Major influencing factors of water flooding in abnormally high-pressure carbonate reservoir

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Abstract: The higher pressure coefficient is the major characteristics of the abnormal high pressure carbonate reservoirs, which the pressure coefficient generally exceeds 1.2 and the initial formation pressure is higher than normal sandstone reservoirs. Due to the large pressure difference between initial formation and saturated pressure, oil wells are capable to production with high flow rate by the natural energy at early production stage. When the formation pressure drops to the saturation pressure, the water or gas is usually injected to stabilize the well productivity and sustain the formation pressure. Based on the characteristics of Kenkiak oilfield, a typical abnormal high pressure carbonate reservoir, a well group model is designed to simulate and analyze the influence factors on water flooding. The conclusion is that permeability, interlayer difference and reserve abundance are the main three factors on the water flooding development in these reservoirs.

1. Introduction

Kenkiak pre-salt reservoir is located in the southern of the eastern border zone of the Peri-Caspian depression. Main productive reservoir was formed in the Carboniferous age [1]. It is characterized by abnormally high-pressure (80 MPa, pressure coefficient of 1.84) with the bury depth about 4300 meters and serious heterogeneity [2]. The difference between initial formation pressure and saturated pressure is 46.2MPa. The density of the crude oil is 0.816g/cm^3. This reservoir is classified as low permeability, high difference between initial formation pressure and saturated pressure, and weak volatile oil [3]. Reservoir distribution is controlled by sediment faces and vuggy effects. Based on the statistics of fractures in cores, the matrix porosity averages 9.35% with permeability of 0.44 md, while the fracture porosity ranges from 0.001 to 1.5% with fracture permeability from 0.025 to 800md[4].

Oil well production in this field is controlled by fractures and vuggy development. Analyzed on the stratum structures, sediment phase, fractures, reservoir development features and production performance distribution, the study area can be divided into high permeability zone and low permeability zone, as showed in Figure 1.

High permeability zone, located below salt-dome in the central-western area, is a fractured-porosity reservoir. Mini-fractures are developed and the permeability in dual-porosity media is over 5md. Low permeability zone is located in the south part of the reservoir. Mini-fractures are underdeveloped and permeability in dual-porosity ranges from 0.5 to 5md.
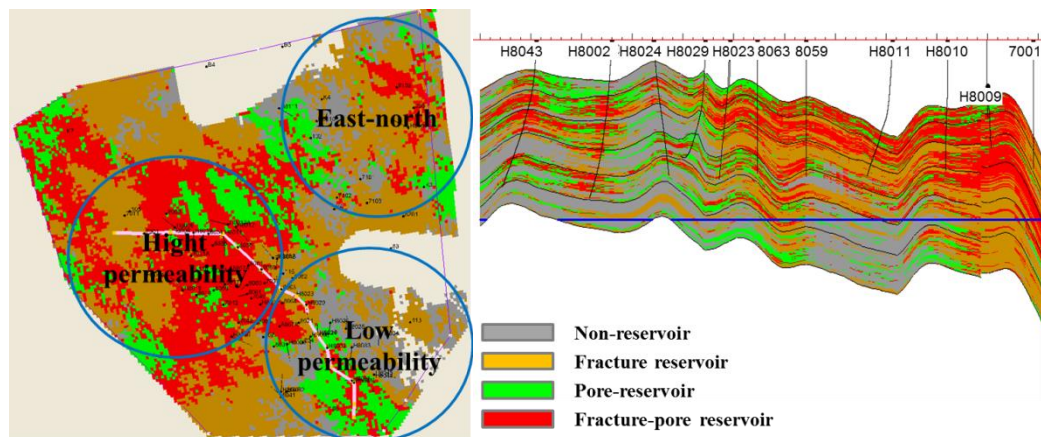
Figure 1. Classification of Carboniferous Reservoir under Salt-Dome (Left: Plane; Right: cross)

2. Production performance

Kenkiak oilfield is an abnormally high pressure carbonate reservoir with large pressure difference between initial formation pressure and saturated pressure which brings enough natural energy in the initial stage of development. However, oil daily production in different zones is significant due to the permeability. In the high permeability zones full of fractures, the horizontal and vertical connectivity greatly increased and the reserve controlled by single well, the fracture plays an important role of communication in the reservoir development. The initial average daily production can reach to 250t/d per well. While the low permeability zone is lack of fractures and the communications both in vertical and horizontal directions are poor resulting in relatively lower initial well productivity of 130t/d per well, which is lesser than that in high permeability zone[5].

