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Similarity parameters clarified in the conditions of gas wells operation with water phase of various mineralization

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Abstract. Determining the effect of the fluid properties extracted from the reservoirs together with the produced gas on the pressure loss in wellbores is an urgent task for many fields and underground gas storages. The similarity parameters clarification of gas-liquid flows in pipes and creation of new modeling methods based on them make it possible to increase the degree of validity of the assigned technological modes at all stages of operation of field facilities containing a liquid phase in the products. Previous experimental studies have made it possible to establish an unambiguous dependence of pressure losses in the well on the amount of fluid represented by condensation water. However, the question of the effect of fluid properties on pressure losses in the path of formation mixture movement from the bottom to the installation of integrated gas treatment remains open.

The article describes experimental studies of gas-liquid flows with liquids of high density, allowing us to make appropriate changes to the calculation formulas. Based on the methods of similarity and dimensions, corrections to the parameters included in the calculated relationships are concretized, conclusions of new formulas are given that take into account the influence of the liquid phase density on pressure losses in well bores. The structure of a new similarity parameter, the clarified Buzinov parameter, is substantiated, which allows us to most accurately calculate the stable operating modes of gas wells in fields and underground gas storage with an aqueous phase of various salinity. Relations for quantitative estimates of the effect of reducing pressure losses in gas-liquid flows due to wetting of the inner surface of elevator pipes are presented for the first time.

Keywords: similarity parameters, Buzinov’s parameter, highly mineralized liquid, final stage of gas field’s development, underground gas storage, calculation method of gas-liquid flow, experimental units research

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Introduction

In addition to condensation water, gas well production may contain reservoir water of high salinity and, accordingly, density, which is already taking place in some underground gas storages (UGS) and fields. The question arises, how will fluids of such density influence pressure loss in wells? In the future, the solution of such a problem will become relevant for fields in Eastern Siberia upon their transition to the final stage of development, where the proportion of produced water with a salinity of up to 350 g/cm^3 is high.

The clarification of similarity parameters for gas-liquid flows (GLF) under the conditions of operation of gas wells with an aqueous phase of various salinity will significantly expand the understanding of the physics of a multiphase mixture motion.

When substantiating the parameters of the operating modes of such wells, it becomes necessary to use modeling methods. As the analysis of published materials shows (Duns, Ros, 1963; Mamaev et al., 1978; Odishariya et al., 1998; Nikolaev et al., 2013; Buzinov et al., 2014; Shulepin, 2017), the existing hydrodynamic models of GLF turn out to be not applicable for calculating the operation of gas fields, since they were developed for conditions of high consumption water content ($\beta_l > 10^{-3}$), while in gas wells this value is extremely small ($\beta_l > 10^{-3}$). In addition, studies of GLF with a liquid denser than water have not yet been conducted.

Analysis of experimental studies

Earlier in the works (Nikolaev, 2012; Nikolaev et al., 2013; Buzinov et al., 2014), based on the analysis of experimental studies of ascending vertical GLF conducted by Gazprom VNIIGAZ in 2005-2012, the concept was introduced of a value of pressure Δi additional losses, which is the contribution of the liquid

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phase to the total pressure loss during the movement of water-gas mixtures in pipes. The physical meaning of Δi is illustrated in Figure 1, which shows the characteristic of a gas-liquid flow in dimensionless coordinates $i = i(Fr^*)$. Here i are the dimensionless pressure loss due to friction, Fr^* is the reduced Froude parameter:

$$i = \frac{\Delta P}{\rho_l g \Delta L}, \tag{1}$$

$$Fr^* = \frac{\rho_g}{\rho_l}\frac{u^2}{g d}, \tag{2}$$

where ρ_g is the gas density, kg/m^3; ρ_l – liquid density, kg/m^3; u is the average gas velocity over the cross section of the pipe, m/s; d is the inner diameter of the pipe, m; ΔL is the length of the pipe section, m; ΔP – pressure loss in the pipe section, Pa; g – gravitational acceleration, m/s^2.

