Kutukov S.E., Bakhtizin R.N.
Ufa State Petroleum Technological University

HYDRODYNAMIC PRECONDITIONS OF GAS CONGESTION IN LIQUID PIPELINE

ANNOTATION

Hydrodynamic preconditions of existence and migration of gases congestion are discussed. Hydrodynamic model of stratified flow in a hilly terrain pipeline is suggested, that allows to predict the possible location of gas congestions in the pipeline from engineering point of view. There is shown an influence of terrain features on pipeline capacity as a physical pattern in the paper.

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PREFACE

Experience of trunk pipelines operation shows some capacity reduction in comparison with their designs. The more pipeline section is underloaded, the more hydraulic resistance is occurred.

Gas-air congestions in higher parts of the cambered profile cause the pipeline capacity reduction. These congestions contain non-organic gases (N_2, CO_2, H_2S and others) and such light hydrocarbon fractions as (CH_4, C_2H_6). There are two points of view on the reason of gases congestions formation: one of them – dissolved gas separation on the uphill section of pipeline with the further coagulation of bubbles into gases congestion (K.G. Donetz [1]); another – jamming of appreciable air volumes in higher sections at pipeline priming after repair or re-construction, which can not be put out from the pipe seeing low velocity of product (A.A. Kalinske [2], L.S. Maslov [3]).

One can found already in B.A. Bakhmetjev’s works dated 1914 [4] the possibility basing of fluid flow consideration in open channel for definition of form and size of gas congestion which is occurred in inclined pipeline section over the top elevation point.

The physical pattern of product flow under the streamless gas congestion is rather close to the model of under gravity forces fluid motion in cylinder channel, which is described in fulsome detail in classical Fluid Mechanics [5, 6, 7].

A lot of foreign and national scientists have studied the steady stratified two-phases flow existence. The most famous diagrams are suggested by A.I. Gudgov [8], and abroad – by Teitel and Dukler [9].

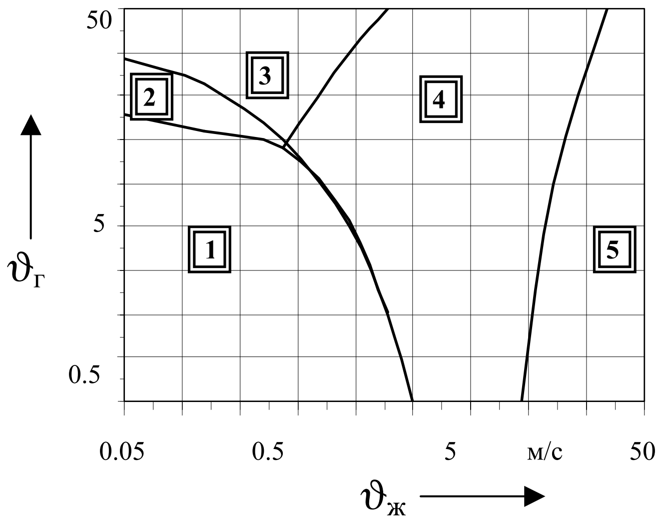


Figure 1. The diagram of gas-fluid flow structure forms.

Different researchers accept from 5 to 9 of gas-oil flow structure forms gradation. Teitel-Dukler model suggests 5 ones [9]:

- Stratified – 1;
- Stratified wavy – 2;
- Intermitted – 3;
- Annular – 4;
- Dispersed – 5.

A.I. Gudgov differs 6 structure forms of flow, V.F. Medvedev – 9 [8]. But it is shown invariably in all the investigations that at small gas velocities (streamless congestion) and fluid velocity equal to 0…1,5 m/s the flow mode is stratified.

MODEL OF STRATIFIED FLOW IN A PIPELINE

Diagram of pipeline elementary section, approximated by straight line with inclination angle on the line profile, one can describe as a model of permanent stratified flow in inclined cylinder channel (figure 2).