In this kind of oilfield, the initial well productivity can be achieved at high level. However, oil rate will decrease rapidly due to formation pressure depleted fast. After more than one decade of development, formation pressure dropped to the level of 39% to 56% of the initial formation pressure, especially the formation pressure in high-permeability zones will be close to the saturation pressure. Then gas will come out of the crude oil with rising producing GOR. In order to sustain formation pressure, water flooding pilot project was initiated in 2009. However, pressure surged near the injector and the water injection rate was too low accordingly. After acidizing, injected volume rose slightly, and well injectivity did not improve much. Energy deficit in the reservoir is so serious that adjustment is an urgent need [6-7].

3. Analysis of major influencing factors in water flooding

In most cases, large pressure drawdown is characterized in the initial development stage of carbonate reservoir with abnormal overpressure. The formation pressure gradually decreases with production time, which leads to the increase of effective stress. The fractures and caves gradually close with the increased effective stress, which finally results in the decrease of reservoir permeability and porosity [8]. Therefore, to recover pressure loss and to maintain formation pressure, water flooding should be implemented when the formation pressure closely drops to saturation pressure. The primary target of water flooding is to keep fractures and pores in open status, which could provide flow channels for oil and improve development performance [9-10]. Based on the geological and physical properties of Carboniferous pre-salt reservoir in Kenkyak Oilfield, a well group model is established and simulated with numerical simulation software to analyse the effects of geological factors on water flooding performance and also provide an optimization criterion for water flooding [11-12].

3.1. Model Parameters and Well Pattern

Geologically, the Carboniferous formation in Kenkyak field can be classified as 9 zones: oil zone - barrier - oil zone - barrier - oil zone - barrier - oil zone-barrier-aquifer (Figure 2). The corresponding

parameters of model are listed in Table 1. The porosity and permeability of each zone are determined by geological statistics of pre-salt reservoir in Kenkyak Oilfield. The pre-salt oil reservoir in Kenkyak Oilfield can be divided into high-permeability and low-permeability regions. In calculations, the parameters of C2bI1, C2bI2, C2bI3, and C1sII1 respectively correspond to four oil zones. C1sII2 and C1sII3 zones are almost below oil-water-contact, which can be treated as a water zone [13-14].
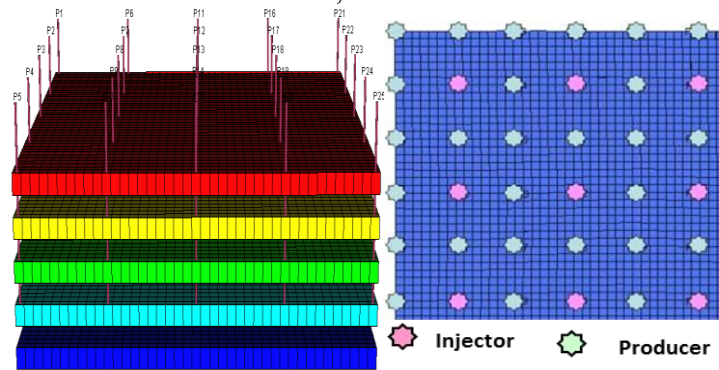

Figure 2. Theoretical model in Water flooding

Table 1. Parameters of geological model

Parameters	Low permeability	High permeability
Cell numbers	2050×2050×180	2100×2050×180
Well pattern	inverted nine-spot	inverted nine-spot
Oil-water interface(m)	4226	4226
Pi(MPa)	78.38	78.38
Pb(MPa)	33.80	33.80

