INCREASING HYDROCARBON PRODUCTION CAPACITY OF RESERVOIR AT FINAL STAGE OF GAS-CONDENSATE FIELD DEVELOPMENT. TECHNOLOGY, MODELING, FIELD TEST

N.A. Guzhov
V.A. Nikolaev
R.M. Ter-Sarkisov

RUSSIA
Gazprom is one of the world’s largest companies producing natural gas both from gaseous and liquid hydrocarbons. Gas-condensate fields play an increasingly important part in hydrocarbon production of the company.

In view of some circumstances, practically all Russia’s gas-condensate fields are being developed under conditions of reservoir energy depletion. In this case the gas is extracted in amounts from 70 to 90% of the initial reserves. Liquid hydrocarbon (gas condensate) recovery ratio, however, does not exceed, on average, 45%.

Worsening of the structure of hydrocarbon reserves under development naturally leads to increase in the cost of gas, condensate and oil production. Therefore, on the one hand, the problem of enhancing hydrocarbon production capacity of reservoir becomes pressing, particularly, of condensate-oil production rate in the fields now in operation, including those at the final development stage, and, on the other hand, technical and economical perquisites are being created for application of enhanced hydrocarbon recovery methods.
In the investigations, VNIIGAZ is giving much attention to the problems related to operation of gas-condensate fields to be at the late development stage. The institute’ specialists proposed several methods to enhance gas-condensate-oil-production capacity of reservoir which has the pressure reduced to the level below the maximum condensation pressure in the main condensate-forming frdrive \( (C_{5+}) \) of formation fluid \( (P_{\text{max, cond.}} = 6 – 7 \text{ MPa}) \).

Thermodynamic research demonstrated that under such reservoir conditions both formation condensate recovery and gas recovery might be noticeably enhanced through low-pressure gas drive. In this case high hydrocarbon gas with \( C_{2+} \) frdrive being removed to the limit might be the optimum drive agent. The hydrocarbon recovery enhancement process is based on interphase equilibrium displacement in the depleted two-phase gas-condensate system tending to evaporation of \( C_{2+} \) components of retrograde condensate, including \( C_{5+} \).

Equilibrium content of \( C_{2+} \) and \( C_{5+} \) in the injected gas at \( P < P_{\text{max, cond.}} \) theoretically is to be higher than at \( P = P_{\text{max, cond.}} \), practically, however, the condensate-gas factor in all producing wells is found to be decreased due to interphase process irregularity. Naturally, to extract retrograde condensate in production quantities large volumes of gas must be pumped through the formation.

When gas impact process is realized in a \( P < P_{\text{max, cond.}} \) pressure zone, gas undersaturated by \( C_{2+} \) flows to a bottom hole of the producer. Therefore, the bottom hole zone is gradually getting free from condensate that accumulates and evaporates continuously there in the process of gas filtration. Thus, low-pressure gas impact makes it possible to decrease filtration resistance in bottom hole zones of producers and to increase productivity of the latter.

To enhance technical and economic attrdrive of the low-pressure gas impact the VNIIGAZ specialists jointly with Severgazprom’s specialists proposed a technology, which, apart from enhancing gas-condensate reservoir recovery, solves the problem of long-term gas and condensate supplies to a processing plant and the problem of transit gas flow irregularity in the interregional gas pipelines.

In this connection, by the Gazprom management decision in 1998 the largest European Russia Vuktyl gas-condensate field was started being translated into the mode of storage – regulator. This mode of reservoir operation allows for pumping considerable gas volumes (from gas pipeline) through the depleted reservoir with pressure up to 3 – 4
MPa. As projected, the active period of pipeline operation will be extended approximately by 20 – 25 years.

Figure 1 illustrates \( C_{5+} \) and \( C_{3-4} \) HC production growth when the field is operated under regulator conditions. Depending on an operation scenario (gas injection 10 or 20 years) there exists the possibility to increase sufficiently liquid HC extrdrive with regard to field depletion conditions.

