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PROSPECTS AND CURRENT STATE OF CHEMICAL EOR METHODS APPLIED IN KAZAKHSTAN

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ABSTRACT

At present, at almost all fields of the Republic of Kazakhstan the main technology of oil recovery enhancement is the traditional method of waterflooding of productive formations. Many oil and gas fields in Kazakhstan are at a late stage of development and are categorized as «mature» fields. In the global experience of mature field development, the key focus is on the application of enhanced oil recovery (EOR) techniques - chemical, thermal, gas and microbiological methods. This paper considers the application of chemical EOR at a number of Kazakh fields such as Zaburunye, North Buzachi, Kalamkas, East Moldabek. As the results of the pilot studies have shown, the most effective EOR here is the application of polymer flooding. It should also be noted that polymer flooding is successfully applied in Kazakhstan for high-viscosity oil fields such as North Buzachi (oil viscosity 316-417 mPa·s), East Moldabek (oil viscosity 246-377 mPa·s). In this case, water cut, smoothing of injectivity profile and, as a result, increase of oil production is achieved. Successful application of the technology largely depends on the parameters of physical and chemical impact at each stage - the volume of injection of gel-polymer composition, concentration of ingredients, the flow rate of filtered water, the presence and linear size of cracks, the permeability of pore channels and etc. Polymer flooding applied in Kazakhstan showed its technological and economic efficiency on the example of pilot tests, laboratory studies, which reduces water cut and increases oil production. Widespread use of EOR methods would allow increasing recoverable oil reserves by at least 5-10 %.

Keywords: Enhanced Oil Recovery (EOR); gas Injection; hydrocarbon recovery methods; chemical EOR methods; thermal EOR methods; oil production; polymer flooding; oil recovery.

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1. Introduction

Kazakhstan has large reserves of hydrocarbon resources and holds one of the leading positions in the world in terms of oil reserves. According to British Petroleum estimates, Kazakhstan ranks 12th with proven reserves of 3.9 billion tons or 30.0 billion barrels of oil, representing 1.7% of the world's reserves and 2700 billion m³ of gas [1]. According to the Statistical Review of World Energy BP report oil production [1] in 2022 was 84.1 million tons and gas production 34.1 billion m³.

The main oil reserves in Kazakhstan are concentrated in 15 major fields - Tengiz, Kashagan, Karachaganak, Uzen, Zhetybai, Zhanazhol, Kalamkas, Kenkiyak, Karazhanbas, Kumkol, Northern Buzachi, Alibekmola, Central and Eastern Prorva, Kenbai, Korolevskoye, of which half are in two giant oil fields: Kashagan and Tengiz (fig. 1,2) [2-3].

At present, at almost all fields of the Republic of Kazakhstan the main technology of oil recovery enhancement is the

traditional method of waterflooding of productive formations. Many oil and gas fields in Kazakhstan are at a late stage of development and are categorized as «mature» fields [4]. In the global experience of mature field development, the key focus is on the application of enhanced oil recovery (EOR) methods - chemical, thermal, gas and microbiological [5-24].

According to statistical data, the most common methods of enhanced oil recovery in the world in the period from 1971 to 2017 were chemical, gas and thermal methods (fig. 3) [19, 20]. As can be seen from the diagram in figure 3, today the use of gas methods prevails: injection of CO₂ and other gases. Since 1974, the «Worldwide EOR Survey» published every two years in the Oil & Gas Journal has been one of the systematic and accessible statistical resources on EOR projects in the world [21-24], which reflected the results of EOR projects.

Gas injection EOR is used in countries such as the USA, Brazil and Canada [19-26]. On a per-country analysis, it can be observed that the most common EOR used in the USA is CO₂ injection especially for carbonate rocks with low permeability/injection capacity [25]. This is due to

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the availability of natural sources of CO₂. According to an updated study, the incremental oil recovery due to CO₂ enhanced oil recovery in the US in 2020 was about 273 thousand bpd, which is about 9% less than the 2019 study (299 thousand bpd) [26].

The use of thermal EOR is dominated in countries such as the USA, Oman, China, Canada, and Indonesia [27-28]. Venezuela, Russia, Kazakhstan, Mexico, Colombia and India can also be pointed out.

