Effectiveness of compaction of the initial well grid in the late stage of oil and gas field development

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Abstract. The Kruk oil and gas field development is characterized by its geological structure and various technological indicators. A comprehensive evaluation of the field's properties has allowed for the determination of recoverable oil reserves using water-based oil displacement techniques. Two scenarios were considered for field development: one with an initial well mesh and another with a densified well grid. The results demonstrated the high efficiency of well grid densification during the later stages of field development. This optimization strategy led to a notable increase in the rate of oil withdrawal and enhanced the recovery of geological reserves. The densification of the well grid improved the overall efficiency of oil production and contributed to maximizing the extraction of available oil reserves. The findings highlight the importance of employing advanced technological strategies to enhance oil and gas field development. By carefully considering the geological structure and implementing well grid densification when appropriate, it is possible to optimize oil recovery, increase productivity, and effectively utilize the available geological reserves in the Kruk field.

1. Introduction

The current values of the oil recovery factor (ORF) of oil and gas fields depending on geological and geophysical conditions and the development system applied vary within a very wide range from 0.1 to 0.7 [1]. In this connection the main problem of the oil-and-gas producing countries is to increase the degree of recovery of the residual geological reserves of the fields under development, because their volumes considerably exceed the forecast reserves of all the oil-prospective regions of the planet Earth [2].

In existing methodologies for calculating oil and gas field development indicators, one of the main parameters determining the oil recovery rate and oil recovery factor is the density of the well grid and well placement patterns [3, 4].

Oil-and-gas fields are usually developed under prevailing water-stress, gas-stress or simultaneous manifestation of both regimes [5]. It is known that in developing a field using oil displacement technology with various agents, the ORF is calculated according to the modified formula of A. N. Krylov.

When developing fields with heterogeneous reservoirs, the value of K is mainly influenced by the density of the grid of wells and their placement schemes. Therefore, in a number of works, this coefficient is called *a grid factor* [2], the value of which depends on the density of the adopted grid of wells (S - oil-bearing area per one well), on zonal heterogeneity and discontinuity of oil reservoirs [6].

Due to great practical importance of this question many scientists and scientific centres have conducted researches on determination of dependence of oil recovery from density of wells net (NWD) [7]. There were obtained many specific dependences of different types for specific fields, which do not allow to explain the reason of difference in degree of ORR reduction as the density of well-set decreases in different mining and geological conditions of fields and used systems of development. These dependencies were not widely used because they did not take into account the parameters of heterogeneity and discontinuity of formations, and therefore they did not have a universal character [8, 9].

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Application in practice did not always give adequate ORF value in real conditions of oil and gas reservoir development. As a result, there is a need to study the effect of SAR on EOR on materials of long-developed fields, to evaluate their effectiveness, to clarify and update the main criteria for the process implementation.

2. Materials

The Kruk field is located within the Spanish-Chandyr uplift, which is one of two major tectonic elements of the southeastern part of the Chardzhou tectonic stage.
The productive Upper Jurassic reservoir at the Kruk field is represented by a rounded reef massif with cross-sectional dimensions of 3.4 km x 3.5 km and heights from 180 m to 240 m. The vaulted portion of the massif is offset to the north-east from the centre and is in the area of wells #1, 11e, 20, 26, 61 and 59. In this most elevated area of the reef, asymmetrical local folds emerge along the -2072 m isohypse: one of them is bounded by wells Nos. 11e, 20,26 and 61, while the other is in the area of wells Nos. 59, 14 and 66 (Figure 1).
In general, the surface of the reef massif is a very irregular structural shape, with numerous bays and protrusions [10]. The predominant strike directions of these bays and protrusions are west-east and south-west-northeast. Dips on the slopes of the reef and reach 40° to 50°. In the north-western part of the reef, in the area of wells Nos. 10, 97, the slope is steeper.

