EOR Application in Large Oil / Gas Fields of West Siberia: Generalisation of the Experience, New Technologies

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Summary

More than 30% of oil and gas-condensate reserves in Russia are contained in the oil fields having gas caps. Annual recovery rate of such reserves is less than 6%. Rate of oil production and oil recovery factor are also very low. The discovery of giant oil fields in the West Siberia, such as the Samotlor oil field, the Lyantor oil field and the Fyodorovskoe oil field as well as many other fields, has demanded application of new technologies for the development of vast under-gas zones.

Pilot and commercial works, aiming on the test of various development systems in huge oil-gas fields, play important role in solution of effective oil withdrawal from oil-gas zones.

A two-side barrier water flooding has been developed and used for the first time in the world practice in the AB₁ and AB₂₋₃ reservoirs of the Samotlor oil field.

A wide scale pilots has being applied at the Lyantor and Fyodorovskoe oil fields W.Siberia to test different well patterns: 9-spot well pattern (in Lyantor) and 5-spot well pattern, a block limited system and drilling of horizontal wells (in the Fyodorovskoe field).

The results of pilot testing for the areas are presented in this paper.

Introduction

Application of barrier water flooding together with some other areal and block systems has allowed to solve the following problems:

- prevented a breakthrough of large volumes of gas from the gas cap due to separation of the under-gas zones from the gas cap and from the oil zone by the rows of injection wells.

- prevented expansion of the gas cap and filling-up of oil wells, what has allowed to improve the conditions of their work.

- provided for the relatively high rates of oil reserves recovery from the under-gas zones (5-7% of the initial recoverable oil reserves).

- provided for the possibility of recovering gas from the gas cap without decrease of pressure in it.

The results of pilot testing at the Samotlor, Lyantor and Fyodorovskoe oil fields have been used at the Varieganskoe, Bystrinskoe and Tarasovskoe oil fields as well as some other giant oil fields of West Siberia.

World rank the Samotlor oil field, the biggest in Russia with maximum oil production reached 154 mln t. per year, is a multi-reservoir oil field. It was put on production in 1969.

Apart from BC₁₀, BC₈ and AC₄₋₅ reservoirs there are other big oil-gas deposits, namely AB₁ and AB₂₋₃. The average permeability of AB₁ and AB₂₋₃ is 120 and 500·10⁻³ μm² respectively. The oil viscosity at the reservoir condition is 1.5 mPa.s (Table 1).

The specific feature of monolith sandstone, alternating with thin sandy-argillaceous layers, is that they have extensive commingling zones with the above-laying gas-bearing formations through lithologic windows.

The conditions of fluids, contained in them, are such that there are extensive developed under-gas zones (the area of which is 89 millions sq.m), represented by rather thin oil-bearing thickness (5-10 m), located under a gas layer (Fig.1 and Fig.2).

There has been no experience in developing such gas-oil deposits.

Results of semi industrial field tests

A pilot technology has been provided to recover oil from extensive oil rims of AB₁ and AB₂₋₃ reservoirs having small thickness in the oil-bearing layer.

It has been stipulated for these layers that under-gas zones must be cut off by the circular batteries of the cutting rows of injection wells and that production wells will be located in rows along injection wells rows in certain areas of under-gas parts.

For layer AB₁ it has been stipulated to create a circular barrier row, whereas for the monolith part of AB₁¹⁻² it has been offer to locate the rows of production wells in the under-gas zone along the internal and external gas-oil contacts and parallel to the circular injection rows.

As to layer AB₂₋₃ two injection rows along the external gas-oil contact and along the 4-m isoline of net thickness in the under-gas zones by the rows parallel to the cutting lines were projected.

Well spacing density is 16 hectares per well. Production from the under-gas zone was supposed to be done by means of two-side barrier water flood. Application of this technique has provided to:

- prevent filling-up of the oil zone by free gas intrusion,
- restrict considerably the intrusion of oil into gas-bearing zone,
- raise the rates of recovery of hard-recoverable oil reserves from the extensive gas-oil zones,
- produce simultaneously from oil, oil-gas and gas zones and, to a great extent, as separate parts of the fields.

All in all, both in AB₁ and AB₂₋₃, 343 barrier injection wells have been projected and drilled.

By 1.01.87 the whole system of barrier water flood had been fully developed.

Study of all the results of the pilot testing work, connected with the application of two-side barrier water flood in AB₂₋₃ and AB₁¹⁻², has shown its high efficiency and allowed to:

- restrict free gas production of the wells to the normal gas-oil ratio and improve operation of production wells.

- increase rates of recovery of hard-recoverable oil reserves up to 7.6-8.3% of the initial recoverable oil reserves.