China, Canada and India take the leading position in the application of chemical EOR [19]. Statistics showed that international EOR oil production accounted for only 3.3% of total oil production, while in China, in 2014, EOR oil production was nearly 17% of total oil production, and in 2016, oil production by chemical flooding and thermal

recovery reached 54.66% and 44.53%, respectively [19].

This paper considers the application of chemical EOR at a number of Kazakhstani fields such as Zaburunye, North Buzachi, Kalamkas, East Moldabek. Wide application of EOR would allow to increase recoverable oil reserves by at least 5-10% [19].

2. Screening analysis of EOR application at a number of Kazakhstani fields

The global petroleum industry has a wealth of experience in the application of EOR. Different conditions, geological and geographical, require a systematic analysis of the applicability of EOR. For screening of enhanced oil recovery methods, we considered the works of authors Taber et al. 1996, 1997, which presented the results of successful EOR projects, covering 633 EOR projects, which were published in «The Oil and Gas Journal» from 1998 to 2008 [29-31]. Later, the work of Taber et al. was updated by Aladasani and Bai, 2010, who summarized the results and included new methods of enhanced oil recovery from EOR projects (table 1) [32].

Table 2 presents the results of screening analysis of a number of Kazakhstani oil fields by applicability criteria according to [32]. The most promising and favorable for the application of EOR for implementation in the fields of Kazakhstan are selected, and it is possible to compare the results of screening with the results of pilot tests (PT) of a number of Kazakhstani fields.

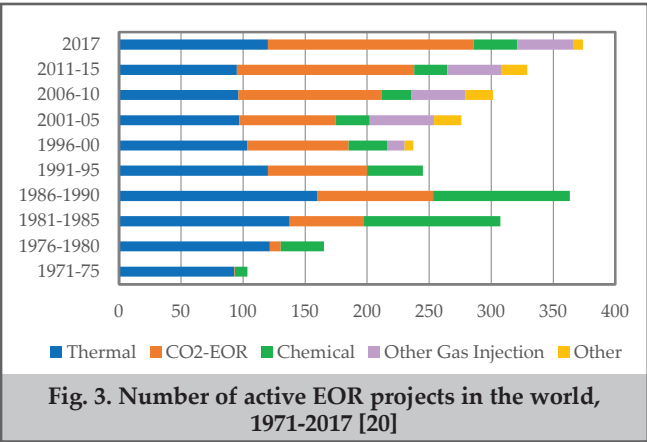
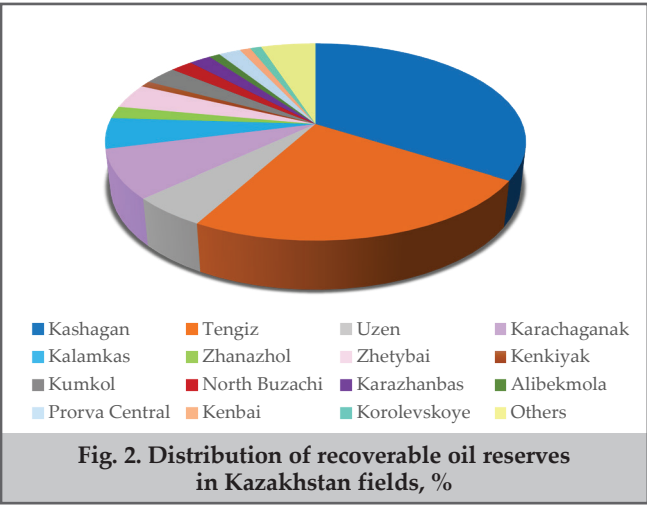


Table 2 Results of screening of EOR application at several fields in Kazakhstan				
EOR Method \ Oil field	Zaburunye (II neocom)	Northern Buzachi	Kalamkas (J-III)	East Moldabek (M-I)
Miscible Gas Injection				
CO ₂	-	+	+-	-
Hydrocarbon	-	-	+	+
WAG	-	-	-	-
Nitrogen	-	-	-	-
Immiscible Gas Injection				
Nitrogen	+	-	+	+
CO ₂	+	+	+	+
Hydrocarbon	-	-	-	-
Hydrocarbon + WAG	-	-	-	-
Chemical				
Polymer	+	+	+	+
Alkaline Surfactant	+	+	+	+
Polymer (ASP)	-	-	-	-
Surfactant +P/A	-	-	-	-
Thermal				
Combustion	+	+	-	+
Steam	-	+	-	+
Hot Water	-	+	-	-
Microbial				
Microbial	+	-	+	-