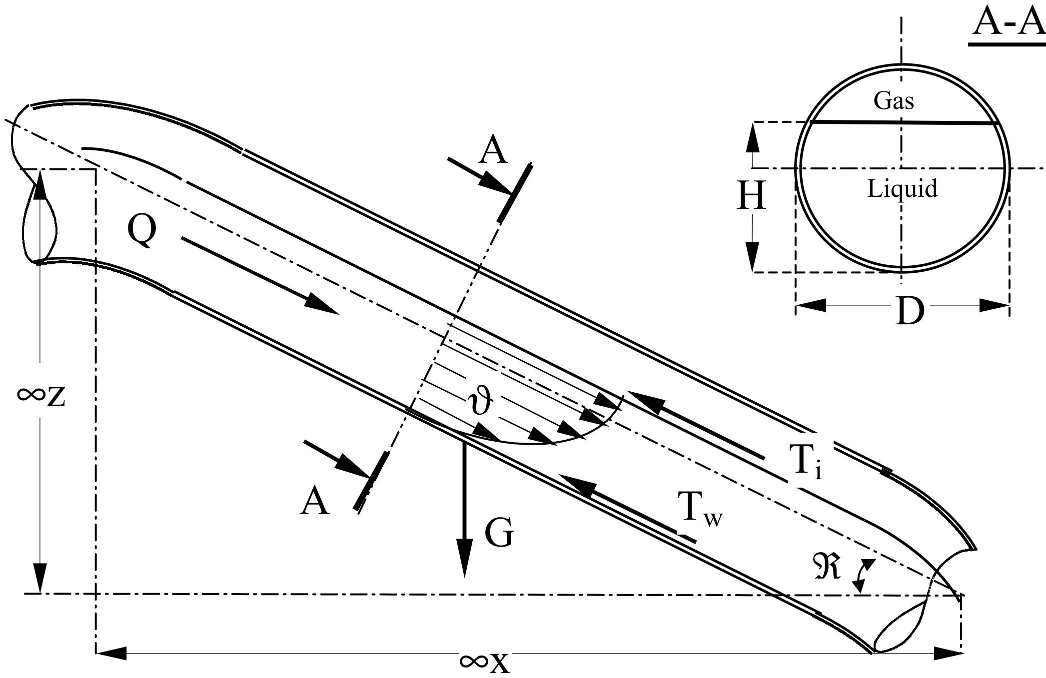


Figure 2. Flow under "streamless" gas congestion.

Let's compose Bernoulli equation for the elementary section described on figure 2 according to a motion direction:

$$tg\alpha \cdot dx + \frac{p_o}{\rho g} + \alpha \frac{\vartheta^2}{2g} = dH + \frac{p_o}{\rho g} + \alpha_0 \frac{(\vartheta + d\vartheta)^2}{2g} + d\,h_{mp} \qquad (1)$$

where ρ_o – pressure in gas congestion;

ϑ, $d\vartheta$ – speed of flow and its change along motion direction;

dH – flow depth increment;

α_o – kinetic coefficient;

dh_{mp} – energy losses due to friction.

Pressure on the free liquid surface under gas congestion is practically invariable, so one can cancel pressure head in both parts of equation. Energy loses on friction dh_{mp} have two components: on pipeline wall dh_w and on the interfacial surface dh_i.

$$dh_w = \frac{\rho_{ж}}{\rho_{ж} - \rho_{г}} \cdot \lambda \frac{\chi}{4\varpi} \cdot \frac{\vartheta^2}{2g} dx, \qquad (2)$$

$$dh_i = \frac{\tau_i}{\rho_{ж} - \rho_{г}} \cdot \frac{a}{\varpi \cdot g} dx, \qquad (3)$$

since $\rho_{ж}$, $\rho_{г}$ – density of liquid and gas; ϖ – cross-section area of fluid flow;

λ – friction factor; a – length of interfacial perimeter;

χ – wetted perimeter; τ_i – shear stress onto interface.

