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The Types and Mechanisms of Shahe Street Reservoir Damage in KL10-1 Oilfield

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Abstract: From 2016 to 2022, the productivity recovery rate of oil well in KL10-1 oilfield continued to decline after the workover operation, and the complex treatment situations increased continuously which caused by the high temperature and corrosion issues since 2018, that multiple wells had been scaling in the downhole central tube, which resulted in extended downtime, annual total production decline of single well and high costs. Through the analysis of reservoir properties, subsurface fluid properties, and rock surface physical chemical characteristics, the article finds that the wells with productivity recovery rate are mainly concentrated in the Es formation which has low-to-moderate permeability and high wax content. The reason is that the inherent potential damage factors of the formation are induced by various external conditions, such as water lock damage and inorganic scale accompany the whole development and production process of the oilfield, as well as wax deposition in the low-to-moderate water cut stage are the main risk factors that cause the absolute permeability or relative permeability of the reservoir decrease significantly, and the oil well production decline.

1. Introduction

Kenli 10-1 oil field in the Bohai Sea is located in the descending wall of the large fault in the south of Laibei low uplift and the north depression of Laizhou Bay depression. It is a fault block structure which is attached to the boundary fault. Since 2016, the productivity recovery rate of the oil wells in the low permeability reservoir of Shahejie Formation of the oilfield has been continuously decreased after the work-over operation, with an average of only 85.9%. Due to high temperature and corrosion problems, the scaling of the down-hole central pipe occurred in multiple wells, and finally resulted in the increase of complex overhaul treatment conditions, prolonged production shutdown and maintenance time, and reduced annual total production of a single well. Based on the exploration of reservoir damage types and mechanism of Shahejie Formation, this author concluded that the cause of low productivity recovery rate is that the inherent potential damage factors of the formation are induced under the stimulation of various external conditions, which causes inorganic scale plugging, organic scale deposition, water locking and other damages, which leads to the large decrease of permeability of reservoir, and finally results in the permanent damage to the reservoir, resulting in a decline in well production, and also the capacity is difficult to recover[1,2].

1.1. Reservoir Physical Property

The main production layer of Kenli 10-1 Oilfield is the lower member of the shallow Minghuazhen Formation, which is followed by the deep Shasan Group of Shahejie Formation. Shahejie Formation reservoir has buried in the depth of -2110 ~ -2764 m, the temperature is 100~116.8 ℃, the original formation pressure is 24.6~29.7 MPa and the well depth is 2263~3359 m. The buried depth of Minghuazhen Formation reservoir is -1180 ~ -1475 m, the temperature is 53.8~71.8 ℃, the original formation pressure is 12.18~14.11 MPa, and the well depth is 1478~3746 m.

1.1.1. Pore Character

The average porosity of Minghuazhen Formation is 29.7%, the average permeability is 3255.7 mD, and the average porosity of each well on the plane is above 25%. In general, the physical property of the reservoir in the plane shows that this area is a high-porosity and ultra-high-permeability reservoir. On the whole, Shahejie Formation has an average porosity of 21.2% and an average permeability of 123.3 mD. It is a typical medium-porosity oil field. However, the permeability of each well area is different. The permeability of well areas 1 and 8 is respectively 25.3 mD, and 29.5 mD is a low permeability well area. See the Table 1 for porosity and permeability parameters of each well area[3].

Table 1: The reservoir porosity and permeability of different borefild in KL10-1 oilfield

Formation name	well field	average permeability /mD	average porosity /%	perforation thickness /m
Minghua town	2	4876.3	31.9	23.7
	9	5540.5	32.1	34.8
	3	3888.0	29.8	41.0
	4	820.0	26.9	13.0
	11	1154.0	27.9	31.6
shahe street	1	25.3	20.6	55.4
	2	101.0	20.7	31.9
	3	219.1	22.0	32.6
	4	184.9	21.5	21.4
	5	128.6	21.8	34.5
	6	100.5	22.1	42.8
	7	197.8	21.4	35.3
	8	29.5	19.2	48.1

