Forecasting Formation Losses of Hydrocarbons in the Process of Development of Oil and Gas Condensate Deposits

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Abstract: One of the important tasks in forecasting and monitoring the development of oil and gas condensate fields is taking into account the current losses of condensate in the reservoir. In this case, it is necessary to use several versions of models that differ in the formation of parameters and thermodynamic properties of hydrocarbon phases. Models are considered in which either the liquid phase dissolves in the gas phase, or it is assumed that heavy fractions are absent in the gas phase. Models of this type are used more often when predicting the development of deposits in the natural depletion mode. Experimental and computational models of equilibrium phase transitions make it possible to improve the prediction of condensate losses in the reservoir. The complexity and laboriousness of the PVT experiment, along with the introduction of new technologies, create a lack of information on the thermodynamic properties of hydrocarbon systems. In order to take into account reservoir losses of hydrocarbons for the development conditions of the Vostochno-Urengoyskoye field, the forecast of the balance of condensate production for the current and final periods of operation was carried out. The model considered in the work allows for adjusting the forecast indicators of condensate production at the current moment of reservoir operation [1,2,3].

1. Introduction

The study of complex multicomponent systems in order to obtain reliable information about phase processes and changes in the composition of reservoir gas in the process of developing oil and gas condensate fields is carried out on the basis of experimental and mathematical modeling.

Numerous works devoted to the calculation of the parameters of the thermodynamic properties of hydrocarbon phases indicate their great practical importance. Based on the equations, a method for calculating the thermodynamic properties and phase equilibria of hydrocarbon systems has been developed. The range of applicability of the method under consideration is established and the problematic points associated with the calculation of phase equilibria of systems at a pressure below the pressure of the onset of condensation are identified. One of the promising ways to solve the identified problems is the development of calculation methods based on theoretically substantiated equations of state. In particular, a method is proposed for modeling the phase transformations of hydrocarbons, which corrects the forecast indicators of condensate production at the current moment of development. It allows identification of the composition of hydrocarbon mixtures and improves the accuracy of calculating formation condensate losses. The purpose of this work is to apply the
methodology in predicting and monitoring the development process of the Vostochno-Urengoy oil and gas condensate field, taking into account the current losses of condensate in the reservoir [4,5].

2. Relevance
The relevance of the research topic is the need to use several types of models that differ in the formation of parameters and thermodynamic properties of hydrocarbon phases. There are models in which either the liquid phase dissolves in the gas phase, or it is believed that heavy fractions are absent in the gas phase. These computational models are used more often when predicting the development of deposits in the natural depletion mode. Multicomponent filtration models are mainly used to predict development indicators using reservoir stimulation technologies, which are characterized by interphase mass transfer. For these models, the thermodynamic properties of the phases are difficult to represent only as dependencies on the pressure decrease, since at the same pressure, gas phases with different component compositions can exist in the reservoir. Such an analysis was carried out by scientists using various software systems EXLIPSE, ROXAR, LLC «Gazprom VNIIGAZ», etc. Experimental and computational models of equilibrium phase transitions make it possible to improve the prediction of condensate losses in the reservoir. thermodynamic properties of hydrocarbon systems. The complexity and laboriousness of the PVT experiment, along with the introduction of new technologies, create a lack of information on the thermodynamic properties of hydrocarbon systems. In order to take into account formation losses of hydrocarbons, forecasting of the balance of condensate production for the period of field development is performed. The model considered in the work allows for adjusting the forecast indicators of condensate production at the current time of the reservoir operation [6,7].

3. Formulation of the problem
When predicting the development process of oil and gas condensate deposits of the Vostochno-Urengoyskoye field, an important task was to determine the loss of hydrocarbons in the reservoir. Forecasting condensate recovery and calculating the balance of hydrocarbon production are carried out to solve the problem using analytical models created on the basis of equations of state. It is important to apply scientifically grounded and adapted techniques to the conditions of specific deposits of the BU16-1-4 and BU17-1-2 formations, taking into account the assumptions and limitations. At the same time, take into account the features of models that differ in the formation of the thermodynamic properties of hydrocarbon phases. Thus, the use of computational models for predicting current development indicators is important, taking into account the required accuracy for specific oil and gas condensate fields [8].

