Simultaneous liquid and gas flow in pipelines needs to be controlled, monitored, analyzed and managed. In the oil and gas industry transport of gas with low liquid yield is normally carried out in infield and trunk pipelines.

For proper design and modeling of these pipelines it is necessary to provide accurate prediction of flow pattern, liquid hold-up and pressure drop which is consistent with thermo- and hydrodynamic properties of the gas-liquid mixture. Many theoretical models and experimental correlations for prediction of pressure drop and liquid hold-up in pipelines were developed during the last 70 years. However no single one works for all flow regimes in multiphase gas-liquid flow. Further, gas-liquid flows with low liquid content are less investigated and information about them is limited.

The purpose of this research is the quantification of the influence of liquid yields to parameters of wet gas patterns in pipelines. The following tasks were carried out for achieving this purpose:

1) analyse existing approaches to determination of patterns of wet gas flow with low liquid loading;
2) work out the algorithm for calculation of liquid film level in wet gas flow with low liquid loading; and
3) test this algorithm at modelling of Stockman trunk line.

Comparison of field data and calculated data for pressure drop in wet gas pipelines

One of the most significant and consistent assessments of the concurrent flow of gas and low loads of liquid was done by Hope et al (1977) [8]. They compared three well known single phase gas equations (AGA, Colebrook-White and Pranhandle) with three two-phase models (Baker et al, 1954; Dukler, 1964 and Beggs&Brill, 1973). They predicted the pressure drop of a North sea pipeline transporting approximately 25.5 MSm³/d of gas with a liquid load of 28 sm³/m³. The single phase models gave better predictions than the two-phase models and the AGA correlation was by far the best single phase model.

Ullah (1987) [13] performed a similar analysis with wet gas system (liquid load in gas is 5.6 sm³/m³) off the coast of the West Indies and came up with similar findings.

Asante and et al (2000) provided the similar investigation for three existing wet gas pipelines: Frigg, Viking u Yacheng [4]. The results indicated that the difference between field and calculated data using AGA correlation was minimum for wet gas with low load of liquid (less than 45 sm³/m³). The Beggs&Brill and the Dukler correlations showed bigger errors of pressure drop prediction (for different production rates).

Gould and Ramsey (1975) [6] looked at an 16 inch pipeline transporting gas with a liquid loading of 56-112 sm³/m³ and concluded that the Beggs&Brill correlation gave better predictions than the single phase Pranhandle model.

Besides, there is a challenge to measure void fraction and hold-up in the two-phase gas-liquid flows. In literature different types of techniques were implemented to measure the void fraction in the two-phase, gas-liquid closed flows: Microwave Flow Sensor, Optical probe, Gamma-ray densitometers, Capacitance sensor, Quick-closing-valves. In addition, synchrotron X-rays, pulsed neutron technique, conductance probe, ultrasonic technique, and ring impedance probe have been used successfully to measure the void fraction in two-phase flow systems [10]. But all these techniques are limited by the amount of liquid they are able to measure. For example, the total uncertainty, based on root-sum square combination of precision (random) and systematic (bias) components at 95% confidence (± 2σ ), was determined for each type of gamma densitometer system (GDS) measurement. The wide beam edge measurement was averaged for a total uncertainty of ± 0.017 in void fraction [12].

The results indicates that up-to-date methods and correlations for predicting of the parameters of two-phase flow with low loads of liquid (including simulators PipePhase, PipeSim, OLGA etc) can lead to significant errors.
Flow patterns in long wet gas pipelines

The fact that the single phase models give better predictions of pressure drop than the two-phase models can be explained by domination of dispersed-stratified flow regime in long distance wet gas pipelines [2,3] (Fig. 1).

These flow regimes (for wet gas with load loan of liquid) are characterised by friction factor values close to dry gas.

Mechanistic model of wet gas flow in pipeline

A mechanistic model for calculation of main parameters of gas flow in pipeline with low loads of liquid is based on the following statements:

Wet gas flow regime is stratified. All liquid in wet gas flow is transferred as a film at the bottom of the pipeline. Dispersed liquid in gas flow is not considered (entrainment of liquid drop from gas-liquid interface were analyzed by authors in [9]).

Stratified transfer of gas and liquid phases is described by their own momentum conservation equation.

