Romanian Journal of Petroleum & Gas Technology
VOL. IV (LXXV) • No. 1/2023

MOVEMENT OF TWO-PHASE GAS-LIQUID FLOW IN HORIZONTAL AND INCLINED PIPES

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DOI: 10.51865/JPGT.2023.01.06

ABSTRACT

Two-phase flows are found in almost all areas of technology. For example, tubular evaporators, boiling water reactors, boiler blowdown systems, heaters, boilers, gas lift pumps, oil and geothermal wells, oil and gas pipelines, refrigerators, process pipelines, and condensers. Two-phase flows are classified as mixtures. According to the composition of the mixture are divided: (a) for single-component (or one-component) - vapor-liquid flows; (b) multicomponent - gas-liquid flows.

One-component mixtures consist of the same substance in different states of aggregation. This can be not only vapor-liquid, but also a mixture of liquid or vapor with a solid phase, a water-ice mixture, or a vapor flow with ice particles, for example, in sublimation installations.

Multicomponent mixtures are a combination of substances of different physical nature. These include not only gas-liquid flows, but also, for example, mixtures of air and sand, water and oil.

The paper presents the main attention is paid to the movement of two-phase flows in the pipeline.

Keywords: two-phase flows, one-component mixtures, multicomponent mixtures, pipes

INTRODUCTION

During the processing and transportation of oil and gas, flows are often moved through pipelines in the gas-liquid state. High operating temperatures, corrosive activity of products, high linear flow rates determine the special attention to pipelines on the part of designers and specialists in the operation of pipelines and technological installations. Mistakes during design lead to operational problems.

The simultaneous presence of two phases leads to the possibility of the existence of a flow with a different structure or flow regime. The simultaneous presence of two phases leads to the possibility of the existence of a flow with a different structure or flow regime. There are a large number of flow regimes for two-phase flows, which depend on the viscosity of the phases, density, the ratio of the mass flow rates of the phases, and the surface tension coefficient.

GAS-LIQUID FLOW STRUCTURES IN HORIZONTAL AND INCLINED PIPES

When a gas-liquid flow moves in the pipeline, several main flow structures can be distinguished, which differ in the shape of the liquid-gas interface (figure-1).