4. Theoretical part
The field studies were carried out by passing all well production through a field gravity separator, with the determination of gas and saturated condensate production rates. Hydrocarbon samples taken in the process of gas condensate studies of wells were studied in laboratory conditions to determine the composition of formation gas. The composition of the reservoir gas of the Vostochno-Urengoyskoye field was calculated according to the standard method, which provides for the determination of the composition of gases of separation, degassing, debutanization, debutanized condensate by gas-liquid chromatography methods. The potential content of ethane, propane, butanes in the gas was calculated based on the accepted composition of the reservoir gas, by multiplying the molar concentration of these hydrocarbons by the corresponding coefficients - 12.5; 18.3 and 24.2. So, on the basis of research, it was revealed that formation gas consists mainly of methane, the concentration of which varies from 80.98 to 83.58% molar. The total content of ethane, propane, butanes in the gas varies from 11.63 to 13.83, non-hydrocarbon components (CO2, N2 and He) - from 0.14 to 1.02 mol%. Condensate content in gas varies from 3.62 to 5.29% by mole. The density of formation gas in air varies from 0.7757 to 0.8494 [7-9].
5. Practical significance

A feature of forecasting the development of oil and gas condensate fields is the determination of the current losses of hydrocarbons in the reservoir. Provided that the current reservoir pressure in the reservoir is lower than the pressure of the beginning of condensation, the data of the experimental PVT-studies on a conditional character. In this case, they are used to define development parameters. In our case, forecasting condensate recovery and calculating the balance of hydrocarbon production is carried out using analytical models created on the basis of equations of state. Presenting the physics of the analyzed phenomena, multiphase systems, it is necessary to understand how correctly the material balance equations describe the processes occurring in the reservoir. At the same time, it is necessary to scientifically adapt the methodology to the conditions of specific deposits, taking into account the assumptions and limitations. With further study of gas condensate systems, the models become more complex, providing the necessary forecast accuracy for specific gas condensate fields. The technique developed by O.F. Khudyakov to determine the condensate content in reservoir gas is a general solution to determine the parameters of the reservoir system; it can be used in the determination of condensate content in reservoir gas, which is based on its material balance, is considered. Material balance equation in the form (4)

\[ q_{\text{rc}}^m = q_{\text{rc}}^n - \sum_{m=3}^{m} \frac{4n_{\text{pc}}^m}{(2n-2m+5)(2n-2m+3)} \cdot q_{\text{pc}}^{m+1}n(2n-2m-1) - \frac{q_{\text{pc}}^m n}{2n-2m+1} \]  

(1)

where \( q_{\text{rc}}^m \) - condensate content in reservoir gas at the end of the m-th stage; \( q_{\text{rc}}^n \) - initial condensate content in reservoir gas; \( m \) - number of the current indicator of pressure reduction; \( n \) - the number of pressure drop values; \( q_{\text{c.d}}^m \) - condensate losses in reservoir gas at the end of the m-th stage of pressure reduction.

The total production of condensate during field development is determined by the formula (2)

\[ q_{\text{pc}}^m n = q_{\text{pc}}^n - \frac{q_{\text{pc}}^m}{2n-2m+1} \cdot \sum_{m=2}^{m} \frac{4q_{\text{pc}}^m}{(2n-(2i-3))[2n-(2i-1)]} \]  

(2)

Researchers of Gazprom VNII GAS LLC propose a model of the material balance of condensate in integral form, which has the following form:

\[ q(p) = \frac{A \cdot \int_{p+d}^{p} q(p)Q_{\text{prod}}(p)Q_{\text{nom}}(p)Q_{\text{gc}}(p)Q_{\text{gwc}}(p) dp}{[1-Q_{\text{prod}}(p)Q_{\text{gc}}(p)Q_{\text{gwc}}(p)]} \]  

(3)