Gas density is less than the liquid one in 10…100 times, so one can be neglected in equations (2,3). Let's imagine the energy loses on inter-phases friction likewise Darcy equation:

$$dh_i = \frac{\tau_i}{\rho_{ж} - \rho_{г}} \cdot \frac{a}{\varpi \cdot g} dx = \frac{2\,\tau_i}{\rho_{ж}\vartheta^2} \cdot \frac{a}{\varpi} \cdot \frac{\vartheta^2}{2g} dx = \frac{2\tau_i}{\pi \cdot \rho_{ж}\vartheta^2} \cdot \frac{a}{D} \cdot \frac{\varpi_0}{\varpi} \cdot \frac{dx}{D} \cdot \frac{\vartheta^2}{2g} \qquad (4)$$

Comparing equation (4) with Darcy equation we conclude that it's enough to compare the friction factor λ with complex $\frac{2\tau_i}{\pi \cdot \rho_{ж}\vartheta^2} \cdot \frac{a}{D} \cdot \frac{\varpi_0}{\varpi}$ for comparing dh_w and dh_i. According to G.E.Korobkov data [11] the meaning of shear stress complex $\frac{\tau_i}{\rho_{ж}\vartheta^2}$ is estimated by value 10^{-7}, the value of the other ones is about unity, friction factor is 10^{-2}. So, interfacial friction forces are estimated with value less than 1% of liquid friction against pipeline sides.

Taking into account the definition of hydraulic radius: $R_1 = \varpi/\chi$ and expression of volume flow rate $Q = \vartheta * \varpi$, we'll get:

$$dh_w = \lambda \frac{D}{4R_г} \cdot \frac{dx}{D} \cdot \frac{\vartheta^2}{2g} = \frac{\lambda}{D \cdot \left(\frac{\pi D^2}{4} \right)^2 2g} \cdot \left(\frac{\varpi_o}{\varpi} \right)^2 \frac{D}{4R_г} \cdot Q^2 dx =$$
$$= 0{,}08263 \cdot \frac{\lambda}{D^5} \cdot \left(\frac{\varpi_o}{\varpi} \right)^2 \frac{D}{4R_г} \cdot Q^2 dx \qquad (5)$$

In the analysis of stratified motion phenomenon in pipelines there are considered such geometric characteristics of cross-section area as:

Dimensionless depth of flow – $\frac{H}{D} = \sin^2 \frac{\Theta}{4}$ (6)

Dimensionless length of interfacial contour – $\frac{a}{D} = \sin \frac{\Theta}{2}$ (7)

Dimensionless wetted perimeter – $\frac{\chi}{\pi D} = \frac{\Theta}{2\pi}$ (8)

Dimensionless hydraulic radius – $\frac{4R_г}{D} = 1 - \frac{\sin \Theta}{\Theta}$ (9)

Coefficient of pipe filling – $\frac{\varpi}{\varpi_o} = \frac{\Theta - \sin \Theta}{2\pi}$ (10)

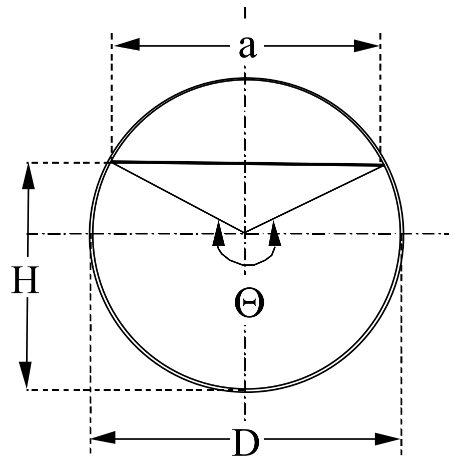


Figure 3 – Geometric characteristics of cross-section.