Maximization of the possible reservoir sweep by injection gas is the major technology component. This is achieved through a flexible system to regulate the reservoir seepage directions. For example, within a gas-conditioning unit (UKPG-8) operation conditions of injection wells have been changed several times by shutting some of them for long periods or switching over to producers for the period since 1993.

![Bar chart](image)

**Figure 1.** Summary indicators of HC production on the Vuktyl oil and gas condensate field when its shifting to regulator conditions

**SCIENTIFIC SUBSTANTIATION OF THE TECHNOLOGY**

Scientific substantiation of the technology for depleted gas-condensate reservoir development with low-pressure gas drive was performed using the results of mathematic modeling and physical simulation of reservoir processes. At the same time it was examined how the interphase mass exchange in the gas-saturated reservoir is effected by capillary forces, features of fine-porosity reservoir, scattered liquid hydrocarbons (residual oil), reservoir pressure level (in the range below \( P_{\text{max. comm.}} \)), quantity of non-equilibrium (dry) gas pumped through the reservoir.
The experiments carried out by S. Rassokhin (VNIIGAZ) have shown that under the conditions typical for the Vuktyl field reservoir rocks a relative permeability for the main gas phase is only a small fraction of absolute permeability. Connate water that always presents in porous medium, dispersed liquid HC (DLH) and retrograde condensate distinct negatively effect gas filtration. Figure 2 illustrates appropriate data (retrograde condensate was simulated with n-heptane).

Thermodynamic calculations carried out by N. Guzhov (VNIIGAZ) show that the presence of liquid HC phase of DLH type sufficiently influences also on the composition of existing gas phase. Figure 3 shows DLH influence on gas content in gas. Under typical DLH saturations, from 10 to 15% of pore volume, condensate content may be 3-5% lower as compared to gas in "dry" reservoir. Physical modeling of depleted gas condensate reservoir with gas injection has allowed to evaluate the influence of injected agent composition on the intensity of retrograde condensate evaporation. Shown in Figure 4 are the results of modeling the process in reservoir depleted to 7 MPa and 3.5 MPa. In both cases retrograde condensate components are extracted more intensively thanks to evaporation when dry gas is injected into reservoir. The same conclusion was made by the results of thermodynamic calculations.

The calculation and experimental results allow to recommend extremely dry, by C₂+, HC gas as an injection agent when the technology of low-pressure gas drive is realized.

FIELD TEST

Field test has been carried out since 1993 at one of the Vuktyl field testing areas consisting of 4 injection wells and 11 producing wells. (Later a number of wells were increased.) The “Tyumen” pipeline gas consisting of more than 98 % of methane was used as an injecting agent. The pre-breakthrough injection agent reservoir sweep efficiency was found to be about 0,20 at the field. While subsequently the reservoir sweep is increasing rather rapidly as still greater quantities of gas are being injected. Converting producing wells into injection ones, and injection wells – into producing ones, periodically changed the reservoir gas flow directions at the testing area. The technology application was gradually expanding, and at present the most part of the reservoir is being operated by injecting gas. The injected agent reservoir sweep at "old" sites exceeds 0,60 and at recent ones is 0,10 – 0,30.
Figure 2. Influence of water-saturated porous medium on relative phase permeability at steady filtration of heptane and methane (absolute permeability of reservoir model - $7 \times 10^{-12} \text{m}^2$).

Figure 3. $C_5^+$ potential vs. pressure at different saturation (S) of liquid HC, the Vuktyl field.
As of 1.01.2006 the field produced additionally (as compared with depletion conditions) more than 4.5 billion cubic meters of gas and about 1 million ton of liquid hydrocarbons ($C_{2+}$), including over 150 thousand tons of stable condensate ($C_{5+}$) due to application of low-pressure gas drive. This large full-scale experiment has shown that even for a reservoir with large nonuniformity of reservoir properties distribution low-pressure gas drive is an effective means for improving well operating conditions at a late stage of gas condensate field development. At the same time this allows to increase recovery factor both for liquid and gaseous hydrocarbons. For the last few years, after the beginning of dry gas injection, an output of the majority producing wells has increased by 20-50% and has kept during many years thanks to draining bottom hole zones.

