Research and Design of Thermophysical Gas-Liquid Mixture Parameters in Product Pipelines

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Abstract. Operational problems are hard to overcome because of the temperature and pressure conditions of the hydrocarbon flow in the pipe, as well as the composition of the hydrocarbon system and the geometry of the pipeline. It is known that energy costs to pump a unit mass of RH in the form of gas 2-3 times exceed energy costs to pump a unit mass of RH in the form of liquid. As far as energy conservation during RH transportation is concerned, an important task is development and application of a method to calculate the gas-liquid hydrocarbons flow, and heat and mass transfer in process and trunk pipelines during their design and operation. The authors have developed a calculation method which is used to analyze the hydrodynamic state and composition of the hydrocarbon mixture in each \( i^{th} \) section of the pipeline when temperature-pressure and hydraulic conditions change. The developed technique was tested on the hydrocarbon mixture of de-ethanized condensate and oil transported from northern oil and gas condensate fields via the main gas condensate line to the refinery.

1. Introduction

Gas condensate fields demonstrate a number of thermodynamic characteristics to be considered when they are developed, as well as when gas condensate is transported and processed. A complicated phase behavior of the gas condensate system, as well as the dependence of the extracted raw materials on the phase state of the deposit other conditions being equal, is a key aspect. Therefore, when designing gas condensate lines the crucial task is to select the most appropriate methods of calculating thermophysical properties and phase equilibrium of the transported gas condensate.

2. Methods, results and discussion

Methods of calculating thermophysical properties (TPP) and phase equilibria are reviewed in quite a lot of scientific publications and reference books [1, 2, 3, 4, 6, etc.]. However, when it comes to such complex systems as oil, gas condensate, natural gas and their by-products, using even the known techniques is a difficult task. As they are located in the near-critical region on the phase diagram, these complex systems are regarded as transition state systems that depending on temperature and composition can be in a single-phase liquid or gaseous state. This uncertainty complicates selection of methods (processes) for design and calculation of condensate lines.

Over the last decade the department of Transportation of Hydrocarbon Resources in Tyumen State Oil and Gas University (TSOGU) has been conducting research in the field of process monitoring in pipeline energy transportation systems. To date, a number of physical and mathematical models have been developed describing the process of transportation and storage of hydrocarbons in the oil and gas industry facilities. The latest development of the authors is a physical-mathematical model of a hydrocarbon mixture flow in the gas condensate line which allows you to perform an operational analysis of the hydrodynamic state of condensate in the pipeline. The main closing relations of the physical-mathematical model are the following.

1) The dependence of the gas condensate mixture density on pressure and temperature.
\[ \rho_{C6+} = \frac{N_{m_n}}{\rho_{sm_0}} - \sum_{i=1}^{n} \frac{N_{m_i}}{M_i} \nu_i, \quad (1) \]

where \( \nu_i \) is the molar volume of other components calculated for both gas and liquid by a single Peng-Robinson equation of state.

2) The viscosity of the condensate mixture is calculated at temperature of 20°C and pressure of 1 atm by the formula:

\[ \mu_{sm_0} = \frac{\sum_{i=1}^{N} z_i \sqrt{M_i} \nu_{ind_i}}{\sum_{i=1}^{N} z_i \sqrt{M_i}}, \quad (2) \]

Recalculation of viscosity on thermobaric conditions in different sections of the pipeline is carried out according to the formula:

\[ \mu_{sm} = 10^{\lg \left( \mu_{sm_0} \right) + 1.4503 \times 10^{-3} \left( P - 0.101325 \right) \left( 5.2054 + \mu_{sm_0}^{0.278} + 0.0239 \right) - 3}, \quad (3) \]

3) The isobaric heat capacity of the gas condensate mixture is calculated according to the additivity rule:

\[ C_{psm} = \sum_{i=1}^{N} z_i C_{p_i} \quad M_i, \quad (4) \]

4) The soil heat transfer is found by:

\[ \alpha_p = \begin{cases} \frac{2 \cdot \lambda_p}{D \cdot \ln \left( \frac{2 \cdot H}{D} + \sqrt{\left( \frac{2 \cdot H}{D} \right)^2 - 1} \right)}, & \text{if } \frac{H}{D} > 3 \text{(Forchheimer r - Vlasov)} \\
\frac{2 \cdot \lambda_p}{D \cdot \ln \left( \frac{4 H_{up}}{D} + \frac{1}{N u_p} \right)}, & \text{if } \frac{H}{D} < 3 \text{(Arson - Kutateladze)} \end{cases} \quad (5) \]

where \( H \) – the depth of the pipeline occurrence in the soil, m.