The permeability contrast ranges of high-permeability and low-permeability regions can be obtained according to the statistics of field geological model (Table 2). The matrix permeability in high-permeability region is 0.05-20 md, fracture permeability ranges from 0.05-50 md, K_f/K_m is 1-100/200 and matrix porosity is 6-20%. The matrix permeability in low-permeability region is 0.05-5 md, fracture permeability is 0.05-5 md, K_f/K_m is 1-100 and the matrix porosity is 6%-18%.

Table 2 Parameters of High-Permeability and Low-Permeability zones

Simulation Zone		Oil zone 1	Oil zone 2	Oil zone 3	Oil zone 4	Aquifer	
Layer		C2bI1	C2bI2	C2bI3	C1sII1	C1sII2	C1sII3
High-permeability zones	Netpay（m）	10.93	14.34	12.9	12.56	6.15	2.5
	Por（%）	9.78	8.86	8.45	8.24	7.31	6.89
	Kx（$10^{-3}\mu m^2$）	4.11	2.95	3.17	4.22	1.3	0.78
	Ky（$10^{-3}\mu m^2$）	4.31	3.14	3.36	4.38	1.41	0.85
	Kz（$10^{-3}\mu m^2$）	1.17	0.68	0.73	1.19	0.27	0.17
Low-permeabilty zones	Netpay（m）	7.94	7.72	7.48	8.24	9.42	5.28
	Por（%）	8.45	7.62	7.61	7.48	7.61	6.9
	Kx（$10^{-3}\mu m^2$）	0.33	0.29	0.36	0.2	0.26	0.076
	Ky（$10^{-3}\mu m^2$）	0.35	0.32	0.41	0.22	0.29	0.079
	Kz（$10^{-3}\mu m^2$）	0.18	0.15	0.15	0.1	0.12	0.062

Considering the field test pressures and formation breakdown pressure, the bottom-hole flowing pressure upper limits of water injector and gas injector are set 78MPa and 50MPa respectively, and the lower limit of bottom-hole flowing pressure for oil producer is 25MPa. Formation pressure should be maintained above the bubble point pressure. According to the analysis of actual well production performances in the high-permeability and low-permeability regions of pre-salt reservoir in Kenkyak Oilfield, the allocated initial well productions for low-permeability and high-permeability regions are 50m³/d and 100m³/d respectively.

An inverted nine-spot well pattern is both deployed in the high-permeability and low-permeability regions in this reservoir. The corresponding well spacing is 500m and 350m respectively in high-permeability and low-permeability regions (Figure 2). According to the image principle, the corner-well and edge-well can be treated as a quarter and a half of a whole well respectively. After producer-injector conversion, 12 producers and 4 injectors are designed in the high-permeability region and 25 producers and 9 injectors are in the low-permeability region.

3.2 Impacts of geological factors on water flooding

The effects of multiple geological factors on the water flooding performance of Carboniferous pre-salt reservoir in Kenkyak Oilfield are investigated by numerical simulation, mainly including permeability, inter-zone permeability contrast, and reserve abundance. First of all, permeability is given within the range of reservoir permeability. Inter-zone permeability variation is utilized to compare the heterogeneity of vertical zones. Barriers are used for the study of lateral dimensions and the extent of development. Reserve abundance is gained on the basis of average reserve within the reservoir.

3.2.1. Impact of Permeability. The injection capacity is greatly dependent on reservoir permeability in water flooding development, which directly affects the water flooding performance. Therefore, the effects of reservoir permeability on the water flooding performances of high-permeability and low-permeability regions in the Carboniferous formation of Kenkyak Oilfield are analysed and the corresponding permeability contrast values used in simulation are listed in Table 3.