Note: + favorable to the application; - not applicable

EOR screening criteria for specific oil properties and reservoir characteristics [32]										Table 1
Oil properties				Reservoir properties						
EOR method	# Projects	Gravity, (kg/m³)	Viscosity, (cP)	Oil Saturation, (% PV)	Formation Type	Porosity, %	Permeability, (mD)	Net Thickness	Depth, (m)	Temperature, (°C)
Miscible Gas Injection										
CO ₂	153	801.7-921.8	0-35 Av.2.1	15-89	Sandstone or Carbonate	3-37	1.5-4500	Wide range	457-4074	28-125
Hydrocarbon	70	750.7-915.9	0.04-1800 Av. 286.1	30-98	Sandstone or Carbonate	4.25-45	0.1-5000	Thin unless dipping	1231 [1219]-4846 (1295-2057)	29-165
WAG	3	829.9-860.2 Av.844.8	0.3-0.9 Av.0.6	-	Sandstone	11-24	130-2000 Av.1043.3	NC	2300-2708.7 Av.2504	90-123 Av.110
Nitrogen	3	762.8-834.8 [849.8] Av.788.3	0-0.2 Av.0.07	0.76 [0.4]-0.8 Av.0.78	Sandstone or Carbonate	7.5-14	0.2-35 Av.15.0	Thin unless dipping	3048 [1829]-5639 Av.4460	87-163 Av.130
Immiscible Gas Injection										
Nitrogen	8	762.8-959.3 Av.849.8	0-1800 Av.2256.8	47-98.5 Av.71	Sandstone	11-28	3-2800 Av.1041.7	-	518-5639 Av.2412	27-163 Av.78
CO ₂	16	849.8-993.0	0.6-592 Av.65.5	42-78	Sandstone or Carbonate	17-32	30-1000	-	350-2591 (716-1570)	27-92
Hydrocarbon	2	788.3-921.8 Av.849.8	0.25-4 Av.2.1	75-83 Av.79	Sandstone	5-22	40-1000 Av.520	-	1828-2134 Av.1981	76-82 Av.79.4
Hydrocarbon + WAG	14	820.3-1004.9 Av.870.8	0.17-16000 Av.3948.2	Av.88	Sandstone or Carbonate	18-31.9	100-6600 Av.2392	-	807-2804 Av.2200	55-131 Av.93
Chemical										
Polymer	53	892.7-979.2	0.4-4000 Av. 123.2	34-82	Sandstone	10.4-33	1.8-5500	NC	[1287-2883]	75-114
Alkaline Surfactant Polymer (ASP)	13	849.8-934.0	11-6500 Av. 875.8	35-74.8	Sandstone	26-32	10-1520	NC	[909-2743]	50-93.3
Surfactant +P/A	3	829.9-921.8 Av.870.8	3-15.6 Av.9.3	43.5-53 Av.48	Sandstone	16-16.8	50-60	NC	190-1615 Av.897	50-68 Av.59
Thermal										
Combustion	27	834.8-1000	1.44-2770 Av.504.8	50-94	Sandstone or Carbonate	14-35	10-15000	[>10]	121-3444	18-110
Steam	271	860.2-1014.3	3-5E6 Av. 32971.3	35-90	Sandstone	12-65	1-15000	[>20]	60-2743	-12-177 Av.40.5
Hot Water	10	904.2-986.1 Av.942.7	170-8000 Av.2002	15-85 Av.58.5	Sandstone	25-37	900-6000 Av.3346	-	152-900 Av.592	23-57 Av.37
Microbial										
Microbial	4	860.2-986.1 Av.895	1.7-8900 Av.2977.5	55-65 Av.60	Sandstone	12-26	180-200 Av.190	-	479-1056 Av.745	30-33 Av.31

3. Chemical EOR methods used in Kazakhstan

Chemical enhanced oil recovery is based on two main mechanisms - macroscopic efficiency enhancement and microscopic displacement efficiency enhancement. Macroscopic efficiency can be improved by polymer flooding. Pumping polymer solution increases the viscosity of the displacing fluid and reduces its effective permeability to water [33-36]. Microscopic displacement efficiency can be enhanced by alkali and surfactant injection by several mechanisms: reduction of interfacial tension (IFT), emulsification of oil and water, solubilization of interfacial films, changes in wettability, etc. The oil recovery efficiency of different methods varies widely because it depends on both reservoir fluid and rock properties, including reservoir pressure and temperature [34]. Economic parameters depend on the oil price, the cost per barrel of injected solution and the chemical injection period [37].