Opening $(\vartheta+d\vartheta)^2$ as $\vartheta^2+2\vartheta \cdot d\vartheta+(d\vartheta)^2$ in equation (1), we neglect $(d\vartheta)^2$ as by the infinitesimal value. After elimination of similar members we get:

$$tg\alpha = \frac{dH}{dx} + \alpha_0 \frac{\vartheta}{g} \frac{d\vartheta}{dx} + 0{,}08263 \cdot \frac{\lambda}{D^5} \cdot \left(\frac{\varpi_o}{\varpi}\right)^2 \frac{D}{4R_г} \cdot Q^2 \quad (11)$$

Flow depth and velocity head changes along length in a steady motion can occur by means of pipeline diameter or its inclination angle to horizon alteration. There are no these components for elementary section of a pipeline in frames of suggested calculated scheme. Let's represent the equation according to coefficient of pipe filling:

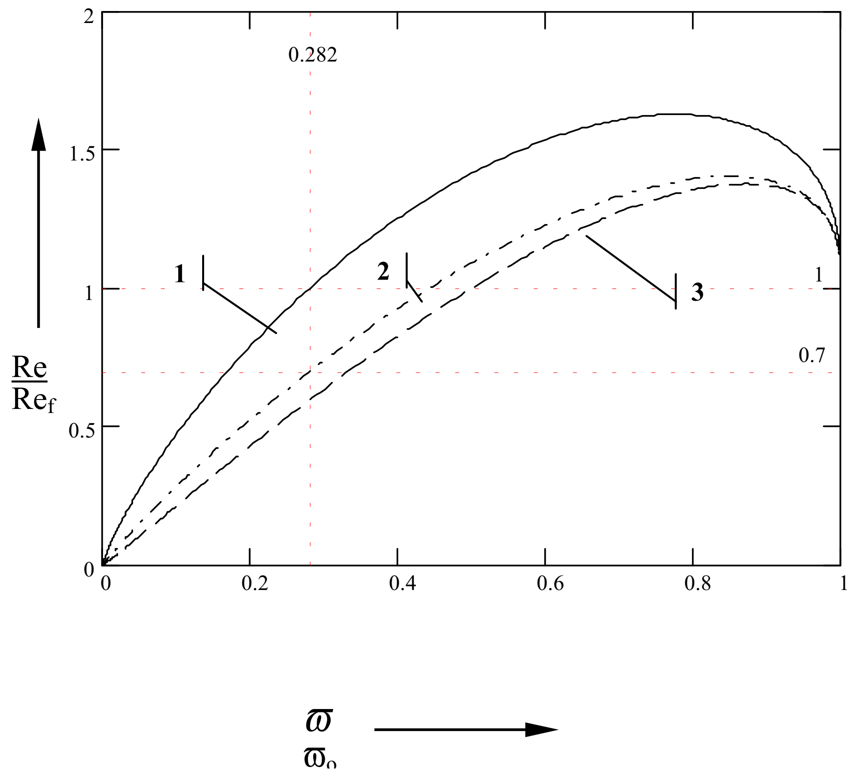
$$tg\alpha = 0,08263 \cdot \frac{\lambda}{D^5} \cdot \left(\frac{\varpi_o}{\varpi}\right)^2 \frac{D}{4R_{\text{г}}} \cdot Q^2 \qquad (12)$$

Friction factor in turn, is determined by flow mode, which is characterized by Reynolds number:

$$\mathrm{Re} = \frac{\vartheta \cdot 4R_{\text{г}}}{\nu} = \frac{4Q}{\pi D \cdot \nu} \cdot \frac{\varpi_0}{\varpi} \cdot \frac{4R_{\text{г}}}{D}, \qquad (13)$$

where ν - kinematics viscosity of liquid.

But the liquid velocity changes with the filling level and, hence, the fluid motion mode of can change, as well as friction zone in turbulent regime. At a small filling level the laminar regime is more probable with further transfer to a turbulent one and in certain conditions – versa vice. There is shown Reynolds number change depending on coefficient of pipe filling and flow mode.



