Modeling of the development of the Vuktyl field hydrocarbon system in the depletion mode using a bench installation

Skibitskaya N.A.1, Volkov A.N.2, Latishev A.A.2, Indrupsky I.M.1, Popov A.A.2, Bolshakov M.N.1, Kuzmin V.A.1, Marutyan O.O.1

1 Oil and Gas Research Institute of the Russian Academy of Sciences (OGRI RAS), Moscow, Russia
2 «Gazprom VNIIGAZ» Ukhta, Russia

E-mail: rgu2006@mail.ru

Abstract. The work substantiates the location of liquid hydrocarbons (LH – oil and retrograde condensate) in the dynamic, filtering part of the capacitive volumes of gas-saturated productive deposits of gas condensate and oil and gas condensate fields (GCF and OGCF). The necessity of the development and bench modeling of the production of LH from gas-saturated deposits of GCF and OGCF in the late stages of field development is shown due to the high geological reserves of LH in them and the need to develop them with the aim of component recovery increasing and extending the life of the fields. The experience of bench modeling on the experimental installation of the life cycle of the oil and gas condensate system of the Vuktyl OGCF for the period of its development on the “depletion” mode is described. On the basis of a highly permeable core model, a simulation of the initial fluid saturation was successfully held which fits the initial state of the reservoir system of the Vuktyl OGCF, including the LC (reservoir oil), and also the current thermobaric state and fluid saturation of the reservoir system were simulated. The total mass of LH (reservoir oil and retrograde condensate) in the reservoir model is determined which can be taken as a basis for calculating the LH extraction rate while carrying out further research on bench modeling of LH production technologies in the late stages of Vuktyl field development on the core model created. As a result of the works described above, an oil and gas condensate system was created in a highly permeable bench core model which is the model of depleted to maximum condensation pressure reservoir of Vuktyl OGCF.

1. Introduction

It is considered that the production of hydrodynamically immobile reservoir liquid hydrocarbons (LH) from gas-saturated productive OGCF deposits is technologically impossible. In this case, a comparison is made with the oil recovery factor (ORF) from productive deposits of oil fields, which differ from oil and gas condensate fields by 100% filling of effective pore volumes with oil.

If in the oil-saturated reservoir the central (structurally pinched for filtration) part of the effective pore volumes is filled with dynamically immobile oil, then in the gas-saturated collector it is filled with structurally-pinched reservoir gas (see Figure 1). At higher gas saturation, the dynamic (continuously connected through channels, filtering) part of the effective pore volume and the central part of the channels connecting the pores begin to fill with gas (see Figure 1) [1].
Figure 1. Structural characteristic of reservoir fluids in the capacitive volumes of the gas-saturated part of gas-condensate and oil and gas condensate fields: 1 - film water (the rock is more philic to water) or film oil (the rock is more philic to oil); 2 – pore corners water (capillary pinched, meniscus) or pore corners oil (the rock is more philic to oil); 3 - dinamical (continuously connected) drained oil (the rock is more philic to water) or drained water (the rock is more philic to oil); in the central part of the pore channels - dynamic drained gas; 4 - structurally pinched gas (when flooding during the development process or with a high concentration of liquid fluids – oil, water).

The dynamic part of the gas is filtered in the reservoir during its development. Structurally pinched in the pores gas is gradually discharged into the dynamic part of the pore volumes during the development process (through its expansion while creating depression on the bed) and only then begins to participate in filtering.

With a high content of LH and full filling of dynamic volumes with it, the gas in the central part of the pore volumes turns out to be structurally pinched, isolated

At gas saturation values exceeding the structurally pinched volumes, and high initial reservoir pressure, the free gas energy may be enough to break the continuity of the liquid hydrocarbon phase in the filtration channels, that ensures single-phase gas filtration in the reservoir even at high saturation of dynamic volumes of gas-saturated rocks with liquid hydrocarbons. As the reservoir pressure decreases during the development the energy of the remaining gas is insufficient to break the continuity of the liquid phase and the two-phase filtration process begins (gas - LH) or if free reservoir water is available the three-phase filtration of reservoir fluids (gas – LH - water) has place.

Such a pattern of filtration of reservoir fluids in a gas-saturated reservoir during the development process, as well as an increase in the saturation of the pore volumes with liquid hydrocarbons due to precipitation of retrograde condensate in the process of reducing reservoir pressure, suggests that the most favorable period of production of LH (oil and retrograde condensate) is the final (late) stage of development of oil and gas condensate fields.