Surfactant flooding involves sequential injection of surfactant rim, polymer rim (25-100% of PV), and displacement water. It is noted that it is necessary to individually select the composition of the rims and concentrations of chemical reagents.

Pure polymer flooding is designed for more viscous oils than surfactant flooding, where polymer is used to equalize the surfactant front. It is recommended to use polymer flooding in reservoirs with heterogeneity in filtration properties of 10 and more times [32]. In Kazakhstan, polymer flooding has been used in high-viscosity oil fields such as North Buzachi (oil viscosity 316-417 mPa·s), East Moldabek (oil viscosity 246-377 mPa·s).

Alkaline flooding requires the presence of naphthenic acids in the oil. This is usually found in oils with low density and relatively high viscosity.

Complicating factors for the use of chemical EOR methods are:

- fractures - rapid breakthrough of the chemical rim without doing any effective work;
- presence of gas cap and bottom water - a common complicating factor causing gas and water breakthroughs into production wells;
- high clay content of the formation - increase adsorption of surfactants, polymers, as a result less part of chemical reagents performs effective work.

In Kazakhstan pilot tests of chemical EOR were conducted at the following fields: North Buzachi, Kalamkas, Uzen, Zaburunye, East Moldabek. Including laboratory studies on the selection of EOR of fields of high-viscosity oils with viscosity of 30 mPa·s and higher showed the effectiveness of thermal EOR - hot water injection and polymer flooding - the displacement ratio increased from 12.9% to 30.3% and 18.9%, respectively [34,38]. Laboratory studies using core from the Kazakhstani field showed the effectiveness of chemical EOR [34, 39].

Zaburunye field. The Zaburunye gas and oil field was discovered in 1981. In terms of recoverable oil reserves, the field is classified as medium-sized and has a complex geological structure [39]. The main productive horizon is the II-ne horizon. The II Neocomian horizon lies in the depth range of 889-960 meters. The thermobaric conditions are as follows: the average temperature and formation pressure of the Neocomian II horizon 38.7 °C and 9.30 MPa, respectively; the oil viscosity in formation conditions averages 15.3 mPa·s (table 3).

According to the results of pilot industrial tests (PIT), since 2017, work has been underway to expand the polymer flooding technology [39].

According to the results of calculation of polymer flood-

Table 3 Geological and physical characteristics of the Neocom II horizon of the Zaburunye field	
Parameter	Mean value
Average depth, m	903
Reservoir type	sandstone
Porosity, unit fraction	0.303
Average oil saturation, unit fraction	0.638
Average permeability, D	0.526
Initial reservoir temperature, °C	38.7
Initial formation pressure, MPa	9.3
Bubble point pressure, MPa	5.4
Oil viscosity in reservoir conditions, mP·s	15.3
Oil density at reservoir conditions, g/sm ³	0.811
Oil density at surface conditions, g/sm ³	0.895
Formation water viscosity, mPa·s	1.15
Formation water density, g/sm ³	1.092
Total formation water salinity, g/l	137
Geological oil reserves, thousand tons	14839