1 - laminar flow; 2 – smooth friction; 3 - ruogh friction;

Re_f - Reynolds number in wholly filled pipe flow.

Figure 4. Reynolds number vs pipe filling.

Ratio $\frac{\text{Re}}{\text{Re}_f}$ reaches its maximum:

$$\left.\frac{\text{Re}}{\text{Re}_f}\right|_{\frac{\varpi}{\varpi_0}=0,778} = 1,626 \text{ in laminar flow;}$$

$$\left.\frac{\text{Re}}{\text{Re}_f}\right|_{\frac{\varpi}{\varpi_0}=0,852} = 1,403 \text{ in smooth friction;} \tag{14}$$

$$\left.\frac{\text{Re}}{\text{Re}_f}\right|_{\frac{\varpi}{\varpi_0}=0,868} = 1,376 \text{ in rough friction.}$$

On the basis of G.E.Korobkov's experiments [11] there were the dependences suggested of Darcy's coefficient for open-channel laminar flow

$$\lambda = \frac{90}{\text{Re}} \tag{15}$$

and smooth friction:

$$\lambda = \frac{0,194}{\text{Re}^{0,187}}, \tag{16}$$

their error doesn't exceed 12%.

Using Colebrook's formula for other turbulent zones of friction [6] and M. V. Lurje's recommendations for transient flow approximation with "intermittent factor" [10]:

$$\gamma = 1\text{-exp}\{-\ 0,2\cdot(\text{Re-2320})\}, \tag{17}$$

we'll get the next algorithm for definition of friction factor:

$$\lambda = \frac{90}{\text{Re}}, \qquad \text{для Re} < 2320;$$

$$\lambda = \frac{90}{\text{Re}}(1-\gamma) + \frac{0,194}{\text{Re}^{0,187}}\gamma, \qquad \text{для } 2320 < \text{Re} < 4000; \tag{18}$$

$$\lambda = \frac{0{,}194}{\mathrm{Re}^{0{,}187}}, \qquad \text{для } 4000 < \mathrm{Re} < 27\left(\frac{D}{k_э}\right)^{1{,}143};$$

$$\frac{1}{\sqrt{\lambda}} = -2\cdot\lg\left(\frac{k_э}{3{,}7D} + \frac{2{,}51}{\mathrm{Re}\sqrt{\lambda}}\right), \quad \text{для } \mathrm{Re} > 27\left(\frac{D}{k_э}\right)^{1{,}143},$$

since $k_э$ – apparent roughness of inner pipe surface.

ANALYSIS OF SYSTEM BEHAVIOUR

Aiming generalization and analysis of the solution let's consider term 'full cross-section discharge' - Q_f designating the flow rate of pipeline's section under conditions when the grade line incline is equal to the pipe axis one. This regime supposes the fluid flow to occur under gravitation forces alone, and the pressure along the length is sustained constant.

$$Q_f = \sqrt{\frac{tg\alpha\cdot D^5}{0{,}08263\cdot\lambda_f}}, \tag{19}$$

since λ_f – friction factor defined according to classical method:

$$\lambda = \frac{64}{\mathrm{Re}}, \qquad \text{для } \mathrm{Re} < 2320;$$

$$\frac{1}{\sqrt{\lambda}} = -2\cdot\lg\left(\frac{k_э}{3{,}7D} + \frac{2{,}51}{\mathrm{Re}\sqrt{\lambda}}\right), \quad \text{для } \mathrm{Re} > 2320. \tag{20}$$

