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THE "SLIP" COEFFICIENT IN TWO-PHASE LIQUID—GAS FLOWS

G. G. Kornilov

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We present experimental data on the variation of the "slip" coefficient in two-phase liquid—gas flows.

The simultaneous flow of gas and liquid phases in pipelines takes place with a relative velocity, and is characterized by a multiplicity of structural forms, depending on the flow-rate gas content in the mixture $\beta (0 < \beta < 1.0)$. The relative velocity is the difference between the velocities of the gas U'' and liquid U' phases averaged over the cross section of the channel. In general, the relative velocity can be positive $(U'' > U')$ or negative $(U'' < U')$. In the analysis of such flows, the "slip" is more conveniently characterized by the ratio U''/U' which is called the "slip" coefficient. For a positive "slip," $U''/U' = S > 1.0$, and for negative "slip" $S < 1.0$. In the absence of "slip," $S = 1.0$.

In addition to β, the main parameter is the true gas content of the mixture α, which is the average fraction of the cross section area occupied by the gas phase, $\alpha = F''/F'$. This relationship can be seen most clearly in the expression for the "slip" coefficient S, which can be written in the form

$$S = (1 - \alpha)/(\alpha/\beta - \alpha). \tag{1}$$

The ratio α/β in (1) contains the physical essence of the flow. The deviation of this ratio from unity to either side indicates a two-channel character of the flow. For example, the value $\alpha/\beta < 1.0$ shows that the gas phase is concentrated in the region of large velocities, in comparison with the liquid phase. The relationship between α/β and the quantities which determine the two-phase flow is therefore of a considerable interest.

Experimental investigations have made it possible to establish a direct relationship between the total drop in pressure in such flows ΔP_{2ph} and S, and they show that S depends both on β as well as on the physical properties of the transported media [1]. In particular, it was shown in [1] that a definite value of S corresponds to a definite value of ΔP_{2ph}, independendently of how the change of S occurs: In one case, the change of S is due to a

TABLE 1. The relationship between μ', the velocity characteristics of phases of the mixture, and the pressure drop ΔP_{2ph}

Transported media	Vol. flow-rate $\cdot 10^3$, m/sec		$\mu \cdot 10^3$ nsec/m^2	$\Delta P_{2ph} \cdot 10^6$ N/m^2	Velocities, m/sec				W_{cm}/U''	S
	Q'	Q''			U'	U''	v	W_{cm}		
Water–air	2,08	3,86	1,01	0,123	1,84	2,61	0,77	2,17	0,83	1,42
Oil–petroleum gas	2,11	3,75	32,10	0,177	1,55	2,70	1,17	1,89	0,70	1,76
Oil–air	2,11	3,75	47,91	0,213	1,49	2,80	1,31	1,87	0,667	1,88
Oil–air	2,11	3,86	69,16	0,237	1,47	2,86	1,39	1,85	0,646	1,95

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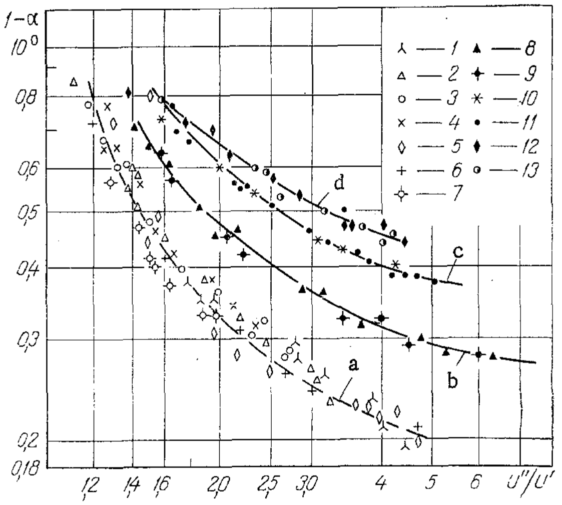

Fig. 1. The change of the "slip" coefficient as a function of the change of the moisture content and viscous properties of the liquid phase. a) Water—air components, $d = 0.0504$ m: 1) $Q' = 0.906 \cdot 10^{-3}$ m^3/sec; 2) $1.288 \cdot 10^{-3}$; 3) $1.731 \cdot 10^{-3}$; 4) $2.044 \cdot 10^{-3}$. $d = 0.0264$ m: 5) $Q' = 0.199 \cdot 10^{-3}$ m/sec; 6) $0.288 \cdot 10^{-3}$; 7) $0.346 \cdot 10^{-3}$ ($\mu' = 1.01 \cdot 10^{-3}$ nsec/m^2). b) Crude oil—air components, $d = 0.0504$ m: 8) $Q' = 0.471 \cdot 10^{-3}$ m^3/sec; 9) $0.693 \cdot 10^{-3}$ ($\mu' = 6.03 \cdot 10^{-3}$ nsec/m^2). c) Crude oil—accompanying gas, $d = 0.0504$ m: 10) $Q' = 0.601 \cdot 10^{-3}$ m^3/sec; 11) $1.559 \cdot 10^{-3}$ ($\mu' = 26.90 \cdot 10^{-3}$ nsec/m^2). d) Aerated crude oil—air components, $d = 0.0504$ m: 12) $Q' = 1.019 \cdot 10^{-3}$ m^3/sec; 13) $2.105 \cdot 10^{-3}$ ($\mu' = 58.89 \cdot 10^{-3}$ nsec/m^2).