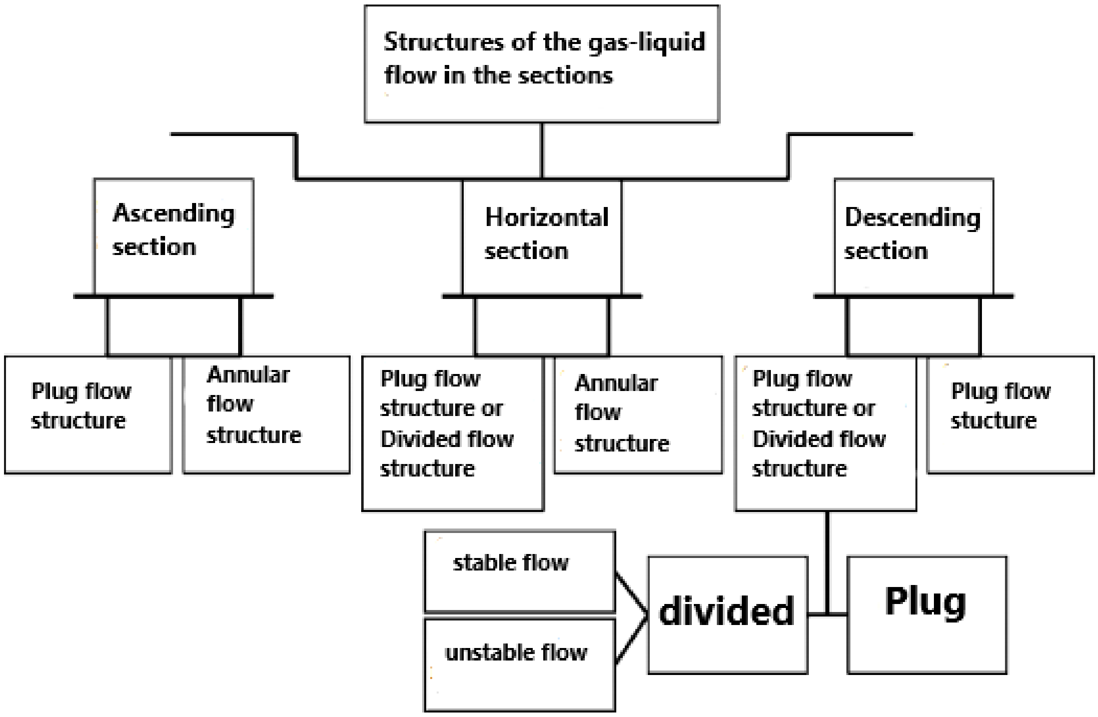

Figure-1: Structural forms of biphasic gas - liquid flow in the pipeline.

The plug flow structure is characterized by the alternation of gas bubbles in the upper part of the pipeline and liquid filling the volume of the pipeline outside the gas bubbles (figure-2) [1].

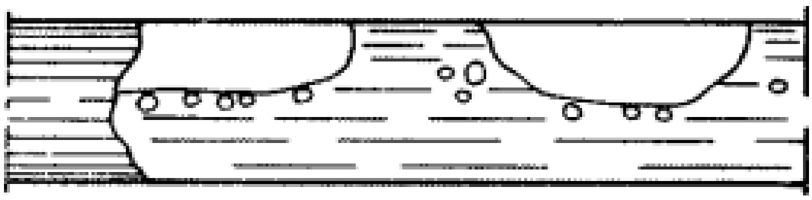

Figure-2: Plug flow structure [1]

A plug flow structure can exist in all sections of a relief pipeline - horizontal, ascending and descending. The divided flow structure (figure-3) is characterized by the fact that the gas moves over the liquid and the interface has an almost flat or wavy shape [1].

In this case, a small amount of liquid in the form of droplets can move with the gas, and gas bubbles are in the liquid. Divided flow structure is observed in the horizontal and descending sections of the pipeline.

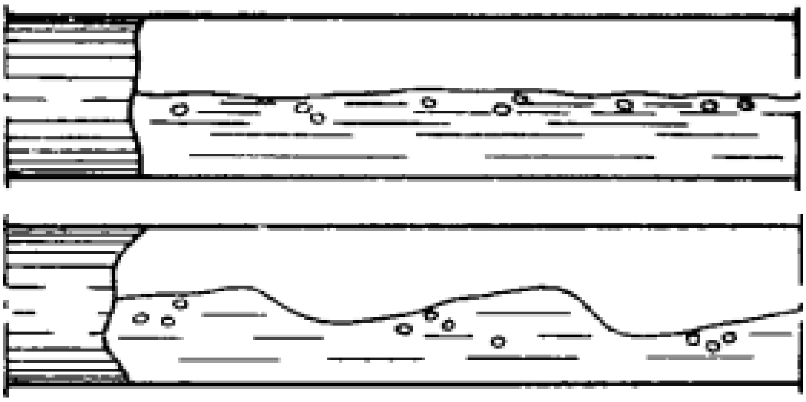

Figure-3: Divided flow structure – characterized by the fact that the gas moves over the liquid and the interface has an almost smooth or wavy shape. [1]

In a relief pipeline, when the descending section changes into an ascending section, the divided flow structure can be stable and unstable.

Stable divided structure (figure-4) is realized in the whole descending section, and the unstable divided structure (figure-5) occupies only the upper part of the descending section [2].

Figure-4: Stable divided flow in the descending section of the pipeline. [2]

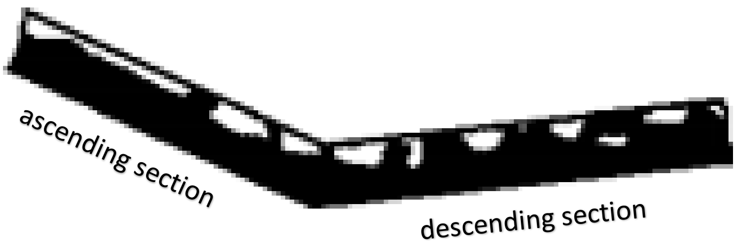

Figure-5: Unstable divided flow in the descending section of the pipeline.
Plug flow in the ascending section captures part of the pipe in the descending section. [2]

In this case, gas bubbles are formed in the lower part of the section, which are periodically carried out by the liquid flow into the ascending section of the pipeline, changing the length of the divided flow and causing waves on the interface.