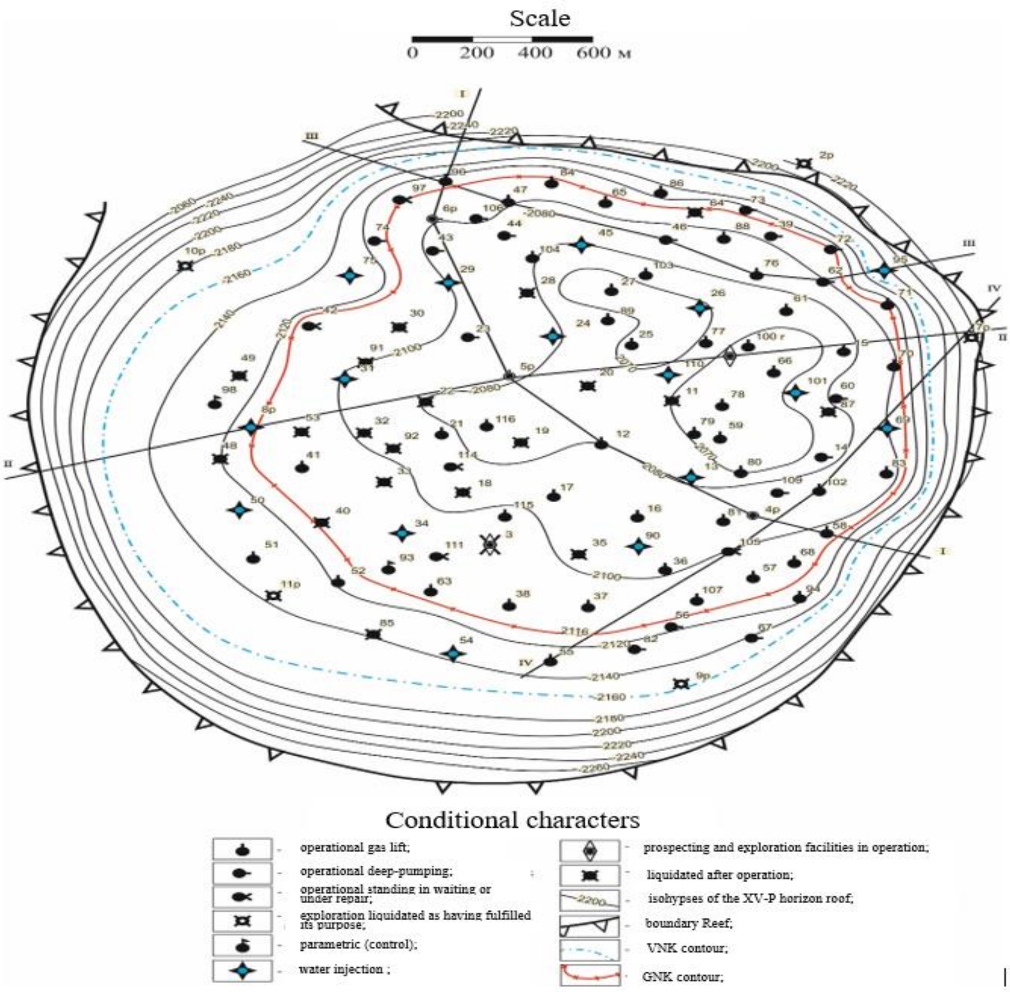

Fig. 1. Kruk field: structural map of the Jurassic carbonate horizon top XV

The surface structure of the XV-P horizon is no longer as detailed as that of the XV-HP horizon due to the large number of production wells penetrating the roof of the Upper Jurassic carbonates, but not always reaching the top of the XV-R horizon.

The surface of the XV-P horizon is represented by a series of domed developed predominantly on the periphery of the reef massif in its eastern and south-eastern parts. The highest absolute levels of the top of the XV-P horizon are recorded in wells Nos. 45, 76, 15, 78 and 87 (-2093 m -2101 m). To the west and south-west of these folds absolute elevations of the topography of the XV-P horizon decrease and in the areas of two bay-like depressions, penetrating from the west and south-west into the territory of the reef massif, reach -2174 m and -2188 m. These two gulf-shaped depressions of the absolute level of the top of the XV-P horizon delineate the level of the surface in question and range from -2144 m to - 2168 m.
The Kruk oil and gas reservoir is confined to the upper half of the reef massif and is of the massive, underlying water type. The position of the GOC and WOC surfaces has been fairly reliably determined by field geophysical surveys and well sampling data. The indicated surfaces are practically horizontal planes at -2116 m and -2160 m, respectively. At these NOC and WOC levels, the oil-bearing level is 44 m, the gas-bearing level is 49 m and the total oil-bearing level is 93 m. The main volume of the reservoir is occupied by the stratified structure (XV-HP horizon); the massive part of the reservoir (XV-P horizon) is involved in oil and gas accumulation only in the north-eastern half of the productive area. The massive part of the reservoir (108.4-10^6 m^3) significantly exceeded the stratified part (71.5-10^6 m^3) in terms of volume of oil-and-gas-saturated rocks.