1.1.2. Composition and Characteristics

From Table 2, it can be known that the reservoir rocks of Kenli 10-1 oilfield mainly include montmorillonite, illite, kaolinite, chlorite and mixed-layer minerals. Montmorillonite expands when meeting water and blocks pore throat. Illite has a tendency to "bridge" between the throats and to form motile particles. However, kaolinite migrates under the action of flow velocity, and the cross-section of its wafer is easily blocked in the pore throat. Chlorite produces acid sensitivity when encountering acid, forming a flocculated precipitate and blocking pore throat. The mixed-bed mineral has the double damage property of end-member minerals, which is more harmful to the reservoir[4].

Table 2: The composition and characteristics of reservoir lithology in KL10-1 oilfield

Project	Shahejie Formation	Minghuazhen Formation
Lithology of reservoir	Medium sandstone, medium to fine lithic feldspathic sandstone, argillaceous and calcareous cementation, loose	Inter-bedding of mudstone and fine sandstone and gravel-bearing fine sandstone with unequal thickness
Clay mineral	Mainly illite, followed by kaolinite and illite/montmorillonite mixed layer	Mainly illite/Mongolian mixed bed, followed by kaolinite, illite and chlorite.
Void Type	There are mainly inter-granular pores, and they are distributed evenly with good connectivity. The throat is mostly point-shaped or sheet-like. The pores and throat are filled with secondary enlarged quartz, kaolinite and a little floc-like illite.	There are mainly inter-granular pores, and the rock pores are well developed and evenly distributed, the connectivity is good, the pore throat shape is mostly irregular, the throat is mostly spot-shaped or flaky, and the throat is evenly distributed.

1.2. Nature of the Crude Oil

The surface crude oil of Minghuazhen Formation has a density of 0.923~0.965 g/cm3 and a viscosity of 91.5~1565.0 mP s. It is a heavy crude oil with high viscosity, low saturation pressure, low gas-oil ratio, medium sulfur and wax. The surface crude oil density of Shahejie Formation is 0.850~0.879 g/cm3, and the surface crude oil viscosity is 6.5~25.0 mP s. It is a light-medium conventional crude oil, which is characterized by low saturation pressure, medium dissolved gas/oil ratio, low crude oil viscosity, high freezing point, high wax content and high wax precipitation point. See Table 3 for specific crude oil property parameters.

Table 3: The oil property in KL10-1 oilfield

formation name	bubble point pressure /MPa	solidifying point /°C	wax appearance point /°C	wax content /%	viscosity /mPa s	density /(g/cm^3)	asphaltene content /%	colloid content /%
Minghua town	6.99~12.28	13	30	2.5~13.08	91.5~1565	0.923~0.965	/	11.4~25.4
Shahe street	9.3~11.1	33	47	19.2~29.6	6.5~25	0.850~0.879	2.1~5.1	5.5~11.0

1.3. Water Property

From Table 4, it can be concluded that the salinity of formation water and injection water in each position of Kenli Oilfield is greater than 10000 mg/L, the salinity is high, and the overall pH is weakly alkaline. The water type is calcium chloride water and sodium bicarbonate. Due to the property of the water body, the water body has a strong scaling tendency in a high-temperature weak-alkali environment and is very easy to generate calcium-magnesium scale[5].

Table 4: The properties of formation water in KL10-1 oilfield

formation name	Ion composition and content mg/L								Total mineralization degree mg/L	pH	water type
	K^+	Na^+	Mg^{2+}	Ca^{2+}	Cl^-	SO_4^{2-}	HCO_3^-	CO_3^{2-}			
Minghua town	83	4957	199	1004	10399	39	137	2	16247	7.44	$CaCl_2$
Shahe street	112	5031	52	207	7246	31	1984	58	15029	8.26	$NaCHCO_3$
injected water	86	5000	78	483	8239	10	1029	0	13555	8.27	$CaCl_2$

1.4. Status of Problems

From 2016 to July 2022, Kenli 10-1 Oilfield has cumulatively completed 75 times of work-over operations with conventional tubing strings. After operation, the productivity recovery rate is generally decreasing, and the proportion of wells without recovery is increasing. Especially, the decline is relatively serious since 2020. See Figure 1 for details.