Table 3. Model Parameters for Permeability Impact

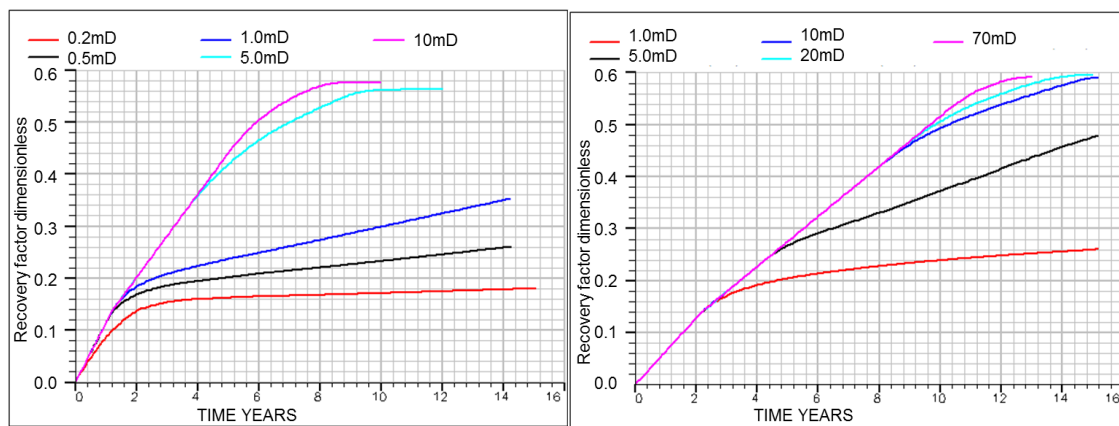| Zone	K_{max}/K_{min}	K_{max}
Low Permeability Zone	1	0.2, 0.5, 1, 5, 10
High Permeability Zone	1	1, 5, 10, 20, 70

Figure 3. Impact of permeability on recovery factor to date in water flooding (Left: low-permeability zone; Right: high-permeability zone)

Figure 3 illustrates that the water flooding performance is greatly dependent on reservoir permeability. The recovery degree increases with the higher reservoir permeability. However, with the increase of permeability, the recovery degree of its impact will be reduced.

3.2.2. Impact of Inter-zones Heterogeneity. The inter-zone permeability contrast should be defined before analyzing the effect of inter-zone heterogeneity on water flooding performance. A reservoir will be divided into multiple subzones in the longitudinal direction, which have maximum permeability (K_{max}) and minimum permeability (K_{min}). Therefore, K_{max} / K_{min} can be used to the inter-zone permeability contrast.

Pre-salt reservoir of carboniferous formation in Kenkyak Oilfield is mainly dominated by reverse rhythm. The maximum permeability appears in the uppermost zone. Therefore, assuming the permeability of the uppermost zone is fixed, by altering inter-zone permeability contrast is to analyze the effect of inter-zone heterogeneity contrast on water flooding performance. The permeability of other zones is determined by geometric progression. The injected water tends to break through along high-permeability zone in case of relatively high inter-zone permeability contrast, which will lead to poor water flooding performance. Figure 4 indicates that the water flooding performance is also greatly dominated by inter-zone permeability contrast. The simulated recovery degree decreases with the higher inter-zone permeability contrast.
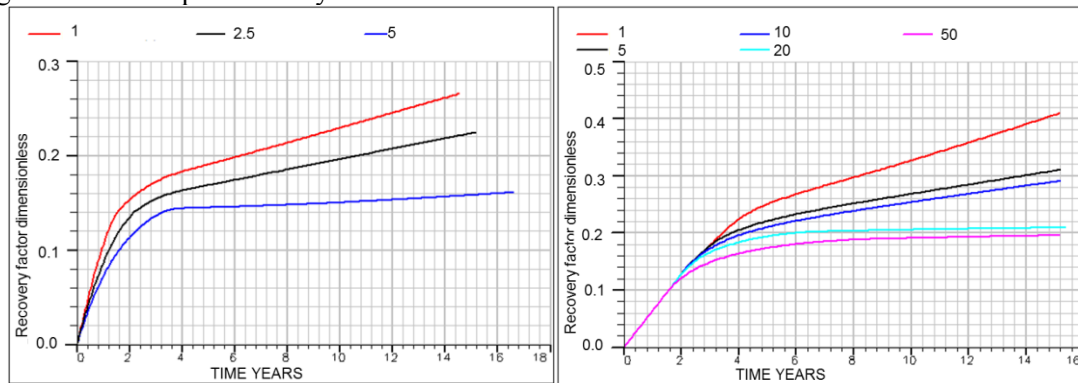