3. Methods

A study of the effect of EOR on EOR is impossible without the use of statistical methods that allow not only to state facts but, most importantly, to elucidate the reasons why the effect of EOR on EOR varies in different mining and geological conditions of oil reservoirs.
There is now a wealth of material on late- and late-stage reservoirs, and a synthesis of the actual data on these fields is of particular value in addressing many of the debates on the impact of technological solutions on the efficiency of the development systems that have been put in place. To assess the effectiveness of densification of the well grid, the incremental final oil recovery factor was used, defined as the difference in the oil recovery factor achieved before and after the change.
It should be noted that this factor is an integrated indicator that characterises reservoir and reservoir fluid properties, development system and economic criteria. To determine the recoverable oil reserves of the selected periods of oil reservoir development, the characteristics of displacement proposed [6] have been used, as this method is the most preferable from the point of view of providing accuracy of calculations (up to 2.6 %) [5].
Oil reserves (Q (∞)), which can be extracted from the reservoir at Q_j ∞ and if the reservoir development system is maintained, were determined using the oil displacement characteristics. The value of coefficient "c" corresponds to the value of recoverable oil reserves at infinite reservoir flushing.
In accordance with the methodological guidelines for calculating oil recovery factors from the subsurface, final straight line segments were drawn on the water displacement characteristics of the study sites to determine the initial recoverable oil reserves for the allocated oil recovery periods. Let us consider the results of applying this methodological approach to assess the effectiveness of increasing SAR in the Kruk oil and gas field.

4. Results and discussion

The development targets in the Kruk field are the productive XV-P and XV-HP horizons. Although the filtration-volume properties of the reservoirs differ slightly, given the massive reservoir structure, the proximity of the reservoir horizons in the section, the identical fluid properties and the hydrodynamic connection between them, the XV-P and XV-HP horizons are combined into a single development target. Accordingly, where XV-P is missing, only the XV-HP horizon is exploitable.
The main geological and physical characteristics of the productive horizons shown in Table 1, compiled on the basis of development project materials, at UzLITIneftgaz JSC.
The oil and gas condensate parts of the reservoir are brought into development in a system of simultaneous development [7]. Since May 1986 the oil part of the Kruk field has been in pilot operation in accordance with the Trial Production Project drawn up by SredazNIPIneft Institute. Wells #3 and #4 were put into trial production with flow rates of 6 tpd and 24 tpd respectively.
The analysis of oil production dynamics shows that with increasing fund of producing wells up to 83 units annual production volumes have been steadily increasing and reached 290.0 thousand tons per year by 1998 (Figure 2).
Subsequently, due to an increase in watercut, by the end of 2005 annual production from the field was 181,200 tonnes, with a producing well stock of 58 wells. During 1986-2005 the field produced only 3962.5 thousand tons of

oil, or 26.67% of its initial geological reserves. Average rate of oil extraction for the period was 1.34%, with its maximum in 1998 - 1.94%, and in 2005 it lowered to 1.22% (of initial geological reserves).
Consequently, in order to increase the rate of oil extraction, densification of the original grid density was initiated in 2006 by increasing the oil production well stock from 58 to 74 wells in 2010. Grid densification has resulted in an increase in the oil recovery rate to 2.0%.

Table 1. Geological and physical characteristics of producing formations.

Parameter name	Objects		
	XV-HP	XV-P-I	XV-P-II
Average depth of the roof, m	2450	2450	2450
Type of deposit	NG	NG	NG
Collector type	К	К	К
Oil and gas bearing area, $1 \cdot 10^3$ m^2	4769	1370	2064
Average total thickness, m	49.48	70.08	36.1
Permeability μm^2	0.196	0.162	0.196
Formation temperature, ºC	106	106	106
Reservoir pressure, MPa	25.1	25.1	25.1
Oil viscosity under reservoir conditions, mPa·s	1.08	1.08	1.08
Oil density in reservoir conditions, kg/m^3	801.2	801.2	801.2
Volume factor, fractions of units.	1.19	1.19	1.19
Sulphur content of oil, %	2.18	2.18	2.18
Wax content of oil, %	1.34	1.34	1.34
Oil gas saturation pressure, MPa	6.9	6.9	6.9
Gas factor, m t^3	-	-	-
Stable condensate content, kg/m^3	198.00	198.00	198.00
Viscosity of water in formation conditions, kg/m^3	1.00	1.00	1.00
Average productivity, m /dayMPa^3	1010	1010	1010
Displacement coefficient, fractions of units	3.7	12.9	5.0