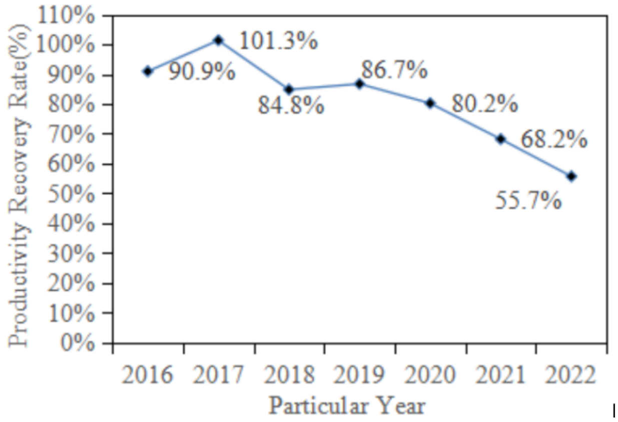


Figure 1: The productivity recovery rate after workove

Figure 2: The scale in downhole central tube of oil well

Since 2018-2020, due to high temperature and corrosion, the complex treatment situation in the work-over operation of the oil well moving string has been increasing, and the scaling of the center pipe occurs in multiple wells. Subsequently, the outage maintenance time is prolonged (see Figure 2 and Table 5), the annual production of a single well will be reduced, and the operation cost will increase.

Table 5: Statistics of workover operation conditions from 2018 to 2020 in KL10-1 oilfield

Particular Year	Workover Wells Amount /well	Complex wells Amount /well	Construction Period /day	Average Construction Period /day
2018	15	3	37	12.33
2019	12	6	85	14.17
2020	13	8	70	8.75

2. Problem Analysis

According to statistics, the wells with low productivity recovery rate after work-over operation in Kenli 10-1 Oilfield are mainly concentrated in Shahejie Formation, while the oil production recovery rate of wells in Minghuazhen Formation is high. The reason for analysis is that the inherent potential damage factors of the formation are induced under the stimulation of various external conditions, so that the absolute permeability or the relative permeability of the reservoir is greatly reduced, and the oil well production is reduced[6]. The specific analysis is as follows:

Shahejie Formation in Kenli 10-1 Oilfield belongs to medium-low permeability and high wax-bearing reservoir. The oil production of single well varies widely, with daily oil production of 2.28~133.58 m3/d and average oil production of 41.61 m3/d. The comprehensive water cut of platform A crude oil is 44.90%, which belongs to medium water cut period. The risk of damage of wax deposit and inorganic scale deposit in normal production process is high, and the damage of water locking is medium. The comprehensive water cut of Platform B is 71%, and the water cut of the single well is 1.8~98%, which is a medium-high water cut period, with moderate wax deposition and water locking damage and high risk of inorganic scale deposition. See Table 6 for specific injury factors and the degree.

Table 6: Risk types of damage to crude oil in ES reservoir during different water cut periods

Water Content Level	Water Lock	Wax Deposit	Organic Matter Deposition	Emulsification Damage	Inorganic Scale
low water cut period	**high**	**high**	Medium	low	low
Medium water cut period	**Medium**	**high**	low	low	**high**
medium-high water cut period	**Medium**	**Medium**	none	none	**high**
High water cut period	low	none	none	none	high

2.1. Wax Deposition Risk

According to statistics, the average shut-in time of the wells before oil well operation in Kenli 10-1 Oilfield from 2019 to 2020 is 60 days (Figure 3). After shut-in of the wells, the well bore temperature will decrease rapidly first, then slowly, and then to ambient temperature.