The performed adaptation of the methodological approach based on experimental data allows one to determine the parameters of the reservoir system; it can be used in the design and control of field development. Formula (3) for predicting the condensate content in reservoir gas is a general solution to the material balance equation. This paper discusses a technique for correctly predicting reservoir losses of hydrocarbons in a reservoir based on the results of gas condensate studies carried out at the current stage of field development, i.e. at the moment when the pressure in the reservoir is lower than the pressure of the beginning of condensation. Initially, the problem of changing the potential content of condensate in reservoir gas, which is based on its material balance, is considered. Material balance equation in the form (4)

\[ M_0 = M_{\text{prod}} + M_{\text{gc}} + M_{\text{gwc}} \]  

(4)

where \( M_{\text{gc}} \) the mass (volume) of condensate remaining in the reservoir, \( M_{\text{gwc}} \) is the mass (volume) of condensate in the gas phase and precipitated when the pressure in the reservoir decreases.
Whereas, when the pressure in the reservoir is below the initial reservoir $P_{\text{init}}<P_{\text{cond.start}}$ (below the pressure of the beginning of condensation) and the proportion of heavy fractions of condensate fell out in the reservoir, in this case, the initial mass of condensate will be the sum of,

$$M_0 = M_{\text{prod}} + M_{\text{rem}}$$  \hspace{1cm} (5)

where $M_0$ - is the total mass (volume) of condensate in the reservoir at initial conditions;

$M_{\text{prod}}$ - mass (volume) of produced condensate at the current reservoir pressure;

$M_{\text{rem}}$ - mass (volume) of condensate remaining in the reservoir at the current reservoir pressure.

The mass of all condensate is defined as:

$$M_0 = Q_{\text{dry.g}} \cdot q_0$$  \hspace{1cm} (6)

where $Q_{\text{dry.g}}$ - is the amount of "dry" gas in the reservoir, m$^3$; (the term "dry" gas is understood as a mixture of C$_1$-C$_4$ hydrocarbons and non-hydrocarbon components, which under normal conditions are in a single-phase gas state); $q_0$ – is the initial content of condensate in reservoir gas based on dry gas, g/m$^3$.

The mass (quantity) of produced condensate is the product of the volume of produced gas and the current content of condensate. Since when the pressure decreases, the condensate content in the reservoir gas constantly changes due to its precipitation in the reservoir, we divide the stage of pressure reduction from $P_0$ to $P$ into n stages with equal gas production:

$$\Delta Q_{\text{prod}}.$$ Then,$$M_{\text{prod}} = \sum_{i=1}^{n} q_i \Delta Q_{\text{prod}}.$$  \hspace{1cm} (7)

Passing to small values $\Delta Q_{\text{prod}}$, we obtain the following formula for the pressure $P$:

$$M_{\text{prod}} = \int_{P_n}^{P_0} q(p) dQ_{\text{prod}}(p)$$  \hspace{1cm} (8)

