming agent) are known, the mass flow rate of the two-phase mixture m is constant throughout the calculation time.

When creating a mathematical model, simplifying assumptions were used [3, 9-11], which for the studied process were formulated as follows: for each value of z, the temperature of both phases (liquid and gas) is the same; when writing the equation of impulses, we will neglect inertial effects and "reactive" forces associated with phase transitions; at the initial time moment ($t = 0$), the temperature on the outer surface of the well is equal to the geothermal one. We will also assume that the gas-liquid flow in the well is steady-state [4, 12].

For this problem formulation, the following system of equations can be written in the one-dimensional approximation [3, 9, 13-15]:

$$m_l + m_g = m = \text{const},$$

$$\frac{dp}{dz} = -F_w - \rho g,$$

$$mc\frac{dT}{dz} = \frac{m_g}{\rho_g}\frac{dp}{dz} - Q_w,$$

$$\rho = \rho_l(1-\alpha_g) + \rho_g \alpha_g, \qquad \rho_l = \text{const}, \qquad \rho_g = \frac{p}{Z_g R_g T},$$

$$Z_g = \left[0.17376 \cdot \ln\left(\frac{T}{T_k}\right) + 0.73\right]^{\frac{p}{p_k}} + 0.1 \cdot \frac{p}{p_k},$$

$$m_l = \rho_l(1-\phi)\, SW, \qquad m_g = \rho_g \phi\, SW, \qquad mc = m_l c_l + m_g c_g,$$

$$\phi = \left(1 + \frac{\rho_g\, m_l}{\rho_l\, m_g}\right)^{-1}, \qquad W = \frac{1}{S}\left(\frac{m_l}{\rho_l} + \frac{m_g}{\rho_g}\right), \qquad S = \pi r_w^2,$$

$$F_w = \frac{\lambda_w \rho W^2}{2r_w}, \qquad Q_w = 2\pi r_w q_w, \qquad q_w = \beta_w (T - T_w)\ ,$$

where p and T are the pressure and temperature of the gas-liquid flow; m_i $(i = l, g)$ is the mass flow rate of the i-th phase through the well section with the coordinate z; c_i and ρ_i $(i = l, g)$ are the specific heat capacity at constant pressure and true density of the i-th phase; λ_w is the coefficient of hydraulic resistance; W is the reduced speed of the mixture; ϕ is the volumetric consumption gas content; R_g and Z_g are the specific gas constant and supercompressibility coefficient [16]; T_k and p_k are the empirical critical parameters for gas; q_w is the specific (per unit area) intensity of heat removal from the two-phase flow; T_w is the temperature of the inner well wall; β_w is the heat transfer coefficient, which depends on the flow structure and on the features of the flow near the channel wall.

To close the proposed mathematical model, empirical relationships were used, in which the results of experimental studies of steady gas-liquid flows with foaming agents were used. On the basis of the given system of equations, a computational algorithm is constructed for calculating the parameters of a gas-liquid flow in a vertical well. According to the proposed algorithm, a computer code was developed that allows one to find, for each time moment, the distributions along the well height of various parameters of the upward flow of the two-phase mixture.

CONCLUSION

A methodology for studying a gas-liquid flow with surface-active substances in a vertical channel has been developed. On the experimental stand simulating a section of a gas wellbore, data were obtained on the parameters of stationary flows of gas-liquid mixtures with various types of aqueous surfactant solutions (type of surfactant and its concentration in solution), different pressure values (up to 1 MPa), and different volumetric air flow rates. Based on the equations of the multiphase media mechanics, a mathematical model of the processes occurring during the movement of a gas-liquid mixture with surfactants in a gas wellbore is proposed.

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