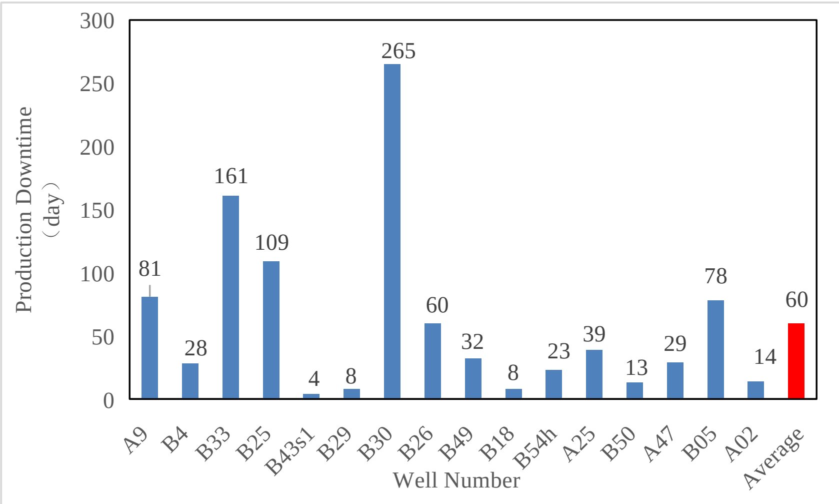


Figure 3: Production downtime before workover operation

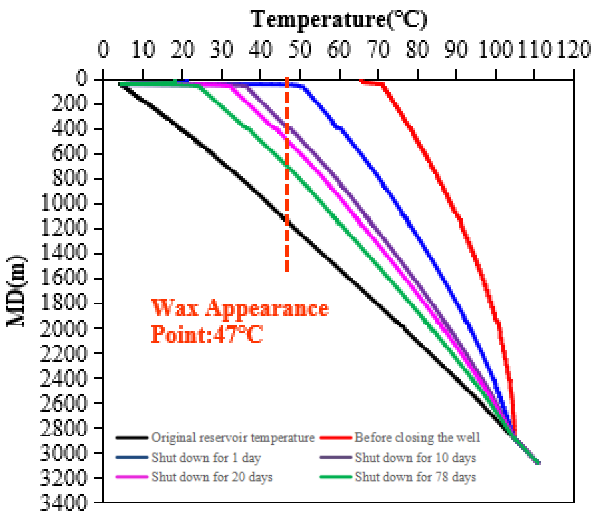


Figure 4: Wax precipitation point of crude oil in ES reservoir

It can be seen from Figure 4 that the wax precipitation point of the crude oil in Shahejie reservoir of Kenli 10-1 Oilfield is 47 ℃. However, with the decrease of formation pressure and temperature, the high-waxy crude oil is easy to be separated out in the formation and well bore, and the paraffin deposition depth of the well bore is deepened, which results in the decrease of formation permeability and the failure of normal production of the oil well[7].

2.2. Asphaltene Deposition Risks

Asphaltenes are macro-molecular mixtures with complex structures and properties. When reservoir conditions change, asphaltenes will be deposited as solids. In order to evaluate the deposition risk of asphalt more accurately, the phase envelope diagram of asphalt is measured experimentally[8,9], and the results are shown in Figure 5.