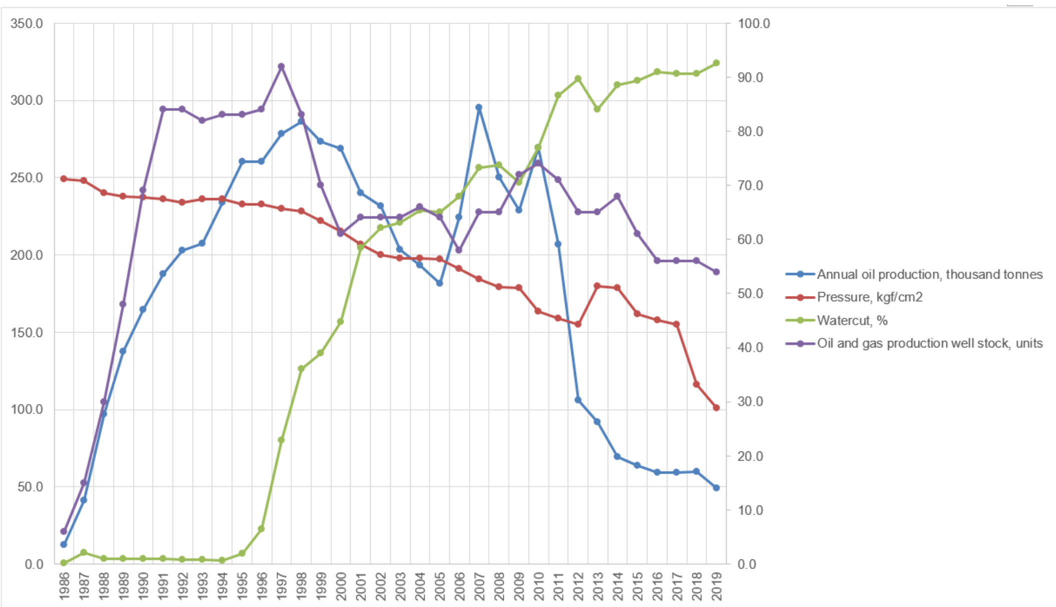

Fig. 2. Dynamics of technological indicators of Kruk field development.

In order to determine the incremental oil recovery from densification of the well grid, an oil displacement characteristic is plotted in Fig. 3 using oil and fluid sampling data (Table 2).

As a result of processing of straight sections of displacement characteristic, the recoverable oil reserves were determined for the case of Kruk field development with initial and compacted grid wells, which were 5980.8 and 7275.4 thousand tons respectively.

Table 2. Kruk gas and oil field development indicators used to build the characteristic of the field.

Years	Annual production, '000 tonnes		Accumulated production, '000 tonnes		Qn - Qzh, million t
	Oil, Qn	Liquid, Qj	Oil, ∑Qn	Liquid, ∑Qj	
1986	12.2	12.2	12.2	12.2	148.8
1987	41.0	41.9	53.2	54.1	2 878.1
1988	97.1	98.0	150.3	152.1	22 860.6
1989	137.7	139.0	288.0	291.1	83 836.8
1990	164.8	166.3	452.8	457.4	207 110.7
1991	187.4	189.3	640.2	646.7	414 017.3
1992	203.1	204.7	843.3	851.4	717 985.6
1993	207.5	209.2	1 050.8	1 060.6	1 114 478.5
1994	234.1	235.5	1 284.9	1 296.1	1 665 358.9
1995	260.1	265.4	1 545.0	1 561.5	2 412 517.5
1996	260.6	278.7	1 805.6	1 840.2	3 322 665.1
1997	278.5	360.8	2 084.1	2 201.0	4 587 104.1
1998	286.5	447.6	2 370.6	2 648.6	6 278 771.2
1999	273.4	448.2	2 644.0	3 096.8	8 187 939.2
2000	268.7	486.8	2 912.7	3 583.6	10 437 951.7
2001	240.1	578.6	3 152.8	4 162.2	13 122 584.2
2002	231.5	610.8	3 384.3	4 773.0	16 153 263.9
2003	203.5	551.5	3 587.8	5 324.5	19 103 241.1
2004	193.4	559.0	3 781.2	5 883.5	22 246 690.2
2005	181.2	517.7	3 962.4	6 401.2	25 364 114.9
2006	224.5	701.5	4 186.9	7 102.7	29 738 294.6
2007	295.4	1 106.4	4 482.3	8 209.1	36 795 648.9
2008	250.0	847.4	4 732.3	9 056.5	42 858 075.0
2009	229.0	776.3	4 961.3	9 832.8	48 783 470.6
2010	269.3	1 170.6	5 230.6	11 003.4	57 554 384.0
2011	206.8	1 543.3	5 437.4	12 546.7	68 221 426.6
2012	105.8	1 071.3	5 543.2	13 618.0	75 487 297.6
2013	91.8	577.4	5 635.0	14 195.4	79 991 079.0
2014	69.4	608.8	5 704.4	14 804.2	84 449 078.5
2015	63.8	596.3	5 768.2	15 400.5	88 833 164.1
2016	59.1	649.4	5 827.3	16 049.9	93 527 582.3
2017	59.4	638.7	5 886.7	16 688.6	98 240 781.6
2018	59.6	640.8	5 946.3	17 329.4	103 045 811.2
2019	49.0	662.2	5 995.3	17 991.6	107 865 039.5