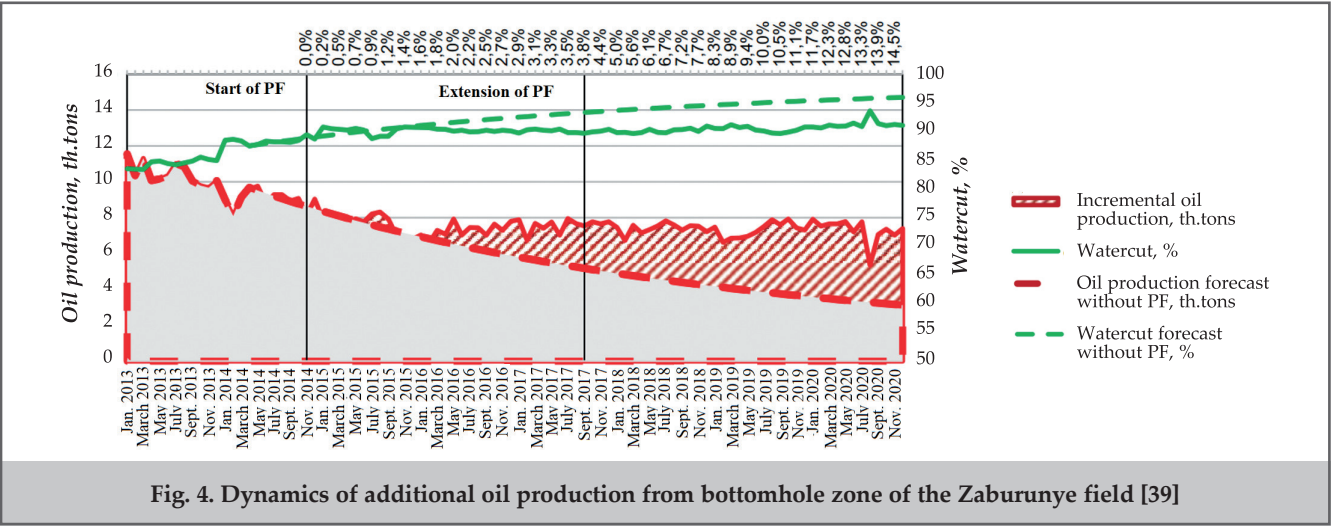


Fig. 4. Dynamics of additional oil production from bottomhole zone of the Zaburunye field [39]

ing (PF) technology efficiency as of 01.01.2021 (fig. 4), the total effect from the beginning of the project implementation is 184635 tons of oil, 14.7% of pore volume pumped, 3640 tons of polymer injected, water cut relative to the base level - 2.0%, additional oil production per 1 ton of polymer - 50.7 tons [39].

Kalamkas field. The Kalamkas field is located in the northern part of the Buzachi Peninsula and is tectonically confined to the northern part of the North-Buzachi arch located at the northwestern end of the Turan plate. The field has two oil-and-gas bearing stages: Cretaceous and Jurassic. The Cretaceous and Jurassic productive strata are separated from each other by a 25-30 m thick clay section. According to the approved project document, 11 main production facilities are identified in the Kalamkas field: horizons J-I, J-II, J-III, J-IV, J-V+VI, J-VII, J-1S, J-2S, J-3S, J-4S, J-5S and a returning object - the J horizon. Table 4 shows geological and physical characteristics of the J-III horizon of the Kalamkas field.

Polymer flooding was first applied in Kazakhstan at the Kalamkas field. In 1981, injection of polymer solution was carried out in formations J-III, J-IV, J-V, and since 1983, a variant of viscoelastic composition-polymer impact was started [40-42].

In the period from 1987 to 1997, pilot works were carried out on formations J-I, J-II, J-III, J-IV. Since August 1987, works on polyacrylamide injection were carried out, and since 1988 a variant of modified polymer impact by injection of PAA and «crosslinking» agents was realized. Since 1991, polymer injection at the Kalamkas field has been discontinued. Reapplication of polymer flooding for enhanced oil recovery in Kazakhstan began in 2014.

The application of polymer flooding (Hydrolyzed Poly-Acrylamide - HPAM) in fields with high water cut and relatively low reserve depletion (as in the Kalamakas field) is a technically and economically effective way to counteract water flows in the highly permeable part of the reservoir and ensure the efficiency of enhanced oil recovery in the highly permeable part of the reservoir and ensure the efficiency of enhanced oil recovery. The oil production increment for all measures for the period 2014-2017 is 93258 tons, and the oil production increment per 1 ton of polymer is 76.6 tons. This method of enhanced oil recovery is promising and requires further development [41].