5) The composition and quantitative ratio of the equilibrium vapor and liquid phases is found using equations of phase concentrations of mixture components.

\[ x_i = \frac{z_i}{V \left( K_i - 1 \right) + 1}, \quad (6) \]

\[ y_i = \frac{z_i K_i}{V \left( K_i - 1 \right) + 1}, \quad (7) \]

6) The actual volumetric gas content is found by:

\[ \alpha_g = \frac{1}{1 + \frac{\nu_g N_{L_g}}{\nu_g N_{p}}}, \quad 1 + \frac{\nu_g}{\nu_g \left( 1 - \frac{1}{V} \right)} \quad (8) \]

7) The flow pattern of the gas-liquid mixture is determined by one of the known techniques, for example, by the methods shown in [7, 8]. For horizontal flows, various authors identified and described the following structural forms of the gas-liquid mixture flow (figure 1).
Figure 1. Structural forms of the gas-liquid flow:
a – separated; b – bubbly; c – slug; d – emulsion.

In commercial pipelines the most common structural forms of the flow are slug and emulsion. There are no clear interfaces between the individual forms of the gas-liquid mixture flow, as there are relatively broad transition zones both in speed and in the gas content.

A characteristic feature of the two-phase hydrocarbon flow patterns is pressure surge, for example in the case of pipeline transportation of gas-liquid mixtures. Pressure surge in a pipeline leads to disruption of normal operation of the pumping equipment, control and measuring devices, etc.

Operational problems in pipelines causes increase in friction loss, hydrostatic pressure drop and often a complete blockage of the pipeline cross-section (formation of local gas clusters, water slugs and crystalline hydrates).

Operational problems are hard to overcome because of the temperature and pressure conditions of the hydrocarbon flow in the pipe, as well as the composition of the hydrocarbon system and the geometry of the pipeline.

The developed physical and mathematical model of the hydrocarbon flow in the pipeline, taking into account a change in the composition of the liquid and gas phases, allowed us to conduct computational and parametric study of thermophysical parameters of oil and gas condensate mixture in various product pipeline sections.

To verify the adequacy of our technique for calculating operating parameters of the product pipeline, let us perform a comparison of the calculated values with the experimental values.

Let us consider the developed calculation technique as applied to the hydrocarbon mixture of de-ethanized condensate and oil transported from oil and gas condensate fields via the product pipeline.

| Composition, mass fraction % |
|----------------------------|
| Methane | Ethane | Propane | i-Butane | n-Butane | i-Pentane | n-Pentane | Hexane + |
|---------|--------|---------|----------|----------|----------|----------|----------|
| 0.09    | 0.67   | 12.98   | 7.02     | 11.63    | 5.9      | 6.33      | 55.38    |
| 0.07    | 0.6    | 12.9    | 11.8     | 7.1      | 6.04     | 5.72      | 55.5     |

Table 1. Performance characteristics of the product pipeline.
Figure 2. Changes in RH pressure along the condensate line route at various pressures in the inlet section.

Figure 3. Hydrocarbon gas-liquid mixture parameters along the product line route.

Figure 3 shows the results of calculating hydrocarbon mixture parameters along the pipeline route. By comparing the calculated and actually observed differential pressure and temperature, we can conclude on the adequacy of the selected computational physical and mathematical model of the condensate line (relative deviation of the calculated differential pressure from actually observed is 4.6% and deviation of the estimated temperature change from the experimental was 1.5%).
Figure 4 shows a computational and parametric study of RH phase state along the pipeline when the pump operating pressure in the initial section of the pipeline changes to 3.1, 2.8 and 2.5 MPa, with the curves showing changes in the two-phase parameter V and the true volumetric gas content of hydrocarbons when lowering the operating pumping pressure by 0.6 MPa at the beginning of the pipeline. It follows from these graphs that with a decrease in operating pumping pressure on the condensate line may arise areas where hydrocarbons enter the gas-liquid two-phase state (molar fraction of the vapor phase is 0<V<1 and acquires a definite physical meaning, equal to the ratio of the number of moles of the mixture in the gas phase to that of the whole mixture). When the hydrocarbon mixture passes in the two-phase gas-liquid state the mixture moves in a two-phase state to the pipeline end section. In this case, the subsequent calculation of hydrodynamic parameters of the product line is carried out taking into account the two-phase flow of hydrocarbons. A two-phase flow pattern in the pipeline is determined by taking into account the known algorithm [8].

3. Summary

1. The influence of temperature and pressure conditions as the hydrocarbon mixture enters the product pipeline on the phase equilibrium and parameters in the outlet section has been determined.
2. The convergence of calculation results of pressure and temperature changes has been confirmed based on the developed model with known full-scale experimental data.
3. For the first time the possibility of using calculations and theoretical principles to determine the valid values of mass concentration of light hydrocarbons in the inlet section of a main condensate line on condition that a single-phase flow regime along the entire length of the pipeline is provided.
4. The developed calculation technique and algorithm allow us to perform a real-time analysis and prediction of the hydrodynamic condition of gas-liquid media in pipelines as the composition, temperature and pressure, and hydraulic conditions change. Therefore, the study results can be used by the control services of oil and gas companies during on-line monitoring of raw hydrocarbon pumping modes.

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