The presence in the gas part of depleted oil and gas condensate deposits of Vuktyl OGCF (more than 200 million tons), Orenburg OGCF (1.406 billions tons only in pore-type rocks) and other OGCF of significant volumes of reservoir oil and retrograde condensate, which, however, do not reach the threshold of hydrodynamic mobility, makes it urgent to search for possibilities of their directional production [2].

Maximum, close to limiting, accumulation of LH due to precipitation of retrograde condensate in reservoir oil and significantly reduced reservoir pressures in the reservoir at the final stages of development before developing the LH production technologies need the preliminary bench modeling of the whole period of oil-gas-condensate system development on the "depletion" mode.

2. Bench modeling of the life cycle of the Vuktyl field’s oil and gas condensate system

Bench modeling according to the developed program was carried out on a bench experimental installation (Figure 2) incuding: reservoir model, hydraulic rock overburden press, pressure transmitters “Metran-150”, gas meter, chromatograph to determine the composition of the gas and liquid phases at the outlet of the reservoir model, measuring separator-meter, low-temperature cryostat to maintain a negative temperature in the separator, piston recombinators with working agents, pumps to maintain a constant pressure in the recombinators.
Figure 2. Experimental installation scheme.
1 – chromatograph; 2 – reservoir model; 3 – press for rock overburden; 4 – pressure transmitter; 5 – separation piston recombinator; 6 – pump; 7 – cryostat; 8 – measuring separator; 9 – gasmeter

Before starting the assembly of the installation and the experimental studies, all measuring and auxiliary equipment was checked and calibrated. Before performing chromatographic analyzes, chromatographs were calibrated using certified calibration mixtures. For the analysis of the composition of the gas phase, a chromatograph of the type “Chromatek-Crystal 5000.1” was used, directly connected to the experimental setup. The composition of the liquid phase was studied also on a chromatograph of the type "Chromatek-Crystal 5000.1". The analysis was carried out on the temperature ramp mode (from 32 to 320 °C) using a high-temperature thin-film capillary WCOT column 30–50 m long and a flame ionization detector. The studies were conducted on a high-permeable core model from rock samples of the Vuktyl OGCF. The high-permeable reservoir model (HRM) is shown on Figure 3 in the form of a scheme created on the basis of electron microscopic cathodoluminescent images (electronic zoom x100) [3].

Bench modeling of the life cycle of the field development includes next key stages:
• simulation of the initial fluid saturation fitting the initial state of the reservoir system of the Vuktyl OGCF, including LH (reservoir oil),
• simulation of the current thermobaric state and fluid saturation of the Vuktyl OGCF reservoir system.
| №№ | Pore space structure parameters                        | 8/19B | 8/20B | 8/15 | 8/13 | 8/20A | 8/19A |
|-----|-------------------------------------------------------|-------|-------|------|------|-------|-------|
| 1   | Pores and channels quantity                          | 2090  | 1900  | 3299 | 3299 | 1914  | 2427  |
| 2   | Sum perimeter of pores and channels, um              | 332761| 326170| 368335| 368335| 381789| 376114|
| 3   | Sum square of pores and channels, um²                | 4144983| 411041| 3580490| 3580490| 5199678| 3440836|
| 4   | Av square of pores and channels, um²                 | 1983,25| 2166,34| 1085,33| 1085,33| 2716,66| 1417,74|
| 5   | Av equivalent diameter of pores and channels, um     | 50,27 | 52,54 | 37,19 | 37,19 | 58,83 | 42,5  |
| 6   | Av perimeter of pores and channels, um               | 159,22| 171,67| 111,66| 111,66| 199,48| 154,98|
| 7   | Coordinate number, Nch/Np                            | 4,49  | 4,34  | 4,74  | 4,74  | 4,35  | 4,39  |
| 8   | Av channel diameter, um                              | 6,47  | 6,32  | 4,84  | 4,84  | 7,25  | 6,1   |
| 9   | Av pore diameter, um                                 | 88,27 | 89,67 | 69,52 | 69,52 | 105,09| 72,5  |
| 10  | Av ratio d_p/d_ch                                    | 13,6  | 14,2  | 14,4  | 14,4  | 14,5  | 11,9  |
| 11  | Porosity (measured), %                               | 19,4  | 17,62 | 18,76 | 17,42 | 17,8  | 16,86 |
| 12  | Permeability (measured) mD                           | 269,18| 226,78| 195,94| 168,95| 168,11| 122,0 |

Figure 3. High-permeable bench model - scheme based on electron microscopic cathodoluminescent images, electronic zoom x100, (pores are white colored).
3. Simulation of the initial state of the reservoir system of the Vuktyl OGCF, including reservoir oil

For simulation of the initial state of the reservoir system, including reservoir oil, the next operation consequence is hold:

- The prepared reservoir model, after measuring porosity and permeability, is exhausted and saturated with the reservoir model water (salinity 230 g/l). The model is drained with reservoir water until the air stops outgoing.
- Residual water saturation is created by pumping modeled degassed reservoir oil through a 100% water-saturated reservoir model until the water phase stops outgoing. Saturation is controlled by matter balance.