The annular flow structure (figure-6) is characterized by a large amount of gas moving so fast that it pushes the liquid toward the inner surface of the pipe, where it moves in the form of a relatively thin annular layer [1].

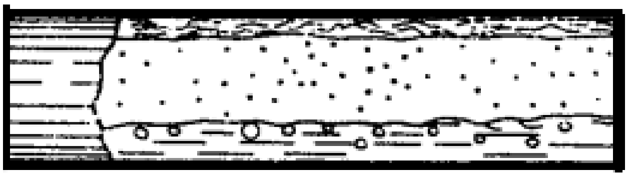

Figure-6: Annular flow structure [1].

Such a flow structure can be along the entire length of the relief pipeline. In each of the structures, the flow regime - turbulent or laminar - can be different for liquid and gas.

The emulsion structure of the gas-liquid flow (figure-7) is characterized by a relatively large amount of liquid and flow rates such that the gas phase moves in the form of separate bubbles at almost the same speed as the liquid phase [1].

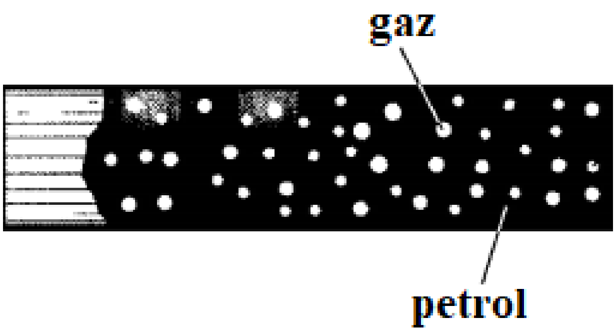

Figure-7: Emulsion structure of gas-liquid flow. [1]

TRUE GAS CONTENT IN GAS-LIQUID FLOW IN HORIZONTAL AND INCLINED PIPES

In a gas-liquid flow, each of the phases, gas and liquid, only partially fills the pipe section. Let us denote the cross-sectional areas of the pipe occupied by gas and liquid as A_g and A_l. We have [4]:

$$A_g + A_l = A \tag{1}$$

where A - the cross-sectional area of the pipe.

The true volumetric gas content is the ratio of the volume of a pipe of unit length occupied by gas to the volume of the entire pipe of the same length.

$$\varphi = \frac{A_g}{A} \tag{2}$$

where φ - the true volumetric gas content.

From formula (2) it follows that the volumetric content of the liquid phase per unit length of the pipe is equal to

$$\frac{A_l}{A} = 1 - \varphi \tag{3}$$

VOLUME FLOW AND VELOCITY OF GAS-LIQUID FLOW IN HORIZONTAL AND INCLINED PIPES

Let us denote by υ_g and υ_l the velocities of gas and liquid in a two-phase flow in a pipe. Then the volume flow rates of gas and liquid through the pipe section will be respectively equal [7]

$$Q_g = \upsilon_g A_g = \upsilon_g A\varphi;\ Q_l = \upsilon_l A_l = \upsilon_g A(1-)\varphi \tag{4}$$

The volume flow rate of the gas-liquid flow is equal to the sum of these rates.

We have:

$$Q = Q_g + Q_l \tag{5}$$

The velocity of the gas-liquid flow υ in the pipe is equal to the ratio of the volume flow to the cross-sectional area of the pipe.

We have:

$$\upsilon = \frac{Q}{A} = \frac{Q_g + Q_l}{A} = \upsilon_g\varphi + \upsilon_l(1-\varphi) \tag{6}$$

The value of this velocity differs from the velocities of the gas and liquid and coincides with them only if the velocities of the phases are equal.

EXPERIMENTAL WORK OF A TWO-PHASE GAS-LIQUID FLOW IN A HORIZONTAL AND INCLINED PIPELINE

Let's do some experimental work and study the movement of liquid and gas through a horizontal and inclined pipeline in the presence of descending and ascending sections where gases can concentrate and gas slugs can accumulate. Let's think that the pipeline is laid on a terrain with difficult terrain like in figure-8.