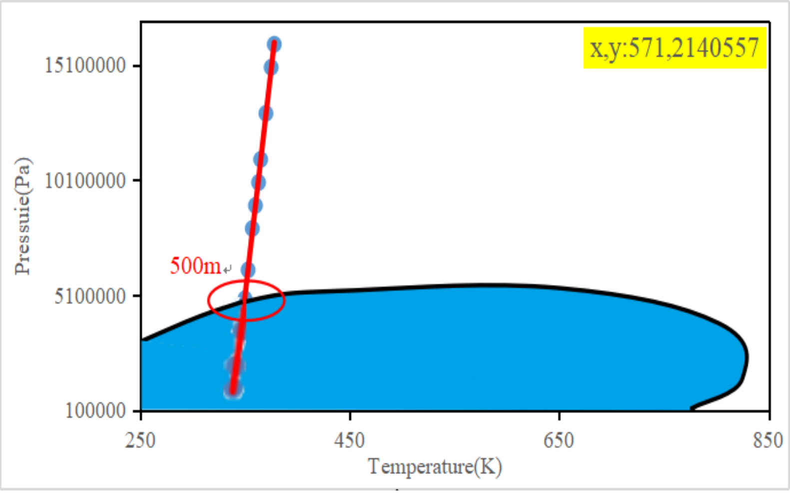


Figure 5: Phase envelope of oil well in ES reservoir

From Fig. 5, it can be concluded that it clearly reflects the stable area and deposition area of asphalt. From this P-T phase diagram, it can be seen that gum asphaltene deposition risk exists in the upper part of tubing during normal production of oil well, but the asphaltene content of crude oil of Shahejie Formation of Kenli Oilfield is low, which belongs to low risk.

2.3. Inorganic Scale Deposition Risk

2.3.1. Scaling Trend

In Bohai Sea Oilfield, the average salinity of production level is 5455 mg/L, while the salinity of Shahejie formation water is 14720 mg/L, and the salinity of injected water is 13555 mg/L. Injection water or source well water is used as base fluid in the process of work-over. Both have high salinity and high scale formation ion content, which is greatly different from Shahejie Formation water type[10]. See Figure 6 for scaling trend.

From Figure 6, it can be concluded that the formation water and injection water of Shahejie Formation have strong scaling capacity. After mixing the two materials, the scaling amount becomes larger, with the maximum scaling increment of 198 mg/L, which is 9.9 times of the normal water quality index (oil content + suspended solids concentration), and severe plugging will occur for medium and low permeability reservoirs.

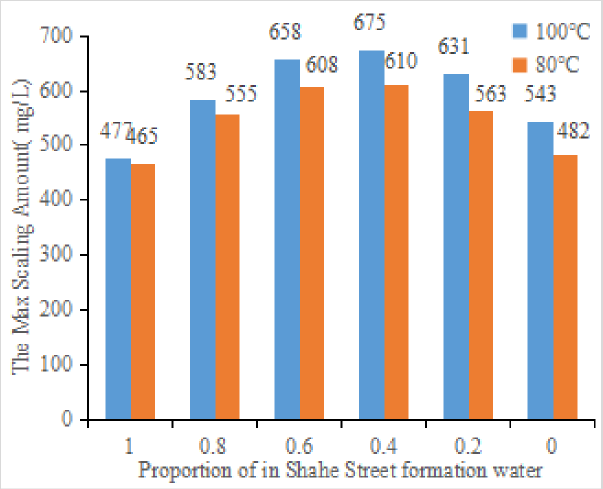
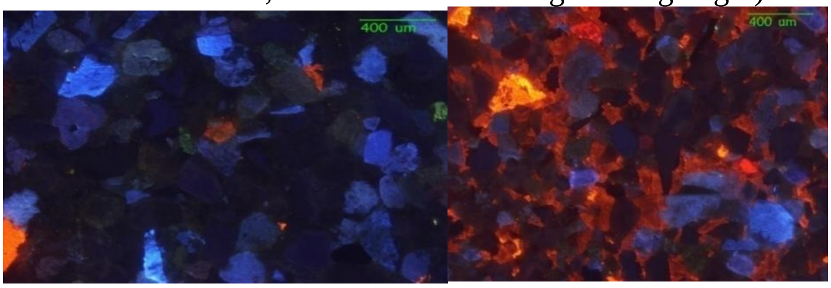


Figure 6: Scale buildup amount of ES formation water with injected water

2.3.2. Scaling Mechanism

When the liquid is extracted from the formation, with the change of temperature, pressure, PH value and other factors, the scale-forming ions such as Ca^{2+}, Mg^{2+}, etc. in the formation water combine with CO_3^{2-} and SO_4^{2-} ions to form the carbonic acid/sulfate scale, which is adsorbed on the formation pore near the well, production screen pipe and electric pump position. On the other hand, the formation crude oil has high viscosity, which inevitably carries the formation solid particles to migrate during the production process. These solid particles provide the core support for the formation of scale and formation plugging, and also cause the formation pore plugging with the increase of scale formation. The Figure 7 shows the microscopic comparison before and after pore plugging of a well reservoir, which visually reflects the reservoir lithology change of Shahejie reservoir after long-term foreign fluid erosion[11] (In the figure: quartz-dark blue light, plagioclase-sky blue light, orthoclase-dark red light, argillaceous matrix-nonluminous-dark gray light, debris and cement: nonluminous; calcite cement: red light-orange light).