Figure 1 also shows the dependence $i = i(Fr^*)$ for a single-phase gas, which, up to a constant factor $(1/\rho_l g)$ corresponds to the Darcy-Weisbach formula:

$$i_g = \frac{\lambda}{2} Fr^*. \tag{3}$$

An analysis of the experimental results made it possible to obtain an empirical formula:

$$\Delta i = k_1 \frac{q_l^{2/3}}{d^{8/3}}, \tag{4}$$

where k_1 is the empirical dimensional coefficient.

As follows from Figure 1, the friction pressure loss i for a gas-liquid mixture is the sum of:

$$i = i_g + \Delta i. \tag{5}$$

The value of the total pressure loss I, taking into account the weight of the gas column in dimensionless units, is determined by the expression:

$$I = i + \frac{\rho_g}{\rho_l}. \tag{6}$$

With the increase in the bank of experimental data and the involvement of additional published data from other authors, dependence (4) was subsequently clarified; the empirical formula for additional pressure losses in a vertical water-gas flow has acquired the form (7):

$$\Delta i = k_2 \frac{q_{\text{ж}}^{2/3}}{d^{13/6}}, \tag{7}$$

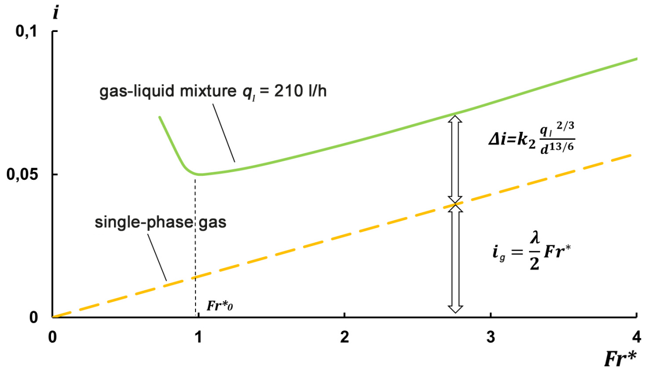

Fig. 1. Illustration of the two components of pressure loss in a vertical GLF. The lower component (dotted line) corresponds to the Darcy-Weisbach relationship.

which differs from expression (4) in terms of the degree of the pipe diameter.

The coordinate of the inflection pint along the x axis (Fr^*) in Figure 1 (green curve) is taken equal to the value Fr_0^*, in parallel, the concept of the right branch of the "elevator characteristic" curve is introduced, where a stable mode of operation of the well is observed, and the left branch of the curve corresponding to unstable mode.

In addition, the analysis of experiments with sodium formate obtained by the authors of this article and the analysis of experimental data (Lutoshkin, 1956; Hewitt et al., 1974; Korotaev, 1996) made it possible to establish that the influence of the density of the liquid phase can be taken into account by the factor $\rho_l^{2/3}$, which leads to a modified formula (8) for determining pressure losses, taking into account the density of the liquid phase:

$$\Delta i = k_3 \frac{w^{2/3} \rho_l^{2/3}}{d^{5/6}}. \tag{8}$$

The coefficient k_3 has a complex dimension; its numerical value and dimension depend on the dimensions of the fluid velocity w, the fluid density ρ_l and the inner diameter of the pipe d. It somewhat depends on the viscosity and surface tension of the liquid.

In the experiments of Shulepin S.A., conducted in 2014 (Shulepin et al., 2016; Shulepin, 2017), the surface tension of liquids varied in the range $\sigma = (45 \div 66) \cdot 10^{-3}$ Pa·m, and the dynamic viscosity coefficient in the range $\mu = (0{,}9 \div 1{,}2) \cdot 10^{-3}$ Pa·s. However, the limited amount of experimental material did not allow a reliable assessment of the influence of these parameters on Δi; therefore, the data of Lutoshkin G.S. (1956) were used for analysis with liquids whose surface tension varied in the range $\sigma = (26 \div 70) \cdot 10^{-3}$ Pa·m, and the coefficient of dynamic viscosity in the range $\mu = (1{,}0 \div 15{,}5) \cdot 10^{-3}$ Pa·s.