At the interface of gas and liquid phases there is a shear stress which mostly depends on the liquid level. It also depends on density, velocity and viscosity of gas. The shear stress causes deceleration of gas phase and speed-up of liquid film.

Geometry of liquid layer is considered as a symmetric annular segment at the bottom of the pipeline (Fig.1, b).

As it seen from above, suggested mechanistic model is based on the basic principles of fluid mechanics and assumption about the interface behavior. Verification of the model should be based on stable solution of set of equations and physical considerations.

The model allows to:
- calculate the liquid level at the pipeline cross section;
- calculate the hold-up;
- calculate the pressure drop;
- determine the borders of stratified-wavy flow regime.

Our mechanistic model is based on Taitel & Dukler approach [5] which includes solution of momentum conservation equations separately for gas and liquid phases in condition of stratified flow regime.

The stratified regime is a basic in Taitel & Dukler approach (Fig.2); change of flow regime occurs when special parameters reach their critical values (these values are determined by experiments).

In our developed mechanistic model (in contradiction to Taitel&Dukler model) the interfacial friction factor and friction factor at gas-wall interface are not equal. The interfacial friction factor depends on liquid level. As calculations show this approach allows to get stable solutions for stratified-wavy flow in wider intervals of production rates and inclination angles of terrain than in Taitel & Dukler approach.

Momentum conservation equations for both gas and liquid phases of two phase stratified flow are [5]:

\[
-A_l \frac{dP}{dx} - \tau_{wg} S_l + \tau_S + \rho_l A_l \sin \alpha = 0
\]

\[
-A_g \frac{dP}{dx} - \tau_{wg} S_g - \tau_S + \rho_g A_g \sin \alpha = 0
\]

The mass conservation equation including phase transition in transported fluid is:

\[
\varphi \rho_g u_g + (1-\varphi) \rho_c u_c = \text{const}
\]

For reduction of equations (1) and (2) to dimensionless form we did the following:
- sum-up the equations (1) and (2) to exclude pressure drop;
- calculate shear stress by traditional formulas;
- calculate friction factors by dimension formulas which are based on Nikuradze’s hypothesis about the dimensional behaviour of axial velocity profile in turbulent flow [14];
use different correlations for the interfacial friction factor and friction factor at gas-wall interface.

As a result the dimensionless balance equation takes a form:

\[
X^2 \left[ \left( \frac{u_G}{A_G} \right)^n \frac{S_G}{A_L} \right] - \left[ \left( \frac{u_G}{A_G} \right)^n \frac{S_G}{A_G} \right] - 4Y = 0
\]

where:

\[
X^2 = \left[ \frac{dP/dx}{dP/dx} \right]_G,
Y = \left( \frac{\rho_L - \rho_G}{\rho_G} \right) \sin \alpha \frac{dP/dx}{dP/dx} \right]_G
\]

\[
S_L = \pi - \cos^{-1}(2\tilde{h}_L - 1), \quad \tilde{S}_G = \cos^{-1}(2\tilde{h}_L - 1),
\]

\[
\tilde{S}_i = \sqrt{1 - (2\tilde{h}_L - 1)^2}
\]

\[
\lambda_L = 0.25 \left( \pi - \cos^{-1}(2\tilde{h}_L - 1) + (2\tilde{h}_L - 1)\sqrt{1 - (2\tilde{h}_L - 1)^2} \right)
\]

\[
\lambda_G = 0.25 \left( \cos^{-1}(2\tilde{h}_L - 1) - (2\tilde{h}_L - 1)\sqrt{1 - (2\tilde{h}_L - 1)^2} \right)
\]

\[
\tilde{u}_G = \frac{\tilde{A}}{A_G}, \quad \tilde{u}_L = \frac{\tilde{A}}{A_L}
\]

\[
D_G = \frac{4\tilde{A}_G}{S_G + S_i}, \quad D_L = \frac{4\tilde{A}_L}{S_L + S_i}
\]

\[
\chi_{LG} = \frac{\lambda_L}{\lambda_G}
\]

For transformation of all variables to dimensionless form it is necessary to:

- variables, measured in [m], divide by \(D\);
- variables, measured in [m^2], divide by \(D^2\);
- variables, measured in [m/s], divide by \(u^*\) and \(u'^*\),

where \(u^*\) and \(u'^*\) – superficial liquid and gas velocities in case when liquid and gas respectively alone in the pipeline with perimeter \(S\).