a) Early exploration stage b) adjustment well

Figure 7: Microscopic comparison of reservoir pores before and after blockage

From Figure. 7-a, it can be concluded that in the initial stage of exploration and development, the lithology of reservoir is mainly quartzite and plagioclase, with less content of sedimentary cement. After long-term water injection development, the calcium scale content in the reservoir in Figure. 7-b increases. The calcium scale particles mainly grow around the periphery of mineral particles. The yellow particles have a particle size of 20-100 μm. When the amount reaches a certain value, the whole pore is filled, causing blockage at the pore throat of the reservoir and aggravating the water locking damage of the reservoir.

2.3.3. Permeability Change

According to the scale-permeability damage degree evaluation test of different permeability cores, the results show that the larger the scale amount is, the greater the damage to the reservoir permeability is, the lower the permeability is, and the greater the reservoir permeability damage is under the same scale amount. The experimental results are shown in Figure 8.

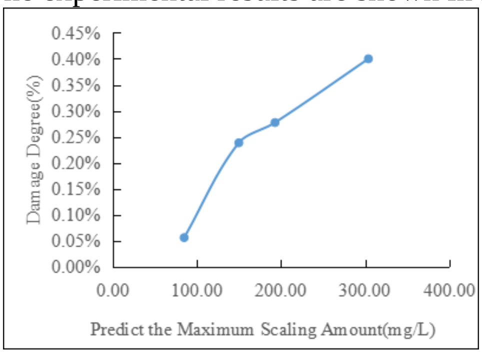


Figure 8: The variation of permeability damage degree with scaling amount

2.4. Water Lock Injury Risk

2.4.1. Work-over Fluid Loss

The core displacement test shows that the formation pressure coefficient of most wells in Shahejie reservoir is lower than 0.8 (see Figure 9), and the work-over fluid is easy to leak (see Figure 10), which results in the increase of water saturation near the well, the Jurin's Law and Jamin Effect in the rock pores, the increase of the additional resistance of crude oil flow and also the decrease of oil well production[12].