North Buzachi field. North Buzachi is a gas and oil field in Mangistau Region, Kazakhstan, on the Buzachi Peninsula. It belongs to the North Buzashi oil and gas bearing area. It was discovered in 1975. Deposits at a depth of 300-550 meters. Initial oil flow rates are 3.4-48 m³/day, initial gas flow rates are 25 to 54 thousand m³/day. Oil density is 938-940 kg/m³ (table 5). The field includes two main development objects. The lower one is Jurassic, the upper one is Cretaceous. The depth of the Jurassic reservoirs is 470 meters on average, while the depth of the Cretaceous reservoirs is 340 meters.

Application of gel polymer flooding at the high-viscosity oil field (316-417 mPa·s) North Buzachi started in 2008. Considering the high viscosity of oil in the North Buzachi field (table 3), the application of gel-polymer composition for enhanced oil recovery was an ambiguous task [43-45].

As of 01.01.2015, the technological effect of works on gel polymer flooding, starting from the first stage of injection into well 6103, is estimated at 172.1 thousand tons of additionally produced oil. In general, polymer flooding has shown its technological and economic efficiency on the example of pilot

Table 4 Geological and physical characteristics of the J-III horizon of the Kalamkas field	
Parameter	Mean value
Average depth, m	784
Reservoir type	sandstone
Average oil-saturated thickness, m	9.5
Porosity, unit fraction	0.27
Average oil saturation, unit fraction	0.6
Average permeability, D	0.552
Initial reservoir temperature, °C	38.5
Initial formation pressure, MPa	9.57
Bubble point pressure, MPa	5.4
Oil viscosity at reservoir conditions, mP·s	19.9
Oil density at reservoir conditions, g/sm ³	0.830
Geological oil reserves, thousand tons	640973.0

Table 5 Geological and Physical Characteristics of Production Objects of North Buzachi Field		
Parameter	Object	
	I («Jurassic»)	II («Cretaceous »)
Average depth, m	470	340
Reservoir type	Terrigenous-porous	Terrigenous-porous
Average oil-saturated thickness, m	20.8	13.6
Porosity, unit fraction	0.34	0.33
Average permeability, D	1.55	0.832
Average oil saturation, unit fraction	0.73	0.64
Oil density at reservoir conditions, g/sm ³	0.920	0.923
Initial reservoir temperature, °C	29.7	26
Initial formation pressure, MPa	5.8	4.7
Oil viscosity at reservoir conditions, mP·s	380	414
Bubble point pressure, MPa	3.9	3.62
Geological oil reserves, thousand tons	308874	

tests, laboratory studies, and evaluation calculations on the geological and hydrodynamic model, which reduces water cut and increases oil production (fig.5) [46].

East Moldabek section of the Kenbai field. The Kenbai field is located in the sedimentary strata of the cover between the Biikzhal uplift and the Koskulskiy basement ledge and is associated with the North Kotyrtas and East Moldabek structures, which are part of the Meso-Cenozoic complex of the Embinsk-Sagiz trough of the Caspian Basin. The Kenbai deposit is confined to a hidden-burst type salt dome, the southeastern slope of which is complicated by a salt «cornice». As a result of detailed patch correlation with the results of sampling and field development, 3 productive

horizons were identified in the section of Cretaceous sediments and 7 productive horizons in Jurassic sediments. The Cretaceous horizons are confined to the Neocomian terrigenous sediments of the Lower Cretaceous, while the Jurassic horizons are confined to the terrigenous sediments of the Middle Jurassic. Oil and gas deposits are associated

with the Cretaceous M-I horizon, and oil deposits with the other horizons. All Cretaceous horizons are combined into 3 development objects:

- I object - M-I horizon (formations M-I-A, M-I-B, M-I-B);
- III object - M-III horizon;
- IIII object - horizons M-III+J-I.
- Jurassic objects – horizons J-I-VII.

The Cretaceous objects contain 70% of all geological reserves of the field. The initial geological reserves of M-I horizon are about 41 million tons, initial recoverable reserves - about 15 million tons and the oil recovery factor at the level of 38%, for M-III: Initial geological reserves - about 10 million tons, Initial recoverable reserves - 3.4 million tons and oil recovery factor at the level of 34%. Geological and physical characteristics of Cretaceous objects of East Moldabek section of the Kenbai field are presented in table 6 [47]. Oil deposits by type of natural reservoir are reservoir, vaulted, tectonically and lithologically shielded, identical in structure and shape, and repeat each other in plan. The boundaries of oil-bearing capacity for all horizons are contour waters and tectonic disturbances.