The first stage of drive process was accomplished without changing a direction of filtration flows in reservoir. The second stage included regulation of reservoir sweep after injection of gas in amount of 1.5 pore volume. Beginning from the second stage $C_2$-$C_4$ and methane recovery rate has increased sufficiently.

**EVALUATION TECHNOLOGICAL EFFICIENCY**

Injected gas consumption can be considered as one of the indices of the drive process technological efficiency as a method of enhancing HC recovery. When this parameter is calculated, one should remember that three physical effects resulting from non-equilibrium dry gas injection make contribution to additional current HC recovery, including:

- Increase in pressure gradients in well-drainage area
• Decrease in filtration resistances in bottom hole zones of producers
• Equilibrium shift in two-phase HC system towards evaporation side

It is better to assess the contribution of the first two effects by assessing additional HC production in volume units (in gaseous state – linear relation). It is better to assess the contribution of evaporation effect by assessing additional production in mass units (inverse relation).

Figure 5 gives the results of specific consumption calculation for two scenarios (final results are given in accepted units: for additional gas - m³/³, for additional liquid HC – thousand m³/t). According to Figure 5, a maximum average dry gas consumption on additionally produced HC in the conditions of the depleted Vuktyl field does not exceed 3.3 m³/m³ for methane and 4.0 thou m³/t for liquid YC (C2-C4 and C5+).

Given in Figure 6 is the dependence of additional HC recovery factor on interphase equilibrium constant and injected dry gas volume. This series of curves gives a definite picture about the dynamics of relative efficiency of the development with dry gas injection. Low-pressure drive technology is rather effective tool for enhancing HC recovery factor, firstly light HC. It is worth to note the continued growth of C₁ and C₂-C₄ production after injection of gas in amount of 2.5 pore volume.

The results of tests of the low-pressure gas drive technology at the Vuktyl field are of great importance for Russia’s gas-producing industry as tens of gas-condensate fields being potential objects for introducing the above technology have entered or will enter the final stage of reserves development within the next few years.
Figure 5. Vuktyl field, area near gas-conditioning unit (UKPG-8). The dependence (to a moment of injection of 2.5 pore volume of dry gas) of specific gas consumption, gas injection, for additional HC production on its constant of interphase equilibrium, $K_i$:

1 – calculation of HC in mass units (t)
2 – Calculation of HC in volume units ($m^3$) at 1 bar and $20^0C$; it is taken conditionally that volumes of 1 mole of $C_2$-$C_4$ fraction and 1 mole of $C_5+$ fraction amounts to 0.024056 $m^3$.

Figure 6. Vuktyl field, area near gas-conditioning unit (UKPG-8). HC additional recovery factor, $K_{rec}$ vs. interphase equilibrium constant, $K_i$.
Figure 1. Summary indicators of HC production on the Vuktyl oil and gas condensate field when its shifting to regulator conditions

Figure 2. Influence of water-saturated porous medium on relative phase permeability at steady filtration of heptane and methane (absolute permeability of reservoir model - 7*10^{-15} m^2)

Figure 3. C_{5+} potential vs. pressure at different saturation (S) of liquid HC, the Vuktyl field

Figure 4. Physical modeling. CGF vs. pumping volume at different pressures: 1.4 – separator gas; 2.5 – rich gas; 3.6 – dry gas (p = 3.5 MPa); and 4.6 (p = 7.0 MPa)

Figure 5. Vuktyl field, area near gas-conditioning unit (UKPG-8). The dependence (to a moment of injection of 2.5 pore volume of dry gas) of specific gas consumption, gas injection, for additional HC production on its constant of interphase equilibrium, K_i:
1 – calculation of HC in mass units (t)
2 – Calculation of HC in volume units (m^3) at 1 bar and 20°C; it is taken conditionally that volumes of 1 mole of C_2-C_4 fraction and 1 mole of C_{5+} fraction amounts to 0.024056 m^3.

Figure 6. Vuktyl field, area near gas-conditioning unit (UKPG-8). HC additional recovery factor, K_{rec} vs. interphase equilibrium constant, K_i