- increase oil recovery in AB₂₋₃ reservoir against the approved value for 6 items due to preventing oil intrusion into the gas zone.

As of 1.01.94 the cumulative oil production from AB₁ and AB₂₋₃ (Fig.3 and Fig.4) had been 670 millions tons, while the cumulative fluid production had been 728.7 millions tons. Total injection volume had reached 3000 millions cu m, 160% of production had been the compensated by injection. The current oil recovery factor has reached the value of 0.34 for AB₁³ and 0.3 for AB₂₋₃, while water cut has been 88.4 and 91.6% correspondingly.

The Lyantor field is one of the largest gas-oil fields in West Siberia.

This field is associated with sandy-argillaceous reservoirs AC₉₋₁₁, AC₁₀ and AC₁₁. As the total thickness of the pool equals to 60 m, the heights of the gas part is 45 m. Thickness of oil rim varies from 0 to 18 m, being 15 m in average. The size of the pool is 70 x 20 km. Free gas occupies 51% of the total volume of the pool. Permeability is $300 \cdot 10^{-3} \mu\text{m}^2$ in the average, oil viscosity under reservoir condition is 6 mPa.s (Table 1).

All the reservoirs are connected hydrodynamically, which makes it possible availability of lithological "windows" and this is confirmed by similarity in levels of gas-oil and water-oil contacts. Stratification ratio is not high - 2.7 in the average.

Large amounts of water, oil and gas are associated with that massive sheet-like type of gas-oil deposits with bottom water.

The pilot testing program included experimental development system for some zones to be drilled in 9-spot pattern with well spacing 400 m (16 hectares per well). The gas zone has not been drilled in. Simultaneous production is meant for all reservoirs.

A number of measures with the aim to enhance oil recovery has been undertaken. They included: drilling of injection double-wells to be used for separate water injection in zones of common occurrence of AC₉, AC₁₀ and AC₁₁, additional perforation in underrunning water contact zone and the gas cap contact zone, injection of surfactants while putting injection wells into operation, application of multi-fold depression technique while putting production wells into operation.

Field results of the pilot test have confirmed the efficiency of the realized system.

405 wells out of 1300 have gas-oil ratio from 60 to 2000 cu m per ton, 116 wells have gas-oil ratio more than 1000 cu m per ton. In some parts of the field gas breakthrough from the gas cap had been used for non-compressor gas lift.

When oil recovery factor was 0.043 of initial oil in place, the oil of production per well was 27 thousand ton, at water cut of 52%. To analyze the efficiency of the whole development system, the primary developed area was selected for the pilot testing work (Fig.5). Within this area AC₉ is gas-bearing, AC₁₁ is water-bearing and AC₁₀ is an object to be developed. There are 12 elements in the area, spaced according to 9-spot well pattern.

The development of the area has been conducted since 1980. Annual oil production has reached 240-260 thousand tons, average flow rates of wells are 20-24 ton per day, withdrawal rate is 2.4-2.7% of the initial recoverable oil. Maximum rate has reached 3.05.

Up to date more than 3 million tons of oil have been recovered from the given area, which totals to 90% of the initial recoverable oil reserves. Water cut is 85%. The review of pattern elements' operation has shown that their efficiency was different, depending on geologic structure and conditions of fluid occurrence. The development of the area has been conducted under two drives: the mixed drive (i.e. expansion together with gas cap drive and dissolved gas drive) and water-oil displacement drive.

The anticipated ultimate oil recovery factors for various elements varied from 0.243 to 0.415, the average value for the area was 0.323 (Table 2), while the water-oil ratio was about 2 cu m per one ton produced oil which is close to the projected value.

It should be noted that the area under consideration is one of the best according to the achieved technological results.

Presently this area is being under final stage of production. Oil production per well is 85.1 thousand tons, water production is 134.5 thousand tons, including 130.2 thousand tons (i.e. 97%) during the period of artificial production. Water cut is 85%, compensated rate of fluid production over water injection is 115%.

The common conclusion is that application of 9-spot pattern together with other measures is efficient for the Lyantor field. It should be noted that in accordance with available information the value of oil recovery for the field as a whole will be less than projected one and will be equal to 0.22.

The Fyodorovskoe oil field. This oil and gas deposit is associated with AC₄₋₈ reservoir and have an expanding, 50 m heights gas cap. The pool has water aquifer along the whole area. Thickness of the oil rim varies from 8 to 14 m, making in average 10 m. The pool size is 51 x 30 km. The pool characteristics are given in Table 1.

There is a good hydrodynamic communication between the layers. Several lithologic windows where

oil is in contact with gas and water are existed at the gas-oil and water oil contacts.

There has been no experience in development of such oil-gas fields.