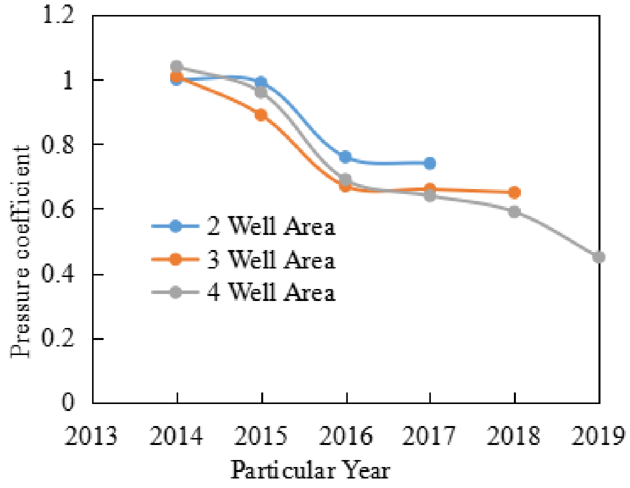


Figure 9: The changes of formation pressure coefficient over time

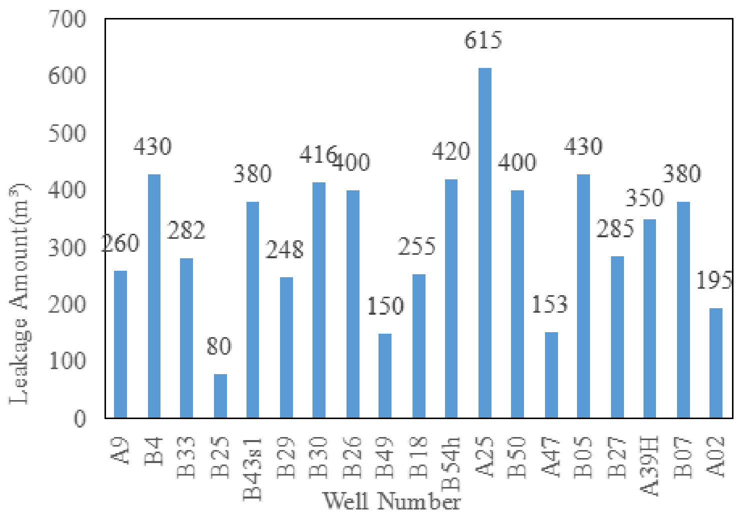


Figure 10: Statistics of single well leakage during workover

2.4.2. Relative Permeability

Once the production of the oil well is stopped, although there is no liquid flow at the wellhead, the fluid in the formation is still in the after-flow state. According to the oil-water seepage principle, the seepage speed of formation water is far higher than that of crude oil. Especially for heavy oil wells, formation water can quickly permeate to the near-well zone and occupy the oil outlet channel, Which results in a sharp rise in water saturation near the borehole, and a large amount of water production for a long time after the oil well is put into production. From Figure 11, it can be seen from the relative permeability curve of the block that the relative permeability of the crude oil in the oil layer is very sensitive to water saturation. Once the formation water saturation rises, the relative permeability of oil will decrease greatly.

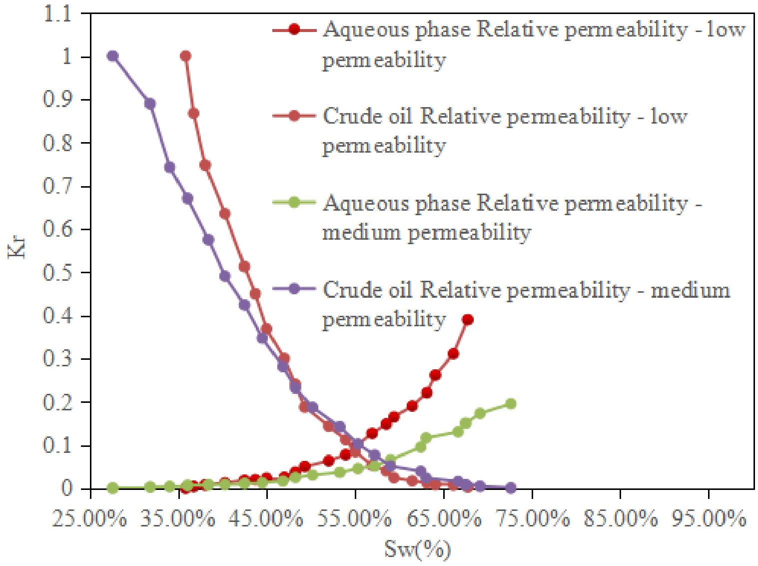


Figure 11: Relationship between relative permeability and water saturation

From Figure. 11, it can be seen from the relative permeability curve of the block that the relative permeability of the crude oil in the oil layer is very sensitive to water saturation. Once the formation water saturation rises, the relative permeability of oil will decrease greatly.

3. Conclusion

(1) The wells with low productivity recovery rate in Kenli 10-1 Oilfield are mainly concentrated in Shahejie Formation with medium-low permeability and high wax content, while the wells in Minghuazhen Formation have high recovery rate.

(2) There are many kinds of potential damage factors in reservoir. There are sensitive factors in different degrees in reservoir physical property, subsurface fluid physical property, physical and chemical characteristics of rock surface and relative permeability characteristics.

(3) The water locking damage and inorganic scale deposition accompanied with the whole development process of the oilfield, and the risk of wax deposition in the middle-low water cut period. The three factors together are the main risky elements of causing significant decrease of the absolute or relative permeability of the oil reservoir and the production of the oil well.

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