An analysis of the data (Shulepin et al., 2016; Shulepin, 2017) allows us to conclude that the dependences of pressure losses on the flow characteristics of liquids using aqueous solutions as a liquid phase in general obey the same patterns that are characteristic of fresh water flows namely, with an increase in the liquid flow rate β_l, the pressure loss in the pipe increases (Buzinov et al., 2010; Borodin et al., 2010; Buzinov et al., 2011). At the same time, it was found that at the same flow rates of liquids of different densities (in the range from 1000 to 1220 kg/m^3), pressure losses increase with increasing density of the liquid phase (Fig. 2).

Based on this, it can be argued that in the studied area of operating modes of watered gas fields and underground gas storages, with an increase in the amount of liquid in the product, the pressure loss in the elevator pipes increases at any value of the water density. Simultaneously with the increase in the density of the liquid phase, the pressure loss increases.

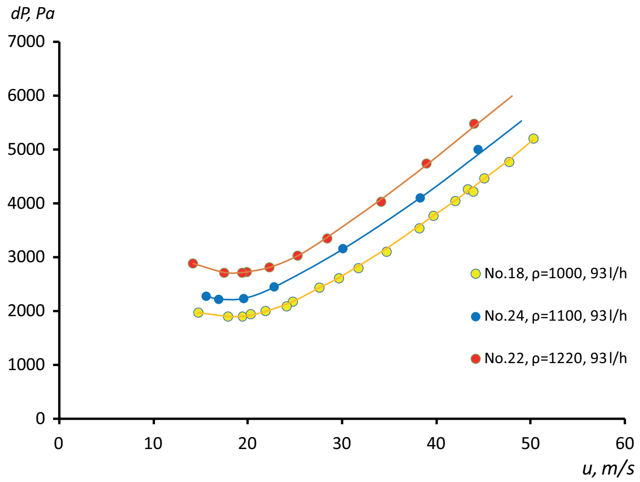

Fig. 2. Dependence of pressure losses in GLF on the gas velocity at the same flow rate of the liquid phase of 93 l/h for solutions of different densities of 1000, 1100, 1220 kg/m³ (Shulepin et al., 2016)

Presentation of clarified similarity parameters

Further analysis using the methods of dimensional theory allowed us to obtain a formula for determining the quantity Δi:

$$\Delta i = k\frac{Fr_l^{1/3}}{E\ddot{o}^{1/4}} \cdot \frac{\breve{\rho}_l^{\,0{,}45}}{\breve{\sigma}^{\,0{,}35}\,\breve{\mu}^{\,0{,}1}}, \tag{9}$$

in which dimensionless parameters appear:

- Froude parameter in liquid

$$Fr_l = \frac{w^2}{gd}, \tag{10}$$

where w is the average velocity of the liquid phase reduced to the pipe section, m/s;

- Eötvös parameter, which characterizes the ratio of the forces of weight and surface tension at the interface between the liquid and gas phases:

$$E\ddot{o} = \frac{\rho_l\, gd^2}{\sigma}; \tag{11}$$

- Dimensionless simplexes:

$$\breve{\rho}_l = \frac{\rho_l}{\rho_0};\ \breve{\sigma} = \frac{\sigma}{\sigma_0};\ \breve{\mu} = \frac{\mu}{\mu_0}. \tag{12}$$

where the symbols with the subscript “0” denote the density, surface tension and viscosity of distilled water under standard conditions:

$\rho_0 = 1000$ kg/m³, $\sigma_0 = 72 \cdot 10^{-3}$ Pa·m, $\mu_0 = 10^{-3}$ Pa·s.

The main dimensionless part of the complex (9) was proposed to be called the “modified Buzinov parameter” (earlier the concept of the “Buzinov parameter” *Bu* was first introduced in (Nikolaev, 2012)) and to introduce the following notation for it:

$$Bu_0^* = \frac{Fr_l^{1/3}}{E\ddot{o}^{1/4}}. \tag{13}$$

For GLF with condensation water as the liquid phase, i.e. for the conditions of the Cenomanian wells, from (9) we can write:

$$\Delta i = kBu_0^*. \tag{14}$$

where k is a dimensionless constant.