The process of residual water saturation modeling in an experimental reservoir model is shown in Figure 4.

![Figure 4. Simulation of residual water saturation in high permeable reservoir model (HRM).](image)

After pumping about 5.8 of pore volumes of oil, the removal of water stopped. The value of residual water saturation was 30.91%.

As a model of degassed oil, a mixture of distillate after 110°C of degassed oil from well 279 of the Severo-Vuktylsksoye field with n-pentane and n-octane in such a proportion to fit the initial density of the degassed oil of well 279 (823.4 kg/m³). The choice of this model of oil is due to two factors:
- estimated proximity of the composition and properties of reservoir oil in the main gas condensate reservoir of the Vuktyl OGCF to the reservoir oil of the Severo-Vuktylsksoye field,
- the need to separate the production of LH and the model solvent - hexane (with the planned production of LH) from the reservoir model according to chromatographic analysis.

The accepted way to the preparation of the reservoir oil model made it possible to almost completely eliminate the content of hexane in it while maintaining the proximity of properties to the degassed reservoir oil of the Vuktyl OGCF.

Residual oil saturation is created by pumping methane through the model of the reservoir until the outflow of oil from the model stops under thermobaric conditions close to the average initial pressure (35 MPa) and temperature (63 °C) of the reservoir system of the Vuktyl OGCF. Saturation is
controlled by matter balance. Modeling of water-, oil- and gas-saturation by methane pumping to the HRM is shown in Figure 5.

![Figure 5. Simulation of water, oil and gas saturation in the process of methane injection to high permeable reservoir model (HRM).](image)

While maintaining pressure and temperature, methane is replaced by a model of a reservoir gas-condensate mixture (GCM) from a recombinator until the composition of the outgoing product is stabilized. The composition is controlled according to the chromatographic analysis of gas and liquid samples.

The model of the reservoir gas-condensate mixture (GCM) is prepared by recombining the gas separator samples of the well 68 from Yuguidsky OGCF and pure hydrocarbon components to achieve the initial hydrocarbon content (HC) of the C₅+ group at 360 g/m³, which is typical for average initial conditions of Vuktyl OGCF [4].

In order to be able to correctly interpret the data of the bench modeling, the experiment of differential condensation with the same GCM model is carried out previously in the PVT vessel and the relative volume of the liquid phase is determined at different stages of pressure reduction. The experiment is carried out in two versions - only with the GCM model and with the GCM model in a mixture with oil and water models in proportions corresponding to the initial phase saturations in the reservoir model.

Thus, in the group hydrocarbon composition of the gasoline fraction (IBP - 125 °C) of the liquid phase of HRM production in the process of replacing GCM methane over time, there is a slight increase in the proportion of alkane compounds with a parallel decrease in naphthenic and aromatic. The change in the group hydrocarbon composition of the gasoline fraction (IBP – 125 °C) of the liquid phase of the HRM production in the process of replacing GCM methane is clearly shown in Figure 6.

Changes are also recorded in the content of normal and isoprenoid alkanes (fraction above 125 °C) of the liquid phase of HRM production. At the initial stage of pumping, isoprenoid hydrocarbons are found in the composition of the liquid phase, even in small concentrations. In the future (after pumping 2.7 pore volumes of the GCM), they are no longer registered as part of the studied fraction. The change in the content of normal alkanes in the liquid phase of HRM production in the process of replacing GCM methane is shown in Figure 7. From Figure 7 it can be seen that the composition of normal alkanes changes according to the observed tendency to lightening of liquid production — at
the beginning of pumping, the length of the concentration range of normal alkanes is traced down to C_{40}, then it is shortened to C_{19}.

In general, according to gas-liquid chromatography (GLC), in the process of replacing GCM methane, the relief of the liquid phase of products was noted, associated with expelling the residual oil and increasing the amount of gas condensate hydrocarbons in the liquid phase of HRM production.