At the same time, specific recoverable oil reserves per one well before and after compaction of SAR were 103.1 and 98.3 thousand tons, respectively, and on compaction wells were 802.9 thousand tons. This fact testifies that part of compaction wells were drilled in areas covered by drainage process with initially placed wells. The received results testify to the fact, that the efficiency of drilling wells in many respects depends on reasonable definition of zones, not covered in the process of drainage by initial fund of wells. Drilling of new wells in zones, covered by draining of earlier drilled wells, leads, as in our case, to reduction of specific recoverable reserves and relatively smaller increase in ORF. For considered two scenarios of Kruk oil and gas field development the calculated final EOR were 40.56% and 49.34%, i.e. 21.6% increase in SAR resulted in 8.78% increase in final EOR.

The results show that the issue of identifying undrained zones of deposits is an urgent task, as it largely determines the choice of strategy for recovering residual oil reserves. Due to the complexity of the nature and mechanism of formation in different geological and physical conditions, different methods are used to identify undrained zones of deposits. Methods for identifying undrained zones.

The following four groups can be conventionally grouped: those based on the volumetric reserves estimation formula; those based on well interaction studies; those based on water displacement characteristics and computerised geological and engineering modelling. Each group of methods has its own advantages and disadvantages. The most reliable are the results of extraction of undrained zones, which are based on geological-production data processing by computer simulation program DV-600, VIP, SigmaProx, Trias, Tempest, Eclipse, Landmark, MORE, etc. [8-10].

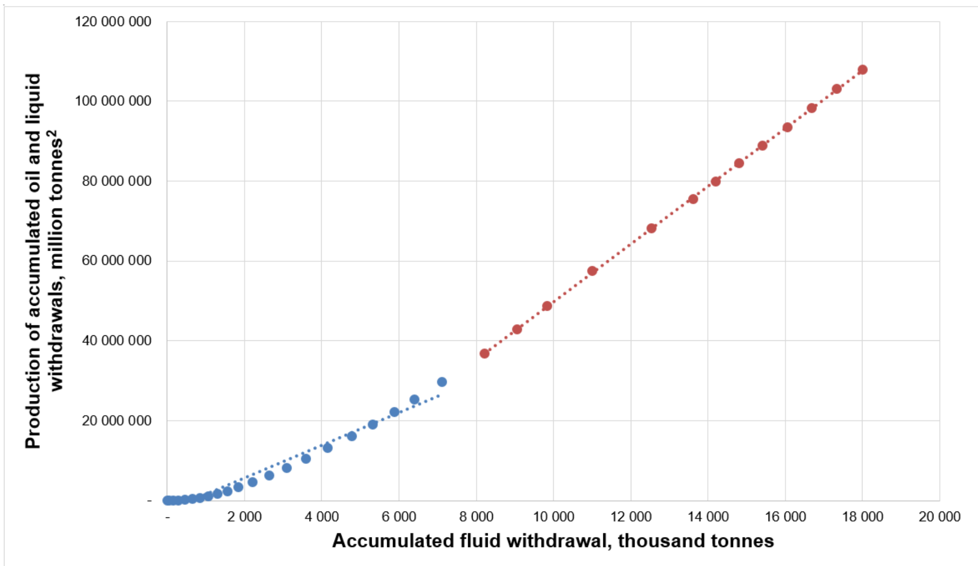

Figure 3. Characteristics of oil displacement by water in the Kruk gas and oil field.

5 Conclusions

As a result of analysis of the results of densification of the well grid at Kruk field, the following conclusions are formulated which have certain scientific and practical value for planning of measures on increase of development efficiency and increase of the oil recovery factor of the objects with similar geological structure:

- The drilling of new wells in areas covered by the drainage of previously drilled wells leads to a decrease in the average specific recoverable oil reserves per well, in the considered case from 103.1 to 98.3 thousand tonnes. At the same time, the average specific recoverable oil reserves per one new well were 80.9 thousand tonnes;
- In our example, 21.6% increase in well stock resulted in increase in ultimate TOC from 40.56% to 49.34%, i.e. 8.78%;
- The effectiveness of drilling sealing wells depends to a large extent on reasonably identifying zones not involved in the process of drainage by the existing stock of wells.

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