change of viscosity of the liquid phase, and in the other case, to a change in β (other conditions are identical: Q' is constant, and the length and diameter of the pipeline are the same). In Table 1 we show the data which give, on a concrete example, the change of ΔP_{2ph}, S, and α/β as functions of μ'.

It follows from the data in Table 1 that, if the flow rates are kept constant relative to one another, one observes an increase of ΔP_{2ph}, relative velocity v, and S, and decrease of U' and of the ratio $\alpha/\beta = W_{cm}/U''$ with increasing dynamical viscosity coefficient of the liquid phase. As the viscosity of the liquid phase increases, and other conditions are identical, the liquid phase flow becomes slower, but it will occupy a large fraction of the cross-sectional area of the pipe, and S increases.

An analysis of the experimental data obtained for mixtures with components water—air, crude oil—air, and crude oil—accompanying petroleum gas gives the following relation for α/β in (1):

$$\alpha/\beta = (\nu''\rho''/\nu'\rho')^{0.0475} = (\mu''/\mu')^{0.0475}. \tag{2}$$

This relation is valid in the so-called "automodeling" region which, for a liquid—gas mixture with components water—air, takes place in the following interval of β, where β is reduced to P_{av}: $0.05 < \beta \leq 0.95$. After the substitution of viscosities of water and air, Eq. (2) reduces to the equality $\alpha/\beta = 0.833$ which was obtained for these media earlier ($t = 20°C$) by suspension of an experimental pipeline [2]. Substituting (2) into (1), one can represent (1) in the form

$$S = [1/\mu^{0.0475} - \beta]/(1 - \beta) = [(\mu'/\mu'')^{0.0475} - \beta]/(1 - \beta), \tag{3}$$

where $\mu = \mu''/\mu'$.

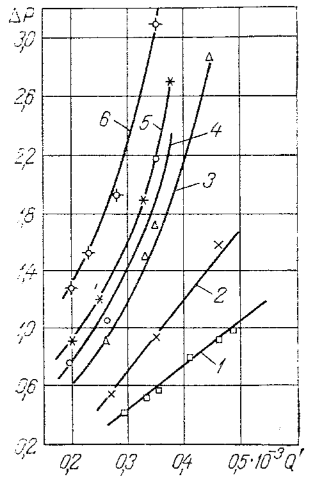

Fig. 2

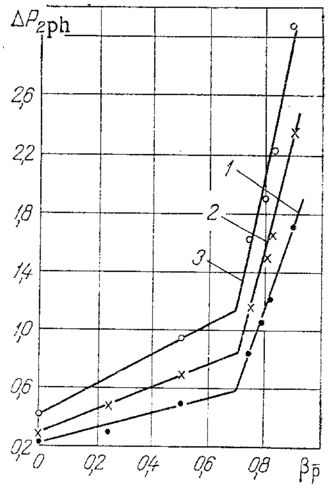

Fig. 3

Fig. 2. The characteristic of the pipeline (d = 0.0264 m) for the work on the water—air components: 1) $\beta = 0.25$; 2) 0.51; 3) 0.75; 4) 0.80; 5) 0.83; 6) 0.90. The quantity ΔP is in 10^5 Pa, and Q' in m^3/sec.

Fig. 3. The character of the change of the energy spent on mixing of the mixture as a function of β_p for a fixed value Q' (from Fig. 2): 1) $Q' = 0.25\cdot10^{-3}$ m^3/sec; 2) $0.30\cdot10^{-3}$ m^3/sec; and 3) $0.35\cdot10^{-3}$ m^3/sec.