The existing difficulties: complex geological and physical structure of productive formations, presence of gas-oil and water-oil zones, weakly cemented reservoir, low initial formation pressure and high viscosity of oil in formation conditions, abundant sand occurrences caused very low rates of oil production and low degree of oil recovery under the current development pattern.

The results of well operation in Cretaceous objects demonstrate poor efficiency of traditional methods of stimulation (fig. 6).

In August 2019, the polymer waterflooding pilot tests were started at the II site (M-III horizon) by injection wells No. 1, 2. The number of responding production wells - 17 units, included according to the results of tracer studies, which were received in October 2019 at the pilot test site. The list of responding production wells also includes wells located in the second row from injection wells #1, 2.

As can be seen from the dynamics of development indicators (fig. 7), the application of polymer flooding allowed to reduce water cut and increase oil production. In general, the total additional oil production since the beginning of the pilot tests implementation amounted to 9584.2 tons. Total dry polymer consumption is at the planned level and amounts to 180 tons. The polymer flooding pilot studies resulted in an 8.9% decrease of water cut.

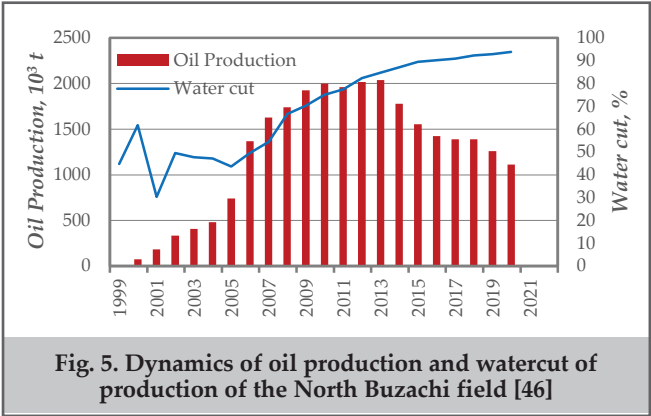
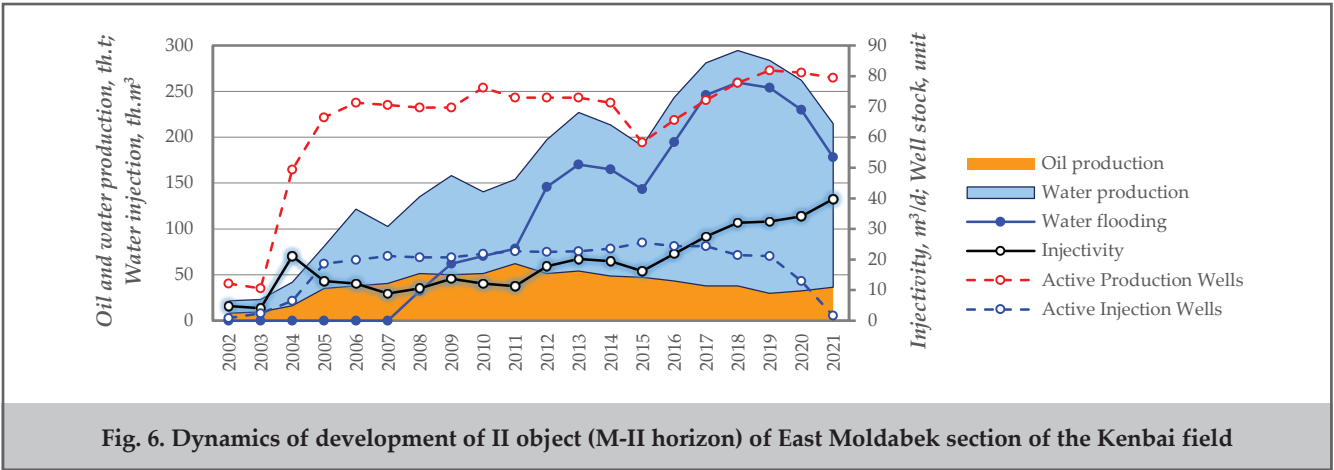