Figure-8: *Horizontal-inclined pipeline.*

Figure-9 shows a schematic representation of an experiment on a two-phase gas-liquid flow in a horizontal and inclined pipeline.

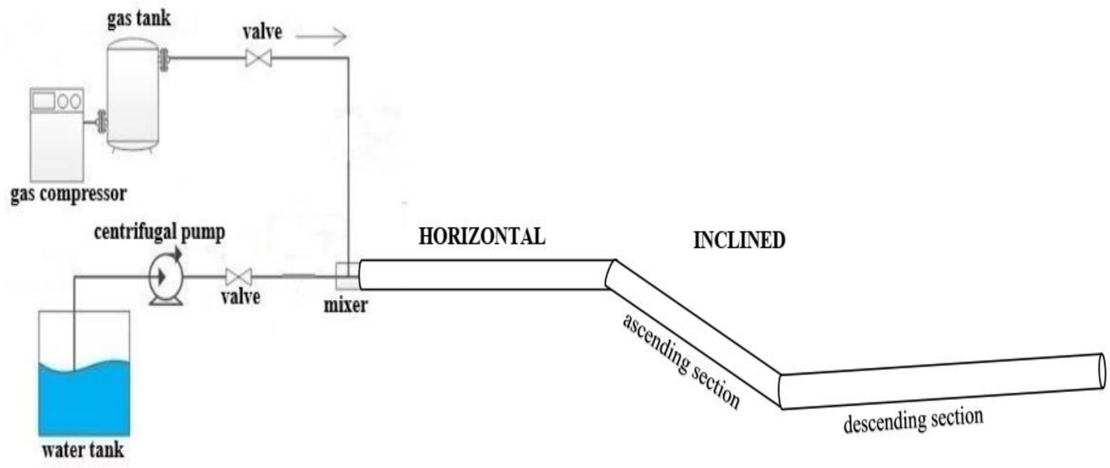

Figure-9: *Schematic representation of an experiment on a two-phase gas-liquid flow in a horizontal and inclined pipeline*.

Horizontal-inclined pipes are made of transparent acrylic resin, on which flows are clearly visible (figure-10). The inner diameter of the pipes is 50 mm. The length of the horizontal pipe is 3 meters, the inclination of the pipe (ascending section) is 1 meter, the descending section of the pipe is 4 meters.

Figure-10: *The pipe is made of transparent acrylic resin*.

In figure-9, water is supplied by a screw pump from the water tank to the mixer, which mixes the water with the gas supplied from the gas tank. The gas-liquid flow passes through a horizontal pipe, then through an inclined pipe with an ascending and descending section.

First, we started the gas compressor to force the gas into the gas tank until it reaches a stable pressure condition. Then water was fed into the pipe at a speed of 0.3 m/s. When the pipe was filled with water, the gas was injected into the mixer from the gas tank at a speed of 4 m/s. We have registered the movement of structural forms of gas-liquid flows in pipelines. Figures-11 and 12 show the results of experimental observations of the gas-liquid flow regimes for sections with different pipe inclinations.

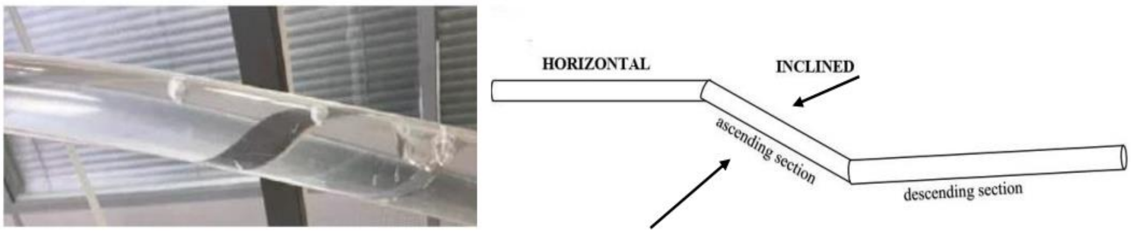

Figure-11: *Structural flow of gas-liquid flow in the ascending section of the pipe*.