For a fixed value of μ', the experimental data are shown more fully in Fig. 1 in the form $S = f(1 - \alpha)$. They are obtained in a stand and immediately at the oil deposits for a motion of the liquid—gas mixtures in pipe with $d = 0.0264$ m and $d_2 = 0.0504$ m, and length of the working part $l_1 = 194.62$ m and $l_2 = 197.20$ m, respectively. The pipes were positioned horizontally. The character of motion along the length of the pipes was observed by means of five transparent links. The stand consisted of pump-compressor equipment, apparatus for measuring the flow rate, pressure, and temperature, separator of the mixture, reservoir, and shut-off equipment. The stand made it possible to vary the fraction of gas in the mixture from 0 to 97% by volume for a given flow rate of the liquid phase. In each experiment we determined the flow rate of the gas and liquid phases. The temperature of the liquid—gas mixture was measured at the beginning, in the middle, and at the end of the pipeline. For the pipe of diameter $d = 0.0264$, pressure was measured at six points, and for the pipe of diameter $d = 0.0504$ at ten points, by standard pressure gauges of accuracy class 0.35. This made it possible to measure the line of falling pressure along the length of the pipeline in each experiment.

The quantity α was determined by an indirect method, by measuring the velocity of motion of the liquid phase U' along the length of the pipeline. The quantity U' was measured by an instantaneous injection of a test liquid which had similar physical properties to the flowing liquid. In the work with the water—air components, a dye was added to the flow, and in the work with crude oil, we used oil—water emulsion. The dye was a water solution of ammonium thiocyanate with ferric chloride (potassium ferricyanide $K_3Fe(CN_6)$). The test liquid was added to the flow in the steady-state regime. We registered the time of passage of the test liquid from the first link to the second, second to the third, etc., and we also noted the time of passage from the beginning to the end of the experimental pipeline (from the first to the fifth link), i.e., we measured the average velocity of motion of the liquid phase both along the individual segments, as well as along the total length of the pipeline.

In the experiments with crude oil, the average velocity of the oil was determined from the time between the introduction of the emulsion in the pipeline and when it appeared in the sensors. The working parameter of the sensor was the electrical capacitance which responds to the change of the dielectric permeability of the medium. The dielectric permeability of the main constituent of the emulsion, i.e., water ($\varepsilon_W = 81$) exceeds considerably the dielectric permeability of crude oil ($\varepsilon_{co} = 1.8\text{-}2.4$) and petroleum gas ($\varepsilon_g = 1.0$). The average area of the liquid phase was found from the continuity of its flow with the use of the equality $F' = F - F'' = F - \alpha F = (1 - \alpha)F$.

The method for measuring α via U' and Q' led to averaging of the cross section of the pipe occupied by the liquid as well as by the gas phases. The separate gas pockets are in this case replaced by a continuous jet of volume equal to the volume of the pockets in the length under consideration.

The experimental data (Fig. 1) were obtained at t = 20°C, and span the region of position "slip" $S > 1.0$.

It follows from an analysis of Fig. 1 that the change of the "slip" coefficient is affected considerably by both the concentration (ratio) and the properties of the phases. For example, if one takes the value $1 - \alpha$ constant and equal to 0.45, the "slip" has the following values: using curve *a*, $S = 1.55$; b, $S = 2.12$, c, $S = 3.24$, and curve d, $S = 4.20$. The different values are due to the difference of viscosities.

In practice, it is most often necessary to keep Q' constant. In this case, if the viscosity of the liquid phase is increased and other conditions kept constant, the velocity of the liquid phase decreases. For example, for $Q' = 2.044 \cdot 10^{-3}$ m^3/sec, $\beta = 0.70$, and $1 - \alpha = 0.45$, the ratio of the true water velocity U' and the true velocity of the liquid phase of curves b, c and d is $U'_a/U'_b = 1.12$, $U'_a/U'_c = 1.24$, and $U'_a/U'_d = 1.3$, and is larger than unity. The decrease of U' for crude oil which contains mineralized water causes separation of the latter as a third free phase. In this case, water condenses in the lower parts of the pipeline, and is the main source of the so-called "groove" corrosion [3].

The investigations also made it possible to establish that the change of S in the region of the possible values β ($0 < \beta \leq 1.0$) is not identical. Using $\Delta P_{2ph} = f_1(S)$ of [1], the confirmation of this fact is Figs. 2 and 3.