During observing the process of replacing GCM methane, it was found by changing of the condensate-gas factor (CGF) and the content of components in the production gas and liquid phases at the outlet of the reservoir model that their stabilization started when approximately seven pore volumes were injected. The pumping up of one more pore volume ensured the constancy of the composition of the mixture within the error of the chromatographic analysis. Then the reservoir model was held for two days to establish sorption equilibrium and uniform distribution of the GCM in the entire pore volume system. At this stage, the preparation of the initial reservoir oil and gas condensate system in the HRM was completed. The residual water saturation was 29.7 %. The value of residual oil saturation at the same time decreased to 5.88%.

![Figure 6](image_url)  
**Figure 6.** Changes in the group hydrocarbon composition of the gasoline fraction (IBP – 125 °C) of the production liquid phase of HRM in the process of replacing GCM methane.
4. Simulation of the current state (depleted) of the Vuktyl OGCF reservoir system

At present, the thermobaric conditions and the composition of the reservoir fluids vary greatly inside the main reservoir of the Vuktyl OGCF. Nevertheless, it can be affirmed that in the most volume of the deposits the reservoir pressure has already reached the value below the pressure of maximum condensation of the reservoir GCM. As for the injection of dry ("Tyumen") gas, which has been implemented since 1992, in general, in relative terms, it did not make a fundamental contribution to the change in the current C_5+ content in the liquid and gas phases [4]. In particular, this applies to the selected pilot sites, where the condition of maintaining of sufficient potential for HC group C_5+ was accepted.

Based on these assumptions, the modeling of the conditional current state of the reservoir system was carried out as follows.

- While maintaining the set temperature of 63 °C, the model was depleted to the pressure of maximum condensation of the reservoir GCM of Vuktyl OGCF - 5 MPa. According to the results of these studies, calculations of the content of hydrocarbon components in the production of the reservoir model were performed.

- The depletion rate was about 0.1 - 0.2 MPa/h to ensure the conditions of condensation of the liquid phase in the reservoir model and prevent carrying out its drops with the gas phase.

Figure 8 shows the dynamics of pressure change over time in the process of reservoir depletion modeling on the reservoir model. The duration of the process of the reservoir model depletion was 290 hours. Experimental studies were carried out at reservoir conditions in around-the-clock mode.
During the experimental studies, the volume of production, the mass of the liquid phase (after the separator box), the composition of the phases by chromatographic analysis of samples were monitored. The final saturation of the reservoir model with water, LHC and gas were estimated. Chromatographic studies of separation gases obtained by simulating the depletion of an oil and gas condensate reservoir on HRM showed that trends in the content of all components of the studied gas phase are similar to the character of changes in the composition of the produced gas reservoir observed in the actual development of Vuktyl OGCF during natural depletion.

Chromatographic studies of the liquid phase obtained in the simulation of the depletion process of the Vuktyl oil and gas condensate reservoir on HRM showed that as the pressure decreases, the resulting liquid products become more light (the molar mass of the condensate decreases, the mole fraction of the heaviest components of the condensate significantly decreases, starting from the sum of the pseudo C_{11} and up to the sum of the pseudo C_{20+}). The revealed dependences are typical for the liquid hydrocarbons, produced in the process of developing a gas-condensate field in the mode of natural depletion of reservoir energy. Experimental studies were carried out on the pVT facility to determine the LHC reserves (condensate + oil) in the reservoir model after reducing the pressure to 5 MPa. In the pVT-cell, the system was recombined (GCM + water + oil) in the ratios obtained in the reservoir model after pumping the GCM.

At the end of the differential condensation test, the degassing of the saturated liquid phase was performed. The mass of LHC (reservoir oil and retrograde condensate) according to the reservoir model was 4.8348 g. This value can be taken as a basis for calculating the LHC extraction coefficient when conducting further research on the development of technologies for extracting hydrodynamically immobile LHC (reservoir oil and retrograde condensate) in the later stages of the development of the Vuktyl field. It should be noted that the additional extraction of LHC entails an increase in the final product content of high-boiling paraffins, resins and asphaltenes, reducing its quality, as well as a decrease in the content of C_{3}-C_{4} components, which must be investigated using additional, for example, optical methods [5-7].

5. Conclusion
Thus, according to the results of depletion in the gas-saturated reservoir model:
- the saturation of LHC was formed, including the original reservoir oil and retrograde condensate from the GCM,
- the saturation of the liquid hydrocarbons with gas and intermediate components to an equilibrium state at the current pressure and temperature took place.

As a result of the work described above, a system was created in the HRM that simulates the reservoir depleted to maximum oil-gas-condensate reservoir condensation pressure. The developed methodical approach can be used to imitate realistic reservoir conditions for bench modeling to estimate the possibility of extracting of hydrodynamically immobile LHC (reservoir oil and retrograde condensate) from the gas-saturated part of the fields at the final stages of depletion.

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