Figure-12: *Structural flow of gas-liquid flow in the descending section of the pipe*.

As a result of experimental studies, the following characteristic structures of the gas-liquid mixture flow in the control section of the pipeline were revealed:

- bubble (emulsion) characterized by the movement of gas bubbles in the liquid flow;
- plug (slug, plug-dispersed) characterized by the alternation of liquid and gas volumes along the length of the pipeline.

The formation, stable existence and change of structural forms of the flow of a gas-liquid mixture in a pipeline depends on a number of conditions at the entrance to the control section of the pipeline: thermophysical properties of the liquid and gas phases; two-phase flow velocity and pipeline inclination angle. The main criteria for the similarity of gas-liquid flows in pipelines include:

The Reynolds number of a gas-liquid mixture characterizes the ratio of the forces of inertia and viscosity:

$$Re_{mixture} = \frac{v_{mixture} d \rho_{mixture}}{\mu_{mixture}} \tag{7}$$

where $v_{mixture}$ - mixture flow velocity, m/s;

d - pipeline diameter, m;

$\rho_{mixture}$ - density of the gas-liquid mixture, kg/m^3;

$\mu_{mixture}$ - dynamic viscosity of gas-liquid mixture, Pa·s.

The Froude number of a gas-liquid mixture characterizes the ratio of surface tension forces and gravity forces:

$$Fr_{mixture} = \frac{v^2}{gd} \tag{8}$$

where g - gravitational acceleration, m/s^2 ;

v – velocity flow, m/s;

d - pipeline diameter, m.

NUMERICAL SIMULATION OF GAS-LIQUID MIXTURES IN HORIZONTAL AND INCLINED PIPELINES

With flows in pipelines, the flow interacts with an external body - with the pipeline wall, namely: force interaction due to friction and pressure, as well as thermal interaction due to heat exchange with the wall. The intensity of these processes for two-phase gas-liquid flows depends on the structure of the flow, in particular, on the presence of a liquid or vapor film on the wall, the distribution of phases over the cross section of the pipeline, and internal processes in the flow [1].

The structure of the flow of a two-phase mixture is usually called the characteristic distribution of interfaces between liquid and gas. In the general case, the formation of one or another flow structure depends on: the flow rate of each of the phases and their physical properties; from the location of the pipe through which the mixture moves; on the methods of input and output of phases of the mixture.

For flows in horizontal and inclined pipes, the principle was formulated and substantiated, which consists in the fact that a change in flow structures does not in all cases lead to a change in the dependencies that determine hydrodynamic quantities (true gas content, hydraulic resistance, etc.). These dependencies change only with a qualitative change in the interface between liquid and gas. Therefore, all types of flow structures that occur in horizontal and inclined pipes with ascending and descending flow directions are conditionally divided into three main zones:

- zone of generalized annular (dispersed-film or dispersed-annular) flow with annular shape of the phase interface;
- zone of generalized slug flow without a clear phase interface.
- stratified flow zone with a smooth or wavy phase interface.

The gas-liquid medium transported through a horizontal and inclined pipeline will be conditionally considered a two-phase mixture of a Newtonian one-component viscous weakly compressible heat-conducting liquid and a Newtonian one-component viscous compressible heat-conducting gas (vapor). Such gas-liquid mixtures, for example, include light low-paraffin oils with their own vapors and hot water with vapors [3].

As a thermal equation of state $\left[p = p(\rho_g, T_g\right]$ for the gas (vapor) phase, when modeling the flows of gas-liquid media, it is recommended to use the Peng-Robinson equation:

$$\left[p + \frac{a}{v_g \cdot (v_g + b) + b \cdot (v_g - b)}\right] \cdot (v_g - b) = R_g \cdot T_g \tag{9}$$

where p - pressure of the transported two-phase medium;

a, b – coefficients;

υ_g - gas velocity;

R_g – gas constant (J/kg·K) $R_g = \frac{R_0}{M_g}$;

where R_0 - universal gas constant (J/mol·K);

M_g - molar mass of gas (kg/mol);

T_g - gas temperature.

$$a = 0{,}457235\left[1 + m \cdot \left(1 - T_S^{0,5}\right)\right]^2 \cdot R_g^2 \cdot \frac{T_c^2}{p_c}; \quad b = 0{,}077796 \cdot R_g \cdot \frac{T_c}{p_c} \tag{10}$$

where T_S - superficial gas temperature $T_S = \frac{T_g}{T_c}$;

T_c - critical gas temperature;

p_c - critical gas pressure;

m – components.