Studies of the Vostochno-Urengoiyskoye field for gas condensation showed that the most productive of the objects is the BU$_{16}^{14}$ formation. The flow rate of separated gas from exploration wells that penetrated this layer varied from 16.2 thousand m$^3$/day (well 205ses) to 268 thousand m$^3$/day (well 93wur), saturated condensate flow rate - from 2.23 m$^3$/day (well 351ejx) to 116.3 m$^3$/day (well 206ses). The yield of saturated condensate varied from 106.3 cm$^3$/m$^3$ (well 302ses) to 880.0 cm$^3$/m$^3$ (well 360ejx), stable - from 76.5 cm$^3$/m$^3$ (well 302ses) to 639.0 cm$^3$/m$^3$ (well 360ejx). The density of stable condensate (according to field measurements) from this formation varied from 0.717 g/cm$^3$ (well 209ses) to 0.807 g/cm$^3$ (well 310wur). Separation gas flow rate during the study of BU$_{16}^{14}$ formation in production wells varied from 44.3 thousand m$^3$/day (well 401ves) to 447.4 thousand m$^3$/day (well 210ses), saturated condensate flow rate - from 10.15 m$^3$/day (well 401ves) to 118.6 m$^3$/day (well 210ses). Saturated condensate yield varied from 138.9 cm$^3$/m$^3$ (well 210ses) to 460.0 cm$^3$/m$^3$ (well 317wur). The condensate density varied from 0.735 g/cm$^3$ to 0.805 g/cm$^3$ (well 317wur). When studying other formations, the productivity of wells for separated gas varied from 22.37 thousand m$^3$ / day (well 911wur, formation BU$_{17}^{13}$) to 294.54 thousand m$^3$/day (well 409zjar, formation BU$_{16}^{18}$). The saturated condensate flow rate varied from 10.18 m$^3$/day (well 4060ses, reservoir BU$_{16}^{2}$) to 103.68 m$^3$/day (well 409zjar, reservoirs BU$_{18}^{1} + BU_{18}^{2}$). The yield of saturated condensate varied from 136.2 cm$^3$/m$^3$ (well 406zjar, formation BU$_{19}^{s}$) to 646.1 cm$^3$/m$^3$ (well 4134ses, formations BU$_{16}^{14} + BU_{17}^{1}$), stable - from 106.5 cm$^3$/m$^3$ (well 406zjar, formation BU$_{19}^{s}$) up to 544.0 cm$^3$/m$^3$ (well 4134ses, formation BU$_{16}^{14} + BU_{17}^{1}$). In the well 301wur, a study was carried out in the interval 3115-3133 m (a.o. 3072-3090 m). The studies were carried out at various modes from 6 to 14 hours. Reservoir pressure is 30.4 MPa. Reservoir temperature 88 °C. Separation conditions: pressure from 1.52 to 6.24 MPa, temperature from 6 to 9 C0. Separation gas flow rate is from 39.23 to 43.21 thousand m$^3$/day. Condensate output from 155.5 to 250.2 g/m$^3$. 
After calculating the shrinkage factor, the flow rate and output of stable condensate were determined. The volumetric flow rate of saturated condensate was determined from the time of filling the calibrated volume of the separator. Specific condensate yield \( q_{\text{sat}} \) was determined from the ratio:

\[
q_{\text{sat}} = \frac{86400 V}{TQ}
\]  

where: \( q_{\text{sat}} \) - saturated condensate output, \( \text{cm}^3/\text{m}^3 \); \( Q \) - separation gas flow rate, thousand \( \text{m}^3/\text{day} \); \( V \) – is the calibrated volume of the separator, \( \text{cm}^3 \); \( T \) - filling time of the calibrated volume of the separator, sec.

The specific content of stable condensate \( q_{\text{stab}} \) was determined taking into account the shrinkage coefficient of saturated condensate \( \eta \)

\[
q_{\text{stab}} = q_{\text{sat}} \eta
\]  

According to the samples taken during the primary gas condensate studies, the density of stable (degassed) condensate varies from 0.7619 to 0.8304 \( \text{g/cm}^3 \), Figure 1.

According to samples taken after 2013, the density of stable condensate varies from 0.7397 to 0.7952 \( \text{g/cm}^3 \). A good correlation of properties is observed when comparing density and boiling point, density and molecular weight of the condensate, Figure 2.

![Figure 1. Comparison of density of stable condensate with molecular weight.](image1)

![Figure 2. Comparison of the density of stable condensate with temperature start to boil.](image2)
The initial boiling point of the condensate sampled during the initial research varies from 540 to 137 °C, according to samples taken after 2013 - from 29.70 to 83 °C. The molecular weight of the condensate sampled during primary research varies from 109 to 193.0; according to samples taken after 2013 - from 107 to 145. Condensates taken during primary research are low-sulfur (0.005 - 0.034%), low and paraffinic (up to 9.7%), silica gel resins vary from 7 to 693 mg / 100 ml. The resin content in the samples is 4499 and 3141 mg / 100 ml, with an average resin content of 160 mg / 100 ml. The condensates sampled after 2013 are low-sulfur (0.006 - 0.050%), low paraffinic up to 1.5%, the paraffin index of which is 4.18%), silica gel resins vary from 0.01 to 10 mg / 100 ml. Taking into account new studies of condensate samples for the content of resins, the reliability of primary studies with indicators of a resin content in a sample of more than 10 mg / 100 ml should be questioned. In terms of the group hydrocarbon composition, the condensate sampled during the initial research belongs to the mixed methane-naphthenic and naphthene-methane type, the concentration of aromatic hydrocarbons varies from 8.5% to 21.3% of the volume. The condensate sampled after 2013 belongs to the mixed type - mainly naphthene-methane, the content of aromatic hydrocarbons varies from 9.86% to 19.58% by volume. The initial phase state of gas condensate systems in reservoir conditions and during the development of deposits for depletion was studied in most cases with violations of the requirements for well operation modes. During gas condensate studies, the wells were unstable in terms of liquid hydrocarbon production, which distorted the picture when the reservoir mixture was recombined in the PVT unit. Poor quality samples accordingly increase the error in determining the properties of the reservoir mixture and, in particular, the pressure of the beginning of condensation. According to thermodynamic studies, the saturation pressure of the mixture with condensate, determined during primary studies, for the BU_{16}^{1,4} formation varies from 27.83 MPa to 38.22 MPa, for the BU_{18}^{1} formation the pressure of the beginning of condensation is 29.79 MPa, at P - 33.08 MPa. For samples taken after 2013, the pressure of the beginning of condensation changes for the formation BU_{16}^{1,4} from 24.91 MPa to 34.46 MPa, for the formation BU_{17}^{1,2} the pressure of the beginning of condensation changes from 23.08 MPa to 32.09 MPa.