The properties of a liquid other than condensation water can be taken into account in accordance with (9) by introducing a dimensionless coefficient:

$$K_{Bu} = \frac{\breve{\rho}_l^{\,0{,}45}}{\breve{\sigma}^{\,0{,}35}\,\breve{\mu}^{\,0{,}1}}. \tag{15}$$

Then the Buzinov parameter for a liquid of any composition can be expressed by the relation:

$$Bu^* = K_{Bu} \cdot \frac{Fr_l^{1/3}}{E\ddot{o}^{1/4}}, \tag{16}$$

and additional pressure loss – by the ratio:

$$\Delta i = kBu^*. \tag{17}$$

Figure 3 shows the experimental dependence $\Delta i = \Delta i(Bu^*)$, constructed according to the data of Hewitt J., Korotaev Yu.P., Lutoshkin G.S., Shulepin S.A., Nikolaev O.V. for liquids of different densities ($\rho_l = 839 \div 1220$ kg/m³), different surface tension ($\sigma = 0{,}026 \div 0{,}070$ Pa·m), different viscosity ($\mu = 0{,}0009 \div 0{,}015$ Pa·s) and pipes of different diameters ($d = 0{,}038 \div 0{,}153$ m); pressures range from 0.1 to 3.2 MPa. Processing the experimental data gives for the dimensionless coefficient k in relation (14) the value $k = 1.881$. Obviously, for the conditions of the Cenomanian wells, $K_{Bu}=1$ and $Bu^*=Bu_0^*$.

The structure of the new parameter of additional pressure losses in the form of (9) and (17) can obviously be further clarified as new experimental data obtained. However, it should be noted that, taking into account the currently available research results, formula (17) most accurately reflects the effect of fluid properties on pressure losses in a stable vertical hydraulic fracturing in gas well operating conditions.

Figure 4 shows the dependence of the dimensionless pressure loss i on the parameter Bu^* (at $Fr^* = 1.5$) in the range of small values of the parameter Bu^*. It can be seen from the figure (raspberry solid line) that at sufficiently low liquid flow rates there is a deviation from regularity (17), which is associated with the well-known effect of

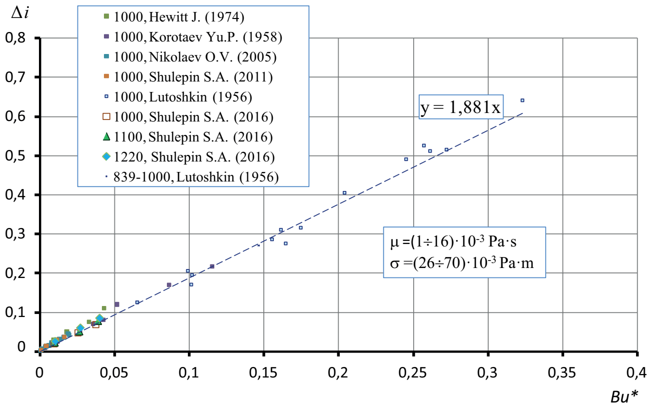

Fig. 3. Dependence of additional pressure losses in a vertical GLF on the right branch ($Fr^*=1.5$) on the modified Buzinov parameter. The legend indicates the density of liquids in (kg/m³) with which experiments were conducted.

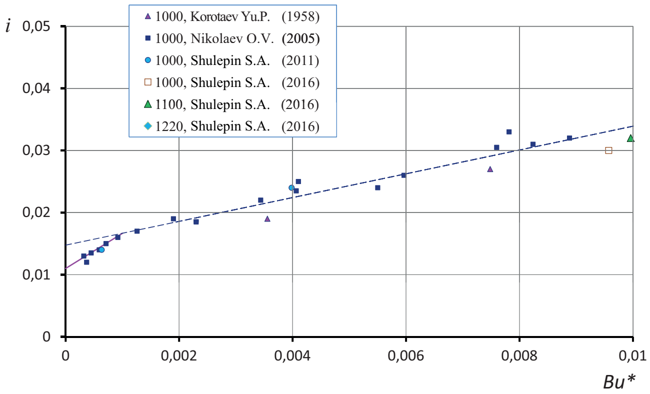

Fig. 4. Dependence of pressure loss on the parameter Bu at low flow rates*

reducing the hydraulic resistance of the pipe with a slight wetting of the pipe surface with liquid.