All dimensionless variables mark by tilde (~).

Let us remember that Taitel & Dukler solved equation (4) providing that \(\chi_{LG} = 1\).

Taking into consideration Hamersma & Hart experimental results, interfacial friction factor is obtained from Eck (1973) [7]:

\[
\lambda_i = \frac{0.25}{\left( \log \left( \frac{15}{Re_G + 0.619\tilde{h}_L} \right) \right)^2}
\]

Gas phase friction factor \(\lambda_G\) is obtained from well known Coulbrook & White correlation.

Liquid holdup is obtained from classic formula:

\[
\varphi = \frac{\tilde{A}_i}{A_L + A_G}
\]

Borders of stratified-wavy flow

According to up-to-date hydrodynamic approach, the regime of wet gas flow with low loads of liquid is dispersed when liquid hold-up \(\varphi\) is equal or less than 0.005–0.006 [4]. It should be noted that these values of \(\varphi\) are based on very poor experimental investigations and very thin liquid films were not considered because of measurement challenges described above. The threshold of dispersed and stratified regimes is specified in this article.

As a criterion of changing regimes (stratified to dispersed) the authors suggest to use the ratio of interface friction factor to friction factor at gas-wall surface \(\chi_{LG}\). If \(\chi_{LG} > 1\) then flow regime is stratified, and model works properly. If \(\chi_{LG} < 1\) then flow regime is dispersed, and the suggested mechanistic model cannot be used for calculation of two-phase flow parameters (the model works only for stratified flow).

Although the accuracy of \(\chi_{LG}\) criterion depends on used equation (13), the authors think that this accuracy is good enough for engineering evaluation of changing the regime from dispersed to stratified. It is important to keep in mind that actual threshold of dispersed and stratified regimes is unknown for PVT parameters in pipelines which transport gas flow through low liquid loads.

The Kelvin-Helmholtz criterion which was modified by Taitel & Dukler [5] is used for determination of the border between stratified and annular or slug regimes:

\[
Fr_M \leq Fr_{rev}
\]

where:

\[
Fr_M = \sqrt{\frac{\rho_G}{\rho_L - \rho_G}} \frac{u^*}{\sqrt{D_G \cos \alpha}}
\]

\[
Fr_{rev} = \frac{C}{\sqrt{1 - (2\tilde{h}_L - 1)^2}} \frac{A_G}{\tilde{A}_G}
\]

\[
C = 1 - \tilde{h}_L
\]

If the inequality (15) is right then flow regime is stratified-wavy.

The following notations are used in equations (1)–(18):

- \(A_L\) and \(A_G\) – flow cross-sectional area occupied by liquid and gas respectively;
- \(S_L\), \(S_G\) and \(S_i\) – perimeter area occupied by liquid, gas and interfacial border respectively;
- \(\tau_{WL}\), \(\tau_{WG}\) and \(\tau_s\) – share stress between pipe wall and liquid, between pipe wall and gas and interfacial respectively;
- \(\rho_L\) and \(\rho_G\) – density of liquid and gas phases respectively;
- \(\alpha\) – angle between the pipe axis and the horizontal, positive for downward flow;
- \(f_L\) and \(f_G\) – friction factors: for liquid phase, for gas phase and interfacial respectively;
- \(u_L\) and \(u_G\) – velocity of liquid and gas phases respectively;
- \(v_L\) and \(v_G\) – velocity normal to the \(x\) direction of liquid and gas phases respectively;
- \(D\) and \(D_G\) – hydraulic diameter occupied by liquid and gas respectively;
Calculation of parameters of wet gas flow with low loads of liquid by the example of Stockman trunkline

The suggested modified Taitel – Dukler model was used for calculation of liquid film level, hold-up and determination of flow regime. The data obtained were compared with results of simulation in OLGA software which was used for hydraulic calculations in FEED project.

The Stockman trunkline consists of two 36 inch lines. Production rate of one line is 35.2 MMSCM/d.

Results of liquid film level calculations (for some parts of trunkline), using considered modified Taitel – Dukler model, are presented in the following table (Table 1).