Table 6 Geological and physical characteristics of Cretaceous objects of East Moldabek section of Kenbai field		
Object	I	II
Parameter	M-I	M-II
Reservoir type	Terrigenous	
Average depth, m	277	285
Porosity by core, unit fraction	0.34	0.35
Porosity log-derived, unit fraction	0.34	0.35
Average oil saturation, unit fraction	0.70	0.75
Permeability, D (by core)	0.271	1.400
Permeability, D (log derived)	0.751	0.799
Average oil saturated thickness, m	6.1	11.8
Initial reservoir temperature, °C	23.9	25
Initial formation pressure, MPa	2.56	2.60
Oil viscosity in reservoir conditions, mPa·s	377.6	246.6
Density of oil in reservoir conditions, t/m³	889	889
Oil density in surface conditions, t/m³	918.2	908.3
Oil formation volume factor, unit fraction	1.035	1.023
Bubble point pressure, MPa	1.29	1.6



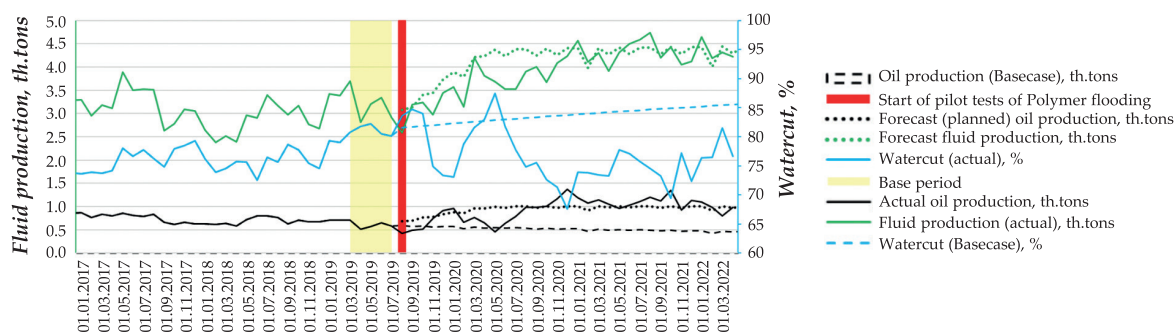


Fig. 7. Dynamics of development indicators of East Moldabek section of the Kenbai field

Conclusions

In Kazakhstan, projects of chemical EOR application at such fields as Zaburunye, East Moldabek, Kalamkas, and North Buzachi have been successfully implemented. As the results of the pilot studies have shown, the most effective chemical EOR here is the application of polymer flooding. Analysis of polymer flooding application in Kazakhstan resulted in the following conclusions:

1. Polymer flooding is successfully applied in Kazakhstan for high-viscosity oil fields such as North Buzachi (oil viscosity 316-417 mPa·s), East Moldabek (oil viscosity 246-377 mPa·s). In this case, water cut, smoothing of injectivity profile and, as a result, increase of oil production is achieved. Successful application of the technology largely depends on the parameters of physical and chemical impact at each stage - the volume of injection of gel-polymer composition, concentration of ingredients, the flow rate of filtered water, the presence and linear size of cracks, the permeability of pore channels and in general the filtration situation in the reservoir. In the case of high-viscosity oil reservoirs complicated by fractures and supercollectors, these EOR methods need to be combined and enhanced.
2. Polymer flooding applied in Kazakhstan showed its technological and economic efficiency on the example of pilot tests, laboratory studies, which reduces water cut and increases oil production. For example, for the East Moldabek field, since the beginning of polymer flooding pilot tests, the water cut of well products has decreased by 8.9%, with additional production of 9584.2 tons. At the North Buzachi field, due to the application of gel polymer flooding, water cut has stabilized and oil production remains at the level of 1000-1500 thousand tons per year. At the Kalamkas field, oil production growth for the period 2014-2017 is 93258 tons. In Zaburunye field, the total effect since the beginning of the project is 184635 tons of oil, 14.7% of pore volume pumped, 3640 tons of polymer injected.

Thus, it is possible to note successful realization of application of chemical EOR - polymer flooding on examples of pilot tests in Kazakhstan. Further research and implementation of chemical EOR on an industrial scale would allow increasing the oil recovery factor in Kazakhstan as a whole.

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