Figure 2 shows the experimental data on the change of the pipeline characteristic as a function of the load with respect to gas and the liquid. The working part of the pipeline with internal diameter $d = 0.0264$ m had length $l = 194.6$ m. The position of the pipeline was horizontal. The liquid—gas mixture consisted of air and water. In each series of experiments, the value of the flow-rate gas content β was constant. The numerical values of β are given in Fig. 2. From the data in Fig. 2, one can construct a graph which reflects the true work of the well in the assembly. For a fixed flow-rate of the liquid phase Q' (well output), it is possible to find the change of the pressure drop ΔP_{2ph} as a function of the change $\beta_{\bar{p}}$ or of the change of the instantaneous gas number (gas factor). In the form $\Delta P_{2ph} = \psi(\beta)$, this graph is shown in Fig. 3 for three fixed flow-rates of the liquid phase. It follows from Fig. 3 that the effect of β on ΔP_{2ph} is not identical. In the interval of β, there are two regions: 1) $0 < \beta \leq 0.70$ and 2) $0.70 < \beta < 0.90$. For values of β close to 0.70, there is a sharp bend of $\Delta P_{2ph} = \psi(\beta)$. Each region corresponds to a specific energy dissipation. For example, for a fixed value of Q' equal to $0.3 \cdot 10^{-3}$ m^3/sec ($Q' = 1.08$ m^3/h) for $0 < \beta < 0.70$ the value of the ratio $\Delta P_{2ph}/\beta = 0.77$, and for $0.70 < \beta < 0.90$, $\Delta P_{2ph}/\beta = 7.6$, i.e., in the second region, the specific energy dissipation is larger by an order of magnitude. An analogous character of the change of parameters as in Figs. 2 and 3 is observed also for other media in the liquid-gas mixture, and for pipes of other diameters. The difference in the energy dissipation in the regions of β under consideration can be explained by an aggregate state of the gas phase as it moves in the flow with the liquid. It was established by numerous experiments that in the first region, the gas phase moves discretely inside the liquid phase in the form of pockets, locks, and shells (beads, gas cylinders). In this case, the gas phase does not have an independent channel. In the region of values β which are close to 0.70, the gas phase disrupts the liquid bridges between gas pockets, and the flow becomes stratified. The gas phase begins to move along an independent channel, and the relative velocity increases. This motion leads to the formation of waves which are initially smooth but later become "squall." In addition to losses to overcome friction of motion, a considerable part of energy is spent on the formation, "life," and destruction of liquid-phase waves as they instantaneously periodically cover the gas channel. This covering leads to pressure pulsations, pipeline vibrations, spray of the liquid phase, its redispersion, and in the presence of water in the oil, to the formation of a stable water—oil emulsion. During this, the pipeline suffers a large mechanical load.

The flow with the formation of covering waves can be classified as the alternation of inelastic hydraulic shocks of a definite frequency, and the flow of the mixture as "flooding" the pipeline. The amplitude of the liquid waves and their wavelength depend on the slip of the gas with respect to the liquid. It was established that, as U" or β increase in a gas phase motion above the liquid, the time interval between coverings increases, and the frequency decreases. This phenomenon can be explained as follows. The quantity U' increases with increasing U" or β. As U' increases for $Q' = \text{constant}$, the area of the pipeline channel occupied by the liquid phase decreases. The channel becomes a "low-water" one. This formation of "low-water" behavior is assisted by the disruption of the covering waves. Each disruption of the covering waves is associated with the spray of the liquid phase, and with the introduction of the liquid phase into the gas phase flow in the form of small jets. The liquid phase is reduced, and it becomes insufficient for the formation of the covering waves. The height of the waves tends to zero. At the same time, in our opinion, one observes the transition of the stratified regime of flow with waves to the disperse-ring type structure form of flow of the liquid-gas mixture.

Noting the phase inversion, the above data make it possible to divide the two-phase liquid—gas flows in horizontal pipelines into three regions, according to the energy consumption for the mixing of the mixture: 1) $0 < \beta \leq 0.70$, gas in liquid; 2) $0.70 < \beta \leq 0.95$, gas above the liquid; and 3) $\beta > 0.95$, liquid in gas.

Since these flows consist of a practically incompressible liquid phase and a compressible gas phase, they can be intentionally acted upon and controlled. In particular, because of the increased relative density of the mixture ρ''/ρ' [4] which is equivalent to a decreased S, one can, for example, transfer the operation of the assembly from the second region to the first by changing the pressure at the separation points. This would decrease the energy consumption and eliminate undesirable effects. This makes it possible to solve many practically important problems, associated with obtaining technical data for technological planning, the choice of depth of the extraction and collecting pipelines, and gives foundation for the solution of thermoinsulating problems.

It is our opinion that the obtained results can also be used in other fields, for example, in the study of two-phase gas—liquid metal flows in magnetohydrodynamic generators.

NOTATION

Here α and β are the true and flow-rate values of the volume gas content of the mixture, respectively; U" and U', true velocities of the liquid and gas phases; v, relative velocity; t, temperature in °C; Q', Q", volume flow rates of the liquid and gas phases; μ', and μ", dynamical viscosity coefficients of the liquid and gas phases; d, internal diameter of the pipeline; F, cross-sectional area of the pipeline; F', F", cross-sectional areas of the pipeline occupied by the liquid and gas phases; l, length of the pipeline; and $S = U''/U'$, "slip" coefficient.

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