Comparison of calculated results shows that OLGA provides conservative evaluation of hold-up along all trunkline. According to OLGA calculation at 80% production capacity slugs come up at the end of trunkline.
and at lower capacity slug flow occurs along all trunkline. Modified Taitel – Dukler model identifies slug regime at 60% production capacity and even at 40% production capacity slugs occur only at the end of trunkline where terrain profile is strongly upward. This analyse allows to make a conclusion that ramp-up level 80% of production capacity, which was provided in FEED, should be considered to decrease.

Criterion $\chi_iG$ (12) and the Kelvin-Helmholtz criterion (15) are used for determination of flow regime at different parts of Stockman trunkline. The results for different production capacities are presented in tables 6-9.

Regime determination criteria show that almost along all Stockman trunkline stratified flow is determined with liquid level from 3 to 10 mm. Only at the end of trunkline where the terrain profile has a big inclination to horizontal (5÷7°) there are conditions for slugging up to 60% of production capacity.

This conclusion was confirmed by investigation results which were presented by Stockman Development AG at workshop "Integrated development of the Stockman gas-condensate field – Phase 1" in Gazprom VNIGAZ (02/12/2009). Pressure drop and hold-up were calculated in different versions of OLGA and results were compared (Fig.3). The calculation results in new generation software Horizon were also presented. Horizon is based on advanced mechanistic model designed for large diameter pipelines and high pressure conditions.

Comparison shows that Horizon, in contrast to OLGA, indicates start of intensive liquid accumulation when production rate decreases to 20 MMSCM/d which is approximately equal to 60% of production capacity.

### Table 5
Results of hold-up calculation for different parts of Stockman trunkline at 40% production capacity

<table>
<thead>
<tr>
<th>Distance from the beginning of pipeline, km</th>
<th>OLGA</th>
<th>Modified Taitel – Dukler model</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.00063</td>
<td>0.00060</td>
</tr>
<tr>
<td>100</td>
<td>0.00293</td>
<td>0.00111</td>
</tr>
<tr>
<td>200</td>
<td>0.00405</td>
<td>0.00114</td>
</tr>
<tr>
<td>300</td>
<td>0.00333</td>
<td>0.00166</td>
</tr>
<tr>
<td>400</td>
<td>0.00407</td>
<td>0.00179</td>
</tr>
<tr>
<td>500</td>
<td>0.00387</td>
<td>0.00191</td>
</tr>
<tr>
<td>573</td>
<td>0.15596</td>
<td>0.00222</td>
</tr>
</tbody>
</table>

### Table 6
Regime determination criterion values for different parts of Stockman trunkline at 100% production capacity

<table>
<thead>
<tr>
<th>Distance from the beginning of pipeline, km</th>
<th>$F_{rM}$</th>
<th>$F_{rev}$</th>
<th>$\chi_iG$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.64</td>
<td>2.43</td>
<td>3.57</td>
</tr>
<tr>
<td>100</td>
<td>0.60</td>
<td>2.17</td>
<td>4.01</td>
</tr>
<tr>
<td>200</td>
<td>0.62</td>
<td>2.04</td>
<td>4.45</td>
</tr>
<tr>
<td>300</td>
<td>0.65</td>
<td>1.95</td>
<td>4.71</td>
</tr>
<tr>
<td>400</td>
<td>0.70</td>
<td>1.89</td>
<td>4.91</td>
</tr>
<tr>
<td>500</td>
<td>0.78</td>
<td>1.86</td>
<td>5.02</td>
</tr>
<tr>
<td>573</td>
<td>0.87</td>
<td>1.77</td>
<td>5.05</td>
</tr>
</tbody>
</table>

### Table 7
Regime determination criterion values for different parts of Stockman trunkline at 80% production capacity

<table>
<thead>
<tr>
<th>Distance from the beginning of pipeline, km</th>
<th>$F_{rM}$</th>
<th>$F_{rev}$</th>
<th>$\chi_iG$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.55</td>
<td>2.34</td>
<td>3.72</td>
</tr>
<tr>
<td>100</td>
<td>0.51</td>
<td>2.00</td>
<td>4.55</td>
</tr>
<tr>
<td>200</td>
<td>0.53</td>
<td>1.94</td>
<td>4.73</td>
</tr>
<tr>
<td>300</td>
<td>0.55</td>
<td>1.89</td>
<td>4.89</td>
</tr>
<tr>
<td>400</td>
<td>0.59</td>
<td>1.87</td>
<td>4.98</td>
</tr>
<tr>
<td>500</td>
<td>0.64</td>
<td>1.85</td>
<td>5.04</td>
</tr>
<tr>
<td>573</td>
<td>0.70</td>
<td>1.85</td>
<td>5.07</td>
</tr>
</tbody>
</table>