$m = 0{,}37464 + 1{,}54226 \cdot \omega - 0{,}26992 \cdot \omega^2$ for $\omega \le 0{,}49$;

$m = 0{,}37964 + 1{,}408503 \cdot \omega - 0{,}16442 \cdot \omega^2 + 0{,}016666 \cdot \omega^3$ for $\omega > 0{,}49$;

where ω - acentric factor. The acentric factor of a given substance is the difference between the decimal logarithm of the superficial saturation vapor pressure at a superficial temperature equal to 0,7 for a substance subject to a universal relationship and the decimal logarithm of the superficial vapor pressure at the same superficial temperature. Simplified methods for calculating the acentric factor for hydrocarbons are described in the monograph. Also, its values are given in the reference literature. So, for example, for methane it is equal to 0.0108; for ethane - 0.0998; for propane - 0.1517; for butanes - 0.1931.

Also, for the gas (vapor) phase, the Redlich-Kwong equation can be used as a simplified thermal equation of state:

$$\left[p + \frac{a}{\sqrt{T_2} \cdot \upsilon_g \cdot (\upsilon_g + b)}\right] \cdot (\upsilon_g - b) = R_g \cdot T_g \tag{11}$$

where $a = 0{,}42747 \cdot R_g^2 \cdot \frac{T_c^{2,5}}{p_c}$; $b = 0{,}08664 \cdot R_2 \cdot \frac{T_c}{p_c}$

When modeling the flows of hydrocarbon fuels (for example, oils), it is recommended to use the Peng-Robinson equation (7) as an implicit dependence $[\rho_l = \rho_l(p, T_l)]$ as the thermal equation of state for the liquid phase. In this case, first, using formula (7) (or 8) the pressure – p is found. Then, as a result of the numerical solution of the nonlinear algebraic equation (7) with the substitution of the found pressure - p into it, the density of the liquid phase - ρ_l is determined.

In practice, the viscosity of the liquid and gas (vapor) phases and their dependence on temperature are determined by laboratory analysis. In the absence of such analyzes, the coefficient of dynamic viscosity of the liquid phase - μ_l for the calculated liquid temperature - T_l in the case of modeling the transportation of oils as Newtonian gas-liquid media can be found by the formula:

$$\mu_l = \nu_l \cdot \rho_l = \nu_0 \cdot \exp[-u \cdot (T_l - T_0)] \cdot \rho_l \tag{12}$$

where ν_l - the coefficient of kinematic viscosity of oil at the calculated liquid temperature - T_l; ν_0 - the coefficient of kinematic viscosity of oil at a given temperature - T_0; u - indicator of the steepness of the viscogram of the transported oil.

To determine the thermal conductivity coefficient of the liquid phase - k_l when transporting oils as two-phase mixtures, it is recommended to use the Krego-Smith formula:

$$k_l = \frac{0{,}137}{\rho_4^{15}} \cdot (1 - 0{,}54 \cdot 10^{-3} \cdot T_l) \tag{13}$$

where ρ_4^{15} - relative density of oil on water for $T_l = 288K$. The specific heat capacity of such a liquid phase - $(C_p)_l$ can be estimated using the Krego formula:

$$(C_p)_l = \frac{1}{\sqrt{\rho_4^{15}}} \cdot (1{,}687 + 3{,}39 \cdot 10^{-3} \cdot T_l) \tag{14}$$

To simplify the presentation of the material, it is advisable to give several auxiliary formulas that will often be used in the construction of a one-dimensional model. These include the formula for determining the density of the transported mixture - $\rho_{mixture}$:

$$\rho_{mixture} = \rho_l \cdot (1 - \psi) + \rho_g \cdot \psi \tag{15}$$

where ψ - the average value of the volumetric concentration of gas over the cross section of the flow, which is a continuous function of time and coordinates $(0 \le \psi(x,t) \le 1$, here x - the spatial coordinate of the considered point, measured along the axis of the pipeline; t – time) [4].