The pilot test has been done in two areas. As for the first pilot-testing area, four pattern elements and 5-spot system with well spacing 600 x 600 m have been tested since 1976. The total number of wells was 20, including 4 injection wells. Wells must be produced under different geological and geophysical conditions perforated at different depth from the gas-oil and water-oil contacts.

867 thousand tons of oil and 3400 thousand tons of fluids have been produced from the first area during 17 years of production period. Oil rate of wells have been 21 tons per day per well, fluid rate have been 104 tons per day at current water-cut of 80%. 3 cum of water have been injected per one ton of oil produced. Since 1989 the injection wells have been put aside.

Two groups of wells have been differentiated in the first area.

The first group includes 8 wells, the productive zone of which does not have clay barriers at the gas-oil contact. The total production per well in this area is 28 thousand tons of oil and 77 thousand tons of fluid at water-oil ratio being equal to 1.8. The wells have a very high gas-oil ratio, being up to 5000 cu m per ton and more. Four wells out of this group have been shut down since 1979.

The second group of wells have clay barriers at gas-oil contact. For this group oil withdrawal per well has been 77 thousand tons at average and fluid withdrawal has been 345 thousand tons at water-oil ratio of 3.5 and water-cut of 86%.

The results of pilot-testing work for the area indicate the possibility of oil recovery but with a very low efficiency. The ultimate oil recovery is estimated not to be more than 10-15%.

Pilot-testing work in the second area started in 1985. The area has been divided into 4 blocks having different types of geological structure. The pilot-tests consisted 9-spot pattern system. All blocks have been enclosed by a common system of injection wells. A separate oil and gas production from one pattern of a closed system has been planned.

A total number of production wells in the first block was 44 including 42 wells under production. The number of injection wells was 73 including 43 wells under operation, 3 wells were out of operation and 27 being put aside.

From the beginning of pilot testing 1600 thousand tons of oil, 4250 million cu m of gas and 13000 thousand tons of fluid have been produced and 60 million cu m of water has been injected.

Taking into account production rates of oil, gas and water and water as well as leaking beyond the area

boundaries, the cumulative compensation of fluid production over injected water is estimated to be 97%. Gas-oil ratio varied, reaching up to 5500 cu m per ton and more. 7 cum of water have been injected per one ton of oil produced. In the average, 37 thousand tons of oil have been produced per one well. Current oil recovery factor was 0.11 at 95% of water cut.

To restrict gas and water production from production wells measures have been taken to produce simultaneously oil from oil bearing zone and gas from the gas cap through special gas wells.

Analysis of results showed that simultaneous gas production from the gas cap leads to oil "encroachment" into the gas-bearing part. It results in irrevocable loss of oil and decrease in oil recovery factor.

In 1993 four horizontal wells were drilled in oil-gas deposits AC₄₋₈. The production data are presented in Table 3.

It should be noted that 3 horizontal wells have no clay streaks near the water-oil contact and one well have no clay streaks near the gas-oil contact.

In general, at the initial stage horizontal wells have higher production (20 tons of oil per day and 163 tons of fluid per day) in comparison with vertical wells (5.3 tons of oil and 132 tons of fluid). However, an experience in oil production through horizontal wells is not sufficient to make a final conclusion as to efficiency of these technologies.

Conclusions

1. Barrier water flooding together with pattern and block flooding allows to develop effectively extensive under-gas zones if thickness of an oil-bearing part of a reservoir is small.
2. As to efficiency of development, presence (or absence) of clay streaks at gas-oil and water-oil contacts plays a big role.
3. When developing an extensive under-gas zones of gas-oil fields (having permeability of $500 \cdot 10^{-3} \mu\text{m}^2$ and oil viscosity of 1.5 mPa·s) it is effective to use two-side barrier water flood, considering under-gas zones as separate parts for development. This will provide for oil recovery factor of 0.30-0.37.
4. For less productive pools (such as the Lyantorskoe field) it is more effective to use pattern water flooding combined with barrier water flooding. Such field development system provides for oil recovery as high as 0.2-0.3.
5. In case of development of extensive under-gas zones with low-permeable monolith objects, having rather big gas-bearing thickness of a reservoir (more than 5 m in the Fyodorovskoe oil field) the above mentioned systems does not give desirable effect. Wells operation is accompanied by production of

large volumes of gas and water. Oil recovery factor under these conditions does not exceed 0.10-0.15. In this case it is promising to use and test horizontal wells, taking into account geological structure and conditions of fluid occurrence.