Obviously, this effect can take place only with a sufficiently small amount of liquid in the flow, since large amounts of liquid lead to an increase in resistance. In Figure 4, a deviation from dependence (17) takes place when:

$$Bu^* < 0{,}001, \tag{18}$$

and a decrease in the hydraulic resistance of the pipe due to the wetting of its surface - when:

$$Bu^* < 0{,}0007. \tag{19}$$

The dependence $\Delta i(Bu^*)$ in the range (18) has the form:

$$\Delta i = 5{,}5\,Bu^* - 0{,}0035. \tag{20}$$

Using these ratios, it is possible to determine the liquid flow rates at which the pipe resistance decreases compared to a single-phase gas flow. These flow rates depend on the diameter of the pipe and the properties of the liquid, which is quite logical. It should be noted that quantitative estimates of the effect of reducing pressure losses in the flow due to wall wetting, reflected by formulas (18)-(20), were carried out for the first time.

Table 1 presents the values of water flow for pipes of different diameters, below which there is a decrease in hydraulic resistance. As follows from the structure of the parameter Bu*, it does not depend on the gas flow rate; therefore, restrictions of the type (18) and (19) can be expressed only in the absolute expression of the liquid flow rate, but not in the relative values of the water-gas factor.

Therefore, in a stable vertical GLF in the region of relatively high gas velocities (at $Fr^* > 1$, depending on the liquid content and pipe diameter) and relatively high liquid flow rates (at $Bu^* > 0{,}001$), pressure losses represent the sum of two independent terms, one of which is proportional to the given Froude parameter (Fr^*) and does not depend on the fluid flow rate, and the other is proportional to the modified Buzinov parameter (Bu^*) and does not depend on the gas flow rate:

$$i = \frac{\lambda}{2} Fr^* + 1{,}881 Bu^*. \tag{21}$$

***D*, cm**	7,3	8,9	11,4	14,0	16,8
***ql*, m^3/day**	0,5	1,0	2,5	5,5	10,0

Table 1. The limit values of water flow, at which there is a decrease in hydraulic resistance of the lift pipes of the field assortment

For the values of the modified Buzinov parameter $Bu^* < 0{,}001$, another formula is used that takes into account the decrease in pressure loss due to the effect of wetting the walls:

$$i = \frac{\lambda}{2} Fr^* + 5{,}5 Bu^* - 0{,}0035\,. \tag{22}$$

It should be noted that according to experiments, the right branches of the characteristics of a single-phase gas and gas-liquid flow (at $Fr^* > Fr^*_0$) are almost parallel. This means that the derivatives $\partial i/\partial Fr^*$ are equal in both cases, and the corresponding sections of the graphs for single-phase and for GLF are at the same angle to the abscissa, the tangent of which is proportional to λ/2.

Let us note that the expression for the dimensional value of pressure loss in a gas-liquid flow has the form:

$$\Delta P_{\text{total}} = i\rho_l\, g\Delta L + \rho_g\, g\Delta L\,, \tag{23}$$

where ΔP_{total} is the pressure loss in the pipe section taking into account the weight of the gas column, Pa.

Conclusions

As a result of the analysis of experimental data, it was possible to show:

- The modified Buzinov parameter (Bu^*) is a dimensionless parameter characteristic of the hydrodynamics of vertical GLFs on the right branch of the "elevator characteristic" and reflecting their similarity;
- The use of the Bu* value instead of the Froude parameter for liquids (Fr_l) allows us to substantially clarify the concepts of the physics of a gas-liquid mixture motion in pipes, including the aqueous phase of various salinity.

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