Consider the volume flow Q taking into account the gas-liquid velocity, we can write:

$$Q_l = w_l \cdot f_l = w_l \cdot (1 - \psi) \cdot f \; ; \quad Q_g = w_g \cdot f_g = w_g \cdot \psi \cdot f \tag{16}$$

where w_l - is the projection of liquid velocity averaged over the flow cross section;

w_g - is the projection of the gas velocity averaged over the flow cross section;

f_l - is the fraction of the cross-sectional area of the pipe occupied by the liquid;

f_g - is the fraction of the cross-sectional area of the pipe occupied by the gas;

$$f_l + f_g = f \tag{17}$$

where f - is the fraction of the cross-sectional area of the pipe.

The inner radius - R of the simulated pipeline is equal to:

$$R = \sqrt{\frac{f}{\pi}} \tag{18}$$

The volume flow rate of the mixture $Q_{mixture}$, as well as the cross-sectional averaged projection of the mixture velocity $w_{mixture}$ on the pipeline axis will be determined as follows:

$$Q_{mixture} = Q_l + Q_g \tag{19}$$

$$w_{mixture} = \frac{Q_{mixture}}{f} = w_l \cdot (1 - \psi) + w_g \cdot \psi \tag{20}$$

The volume flow concentrations of liquid and gas - β_l , β_g are expressed as:

$$\beta_l = \frac{Q_l}{Q_{mixture}} = 1 - \beta_g = \frac{w_l \cdot (1-\psi)}{w_l \cdot (1-\psi) + w_g \cdot \psi}; \; \beta_g = \frac{Q_g}{Q_{mixture}} = \frac{w_g \cdot \psi}{w_l \cdot (1-\psi) + w_g \cdot \psi} \tag{21}$$

The Reynolds number for a gas-liquid mixture - $Re_{mixture}$ is defined as follows:

$$Re_{mixture} = 2 \cdot R \cdot \frac{\rho_l \cdot w_l^2 \cdot (1-\psi) + \rho_2 \cdot w_g^2 \cdot \psi}{\mu_l \cdot w_l \cdot (1-\psi) + \mu_g \cdot w_g \cdot \psi} \tag{22}$$

where μ_l, μ_g - coefficient of dynamic viscosity of liquid and gas.

The Froude criterion for the transported mixture - $Fr_{mixture}$ can be calculated using the formula:

$$Fr_{mixture} = \frac{\rho_l \cdot w_l^2 \cdot (1-\psi) + \rho_2 \cdot w_g^2 \cdot \psi}{2 \cdot R \cdot g \cdot [\rho_l \cdot (1-\psi) + \rho_2 \cdot \psi]} \tag{23}$$

CONCLUSIONS

The gas-liquid flow when moving in the pipeline, the phase velocities are not similar. In the horizontal and ascending sections of the pipes, the velocity of the gas phase is greater than that of the liquid, and in the descending sections of the pipes, the velocity of the gas phase is less than that of the liquid [8].

Two examples of inclined flow common in the petroleum industry are directional wells and pipelines passing through areas of hilly terrain. The number of directional wells is increasing rapidly as offshore drilling increases. Also, wells drilled in urban areas such for example Los Angeles and in areas where rig foundations are expensive, such as for example in Alaska, are usually directionally drilled. In many offshore operations the two-phase streams are brought to shore before separation. As the sea floor is seldom horizontal, an inclined flow situation exists [6].

The design and technological characteristics of the experimental facility provide for the possibility of simulating and studying gas-liquid flows in pipelines, simulating the flow of a gas-saturated hydrocarbon liquid, and analyzing hydrodynamic and heat transfer processes during pipeline transport of two-phase flows.

According to the results of experimental studies, it was revealed that the plug (slug) and emulsion structural forms of the flow are the most characteristic for the given hydrodynamic pumping regimes.

This experimental work can serve as a good guide for predicting slug flow characteristics in horizontal and inclined pipelines, which are important for improving flow stability.

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Received: November 2022; Revised: January 2023; Accepted: February 2023; Published: February 2023