Table 1

Characteristics of oil-gas pools in West Siberia

Field, production pay	α	Heith of pay, m	Coefficients, fractions			Permeabi lity 10^{-3} μm^2	Net thick ness, m	Viscosity mPa.s	k h/ μ , D cm/ mPa s	At maximum oil production			Pressure, MPa		Planned oil rec.	Estimated oil recovery	Development system
			sand ratio	layer ratio	discon tinuity					oil flow rate	fluid flow rate	water cut %	initial	satur ation			
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Samotlor AB ₂₋₃	4.7	75	0.39	5.9	0.411	518	8.5	1.51	291	78.9	167.8	53.0	17.3	11.6	0.45	0.4-0.44	barrier block water-flood
Samotlor AB ₂₋₃ under-zone	4.7	75	0.39	5.9	-	491	-	1.51	277	75.0	155.9	51.9	17.3	11.6	0.30	0.25	two-side water- flood
Samotlor AB ₁	9.7	75	0.48	4.0	0.02-0.2	119	7.0	1.45	57	71.62	106.9	33	17.6	10.3	0.5	0.34	barrier block water flood
Lyantorskoe AC ₉₋₁₁	51.0	15	0.74	2.7	0.039	300	5.5	6.35	26.0	29.5	54.09	43.7	21.0	14.2	0.36	0.11-0.15	9-spot pattern 16h/w and square pattern
Lyantorskoe AC ₁₀ (1-12 elements)	54.0	15	0.67	4.0	0.039	574	9.1	5.56	94.0	29.5	58.7	24.3	21.0	16.6	0.33	0.25	ditto
Fyodorovskoe AC ₄₋₈ (I-IV elements)	52	11	0.56	5.7	-	209	8.6	5.41	33.0	30.1	122.1	64.0	18.8	14.8	0.299	0.12	5-spot pattern 600 x 600 m

Table 2

Lyantor Field, W.Siberia: Production data

Element number	Oil in place, Thous. cum	Cumulative production Thous. cum		Cumulative water injection Thous. cum	Oil recovery factor
		oil	fluid		
I	609.4	174.3	334.9	405.6	-
II	814.8	234.6	320.3	190.9	-
III	677.5	187.2	503.7	1001.8	0.295
IV	649.4	161.6	293.8	18.5	0.358
V	722.5	267.0	723.6	1074.4	0.380
VI	1142.8	303.4	836.0	1340.3	0.280
VII	1339.5	310.9	704.8	1022.3	0.290
VIII	1392.5	345.5	833.8	1261.9	.295
IX	1390.4	474.8	939.0	741.4	0.400
X	1140.2	412.4	845.3	0	0.415
XI	1387.4	383.6	988.9	1414.2	0.300
XII	1186.5	266.1	804.8	839.6	0.243
For whole area	12453.0	3521.4	8128.7	9310.8	0.323

Table 3

The Fydorovskoe oil Field: Characteristics of horizontal wells

Presence of clay streaks at GOC/WOC m	Distance of horizontal bore hole from GOC/WOC m	Length of horizontal part of well, m	Cumulative production, thousand tons		Flow rate, ton per day		Water cut, %	Gas production, thousand cu m
			oil	fluid	oil	fluid		
6.9/0	6/6	50	14.5	103.5	29.9	292.7	85	665
3.0/0	4-6/6-8	220	11.0	113.5	12.8	333.8	95	498
2.2/0	6-7/3-5	132	9.0	11.8	31.0	58.0	47	415
0/3-4	8/5	70	27.7	50.4	109.0	227	52	1272

Fig. 1 Samotlor oil field, AB2-3, Central part: Well location

- ✕ designed producing and injection wells
- ✕ operated producing and injection wells
- v- external GOC - areas boundary
- ^-- internal GOC

Fig.2 Samotlor oil field (South - east part): Reserves withdrawal in the common occurrence of AB1³ and AB2-3

1,2 - gas bearing and oil bearing sandstone, 3 - sandstone under injection, 4 - clay, 5 - oil bank, 6,7 - perforated intervals in which gas is replaced by fluid, 8,9 - barrier wells, observation wells, 10 - initial GOC

Fig. 3 Samotlor oil field, AB₂₋₃, : Estimated (1) and actual (2) production data

--- 1 ----- 2

Fig.4 Samotlor oil field, AB₁₃: Production history

Fig. 5 Lyantor oil field, AC₁₀: Well location

○ production wells	— x — external GOC
⊙ wells, perforated in oil & water zones	- - - internal GOC
⊕ injection wells	○—○ boundary of area
⊞ wells, perforated clean oil and oil & water intervals	

Fig.6 Lyantor oil field: Cross section

Reservoir:

	gas saturated
	oil saturated
	water saturated
	clay
	tight

Wells:

▽	injection
▲	production
	perforation interval

Fig. 7 Fyodorovskoe oil field, AC₄₋₈: Cross section