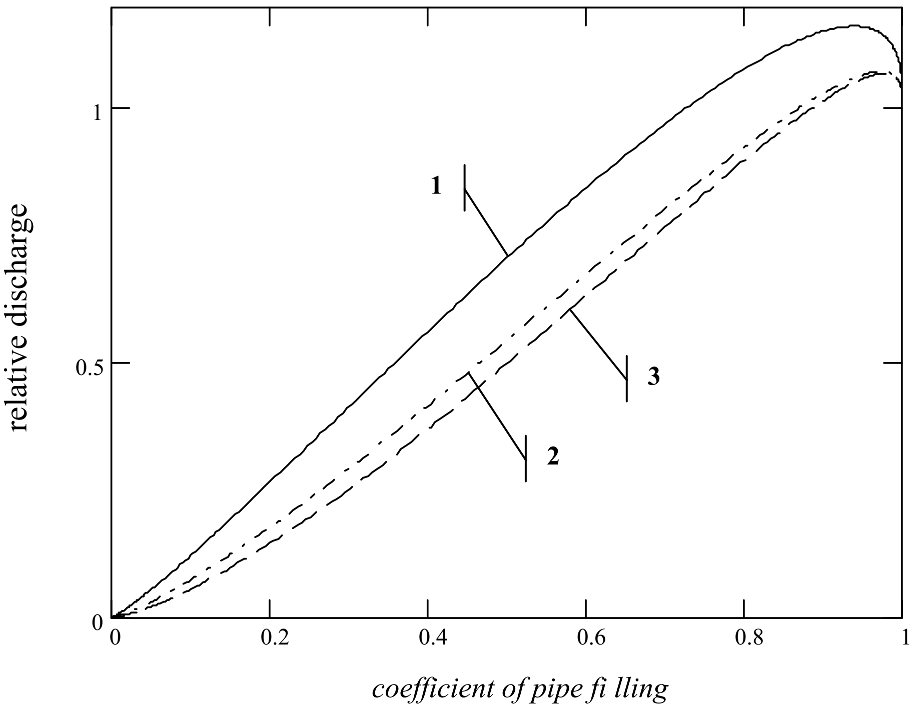
So, the full cross-section discharge includes the inclination to horizon as well as rheological properties of the flowing liquid.

Though this tendency is analogical and there is seen the maximum point in all the figures (most possible gravitational discharge through pipeline section), but its value and argument meaning at which this maximum occurs, are different.

Relative discharge can be defined from the expression:

$$\frac{Q}{Q_f} = \frac{\varpi}{\varpi_0}\sqrt{\frac{\lambda_f}{\lambda}\frac{4R_г}{D}} \tag{21}$$

There are shown on figure 7 the curves of pipeline relative discharge $\frac{Q}{Q_f}$ versus coefficient of pipe filling $\frac{\varpi}{\varpi_o}$.



1- laminar flow;

2- turbulent flow in smooth friction;

3- rough friction in all range of pipe filling coefficient.

Figure 5. Pipeline discharge vs coefficient of pipe filling.

Taking into consideration the expressions through the central angle Θ of dimensionless hydraulic radius (9) and coefficient of pipe filling (10), and also the equations for definition of friction factor λ (18), one can be found the analytical equation for relative discharge in central angles range Θ within the one friction zone:

$$\frac{Q}{Q_f} = 0{,}3989\frac{(\Theta - \sin\Theta)^{3/2}}{\Theta} \text{… for laminar flow;}$$

$$\frac{Q}{Q_f} = 0{,}2003\frac{(\Theta - \sin\Theta)^{3/2}}{\Theta^{5/8}} \text{… for smooth friction;} \qquad (22)$$

$$\frac{Q}{Q_f} = 0{,}1591 \frac{(\Theta - \sin\Theta)^{13/8}}{\Theta^{5/8}} \ldots$$ for rough friction.