Figure 4. Impact of inter-zones permeability variation on recovery factor (Left: low-permeability zone; Right: high-permeability zone)

3.2.3. Impact of reserves abundance. The influence of reserve abundance on the water flooding performance of Carboniferous pre-salt reservoir is inquired by slightly altering the average reserve abundance in the high-permeability and low permeability regions. The reserve abundances in the high-permeability and low-permeability regions are all set as 0.5, 0.8, 1.0, 1.2 and 1.5 respectively.

Figure 5 reveals that the water flooding performance is partly dependent on reserve abundance, which is slightly less than that of reservoir permeability and inter-zone heterogeneity. The reserve abundance and formation pressure in the low-permeability region are too low to achieve a production with constant recovery rate. Actual production follows constant injection-production pressure drawdown with production decline. The producer is shut down when daily oil production decreases to less than 8m^3/d, which results in the relatively low recovery degree. In the high-permeability region, constant recovery rate can be achieved by constant well oil production due to high reserve abundance. The recovery degree reduces with the increase of reserve abundance under equal oil recovery rate. However, the production lasts a long period with high reserve abundance and no significant difference in recovery degree can be found when water-cut reaches to 98%.

4. Conclusions

Permeability, inter-zone permeability variation, and reserve abundance are the major factors to influence water flooding performance in both porosity-type and fractured-porosity reservoirs. Permeability depending on fractures has the most pronounced impact. The higher permeability is, the higher the oil recovery degree is. The difference between layers may result in reducing the water drive effect. The reserve abundance also has influence on the water flooding development.
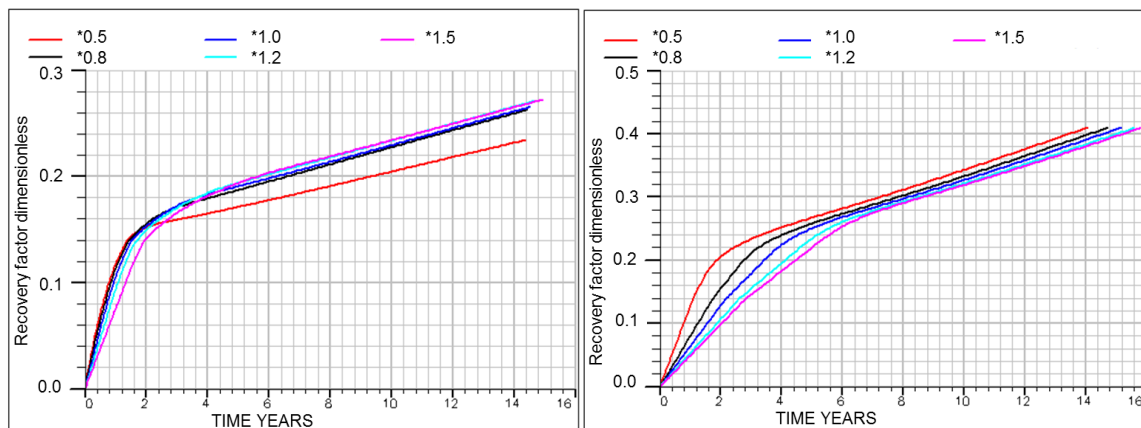
Figure 5. Impact of reserves abundance on recovery factor (Left: low-permeability zone; Right: high-permeability zone)

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