### Table 8
Regime determination criterion values for different parts of Stockman trunkline at 60% production capacity

<table>
<thead>
<tr>
<th>Distance from the beginning of pipeline, km</th>
<th>$F_{rM}$</th>
<th>$F_{rev}$</th>
<th>$\chi_iG$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.40</td>
<td>2.28</td>
<td>3.83</td>
</tr>
<tr>
<td>100</td>
<td>0.38</td>
<td>2.04</td>
<td>4.41</td>
</tr>
<tr>
<td>200</td>
<td>0.39</td>
<td>2.03</td>
<td>4.45</td>
</tr>
<tr>
<td>300</td>
<td>0.41</td>
<td>1.89</td>
<td>4.87</td>
</tr>
<tr>
<td>400</td>
<td>0.43</td>
<td>1.86</td>
<td>4.97</td>
</tr>
<tr>
<td>500</td>
<td>0.48</td>
<td>1.84</td>
<td>5.06</td>
</tr>
<tr>
<td>573</td>
<td>0.53</td>
<td>1.79</td>
<td>5.26</td>
</tr>
</tbody>
</table>

### Table 9
Regime determination criterion values for different parts of Stockman trunkline at 40% production capacity

<table>
<thead>
<tr>
<th>Distance from the beginning of pipeline, km</th>
<th>$F_{rM}$</th>
<th>$F_{rev}$</th>
<th>$\chi_iG$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.43</td>
<td>2.16</td>
<td>4.03</td>
</tr>
<tr>
<td>100</td>
<td>0.23</td>
<td>2.10</td>
<td>4.17</td>
</tr>
<tr>
<td>200</td>
<td>0.24</td>
<td>2.02</td>
<td>4.40</td>
</tr>
<tr>
<td>300</td>
<td>0.25</td>
<td>1.95</td>
<td>4.61</td>
</tr>
<tr>
<td>400</td>
<td>0.27</td>
<td>1.94</td>
<td>4.66</td>
</tr>
<tr>
<td>500</td>
<td>0.31</td>
<td>1.82</td>
<td>5.09</td>
</tr>
<tr>
<td>573</td>
<td>0.35</td>
<td>1.81</td>
<td>5.13</td>
</tr>
</tbody>
</table>
Fig.3. OLGA versions sensitivity to pressure drop and hold-up

References


Новая механистическая модель течения сырого газа с малым содержанием жидкости в трубопроводах

В.А.Сулейманов, О.А.Бычкова
(Газпром ВНИИГаз)

Реферат

На основе обобщения результатов теоретических и экспериментальных исследований режимов течения сырого газа с малым содержанием жидкости в протяженных морских трубопроводах разработана методика определения основных параметров его течения. Данная методика основана на усовершенствовании методики Тайтела-Даклера и учете в ней коэффициента гидравлического сопротивления на поверхности раздела фаз. Кроме того, для рассматриваемых двухфазных систем разработаны критерии для определения границ перехода расслоенно-волнового режима в дисперсный и пробковый режимы. Представленная методика апробирована на примере проектируемого газопровода Штокмановское ГКМ – берег.

Boru kəmərlərində az maye tərkibli xam qazın axınının yeni mexanistik modeli

V.Ə.Süleymanov, O.A.Bıçkova
(Qazprom VNİİQAZ)

Xülasə

Uzaq məsafəli dəniz boru kəmərlərinə, az maye tərkibli xam qazın axınının yeni mecəniq modeli

V.Ə.Süleymanov, O.A.Bıçkova
(Qazprom VNİİQAZ)

Boru kəmərlərində az maye tərkibli xam qazın axınının yeni mexanistik modeli

V.Ə.Süleymanov, O.A.Bıçkova
(Qazprom VNİİQAZ)

Xülasə