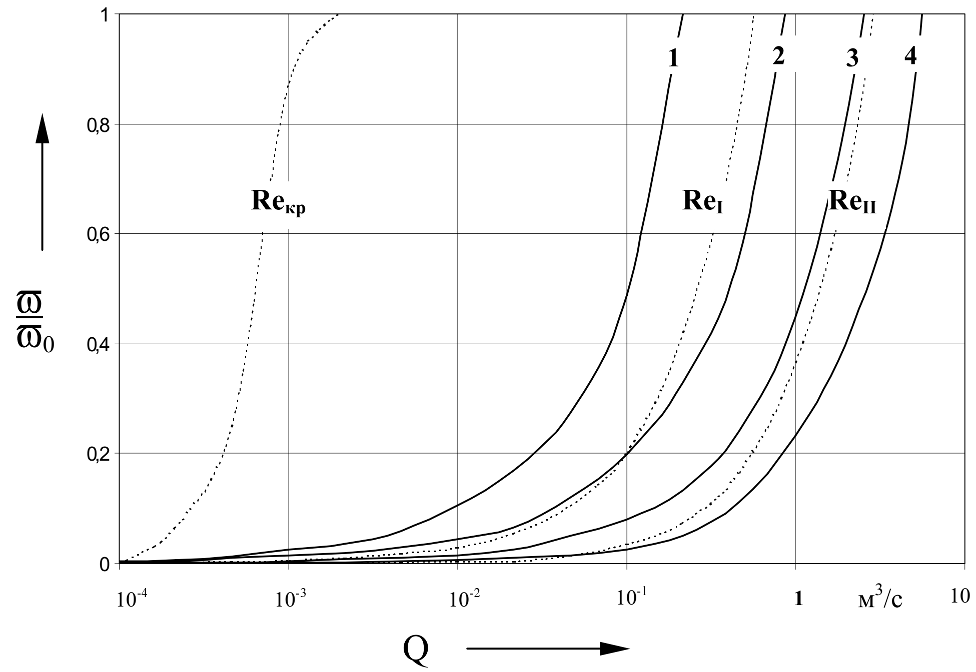
The digital calculation of these equations gives the next meanings of maximums:

$$\left(\frac{Q}{Q_f}\right)_{max}\Bigg|_{\Theta=4{,}91} = 1{,}161 \ldots \text{ for laminar flow;}$$

$$\left(\frac{Q}{Q_f}\right)_{max}\Bigg|_{\Theta=5{,}25} = 1{,}073 \ldots \text{ for hydraulically smooth pipes;} \qquad (23)$$

$$\left(\frac{Q}{Q_f}\right)_{max}\Bigg|_{\Theta=5{,}29} = 1{,}069 \ldots \text{ for rough friction.}$$

There is shown the pipe filling level change depending on pipeline ∅ 1200 inclination for different flow mode with viscosity 1 cSt in discharge range [10^{-4}…10 m/sec] on figure 6.



1 - tgα = 10^{-4}; 2 - tgα = 10^{-3}; 3 - tgα = 10^{-2}; 4 - tgα = 10^{-1}.
Figure 6. Pipe filling level depending on discharge.

The curves got from the equations (22) $Q = f(\Theta)*Q_f$ for appropriate flow mode. Boundaries of friction zones are determined by formula:

$$Q = \frac{\mathrm{Re} \cdot D \cdot \nu \cdot \Theta}{8}, \qquad (24)$$

where Re = $Re_{кр}$ for differentiation of laminar and turbulent flow mode;

Re = Re_{I} – smooth and mixed friction;

Re = Re_{II} – mixed and rough friction.

So, prerequisite of gas-air congestion existence in pipeline downhill section is the ratio:

$$Q < Q_{max}, \qquad (25)$$

since Q – instant pipeline discharge;

Q_{max} – most possible gravitational discharge through pipeline section.

CONCLUSION

Gas-air congestion position in a pipeline is stipulated by following hydrodynamic conditions:

- congestion is situated in a downhill pipeline section, beginning near the highest (top elevation) point;
- the prerequisite of gas-air congestion existence is restraint of discharge within the range Q = [0…Q_{max}];
- cross-section square of the congestion on each section of the pipeline is limited by the appropriate coefficient of pipe filling …;
- gas congestion length is stipulated with gas presence.

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