It should be noted that the pressure of the beginning of condensation in almost all samples (with the exception of four samples taken at large drawdowns with the possible capture of a part of the condensate that fell out in the bottomhole zone) was lower than the initial reservoir pressure. However, there are no clear-cut patterns in the dynamics of the pressure of the onset of condensation or the final condensate recovery factor (CER) in the reservoirs.

In the calculations of differential condensation, it is proposed to focus on the pressure of the beginning of condensation less than the initial reservoir pressure for the deposits.

There are doubts about the accuracy of the estimation of the condensate recovery factors because in the conditions of the PVT bomb all physical processes that can occur in a real reservoir (taking into account the filtration-capacity properties of rocks, the presence of residual water saturation, etc.) are not reproduced.

According to the results of thermodynamic studies, the final condensate recovery factor varied from 0.560 to 0.763 for the BU_{16}^{1,4} formation, and from 0.590 to 0.670 for the BU_{17}^{1,2} formation. Since the gas condensation studies were carried out in violation of the requirements for the technological modes of well operation, and the results of PVT studies of the recombined samples fluctuate within rather wide limits, the CFC value for the final pressure of 0.1 MPa was estimated based on the results of calculating the phase states. The profitable condensate recovery factors for the injection pressure were refined based on the results of calculations of development indicators on a permanent three-dimensional three-phase geological and technological model. The nature of this factor is very arbitrary, since the pressure in the reservoir cannot be reduced to atmospheric, therefore, the recovery factor is often calculated on the pressure when further development of the field in the natural depletion mode is impractical. Also, based on the results of this PVT experiment, the final condensate recovery factor is determined, which is found from the following expression:
where \( q_0 \) – is the initial condensate content in the formation gas per 1 m³ of “dry” gas loaded into the PVT bomb, g/m³; \( q_{0.1}^{\text{cond}} \) – the content of condensate dropped out in the PVT bomb when the pressure is reduced to a pressure of 0.1 MPa based on 1 m³ of “dry” loaded gas, g/m³.

At the next stage, a series of PVT experiments on differential condensation in pressure reduction stages is carried out. In this case, after reducing the pressure and establishing equilibrium, the amount of precipitated condensate is measured, it is released, degassed, and the composition of the degassing gas and degassed condensate is determined.

\[
K_{\text{rec}} = \frac{q_0 - q_{0.1}^{\text{cond}}}{q_0}
\]  (11)

Figure 3. Results of primary PVT-studies of formation mixtures of formation BU161-4 Vostochno-Urengoy field.

Figure 4. Results of primary PVT-studies of formation mixtures for formation BU171-2 Vostochno-Uren Goy field.
6. Conclusion
Thus, the proposed mathematical apparatus makes it possible to carry out predictive calculations with a sufficient degree of accuracy, taking into account the information obtained during the PVT studies of samples taken at the current stage of field development. However, like each predicted dependence, it needs to be confirmed based on the results of actual wells studies of the fields being developed. It is also necessary to assess the influence of various factors on the results obtained, taking into account special experiments to study the phase processes of reservoir systems with different condensate content with a decrease in pressure in the reservoir.

7. References
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