The Factors of Threshold Pressure Gradient for CO_2 Miscible Flooding in Low Permeability Reservoir

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Abstract. The threshold pressure gradient of CO_2 miscible flooding is very complex in the low permeability reservoir. And the short low permeability core experiments are adopted to study it in this paper. Studies show that the curve of pressure gradient and flow rate presents a concave distribution and the threshold pressure gradient is found. Under the same conditions, the threshold pressure gradients are ranked as an order. The threshold pressure gradient and core permeability / fluid mobility bases on a power function. And the fluid viscosity is one of the main factors affecting the threshold pressure gradient.

Introduction

With the development of petroleum industry, the exploration and development of oil and gas are gradually turning to low permeability oil fields in China. At present, the low permeability reservoir has become a main body of the new area productivity construction and the oilfield production.[1] According to the actual production characteristics, the low permeability reservoirs are mainly divided into low permeability reservoir (permeability: $50{\sim}10\times10^{-3}\mu m^2$), extra-low permeability reservoir ($10{\sim}1\times10^{-3}\mu m^2$), ultra-low permeability reservoir ($1{\sim}0.1\times10^{-3}\mu m^2$) and non permeability reservoir (less than $0.1\times10^{-3}\mu m^2$). The low permeability reservoir has many different typical features of the conventional reservoirs, with poor reservoir property, low sediment maturity, small pore throat radius, low matrix permeability, strong stress sensitivity, developed crack, strong heterogeneity, and so on. The special physical properties of low permeability reservoir make its oil and gas migration particular that the seepage rule of fluids deviates from the Darcy's law, and it has the threshold pressure gradient.[2-3]

In the process of low permeability reservoir development, the problems that the threshold pressure gradient is big and the water injection development is difficult which decide to take the development by the way of gas injection, especially the CO_2 injection development is an effective way of exploitation.[4-5] As an effective method of utilizing the greenhouse gas comprehensively, the technology of CO_2 flooding is taken increasingly to enhance the oil recovery. And the CO_2 miscible flooding technology also has a good application prospect in the low permeability reservoir development.[6-7] On the premise of miscible flooding, this paper puts forward that the displacement process can be divided into four displacing phase zones: original oil phase zone, frontal phase zone of gas injection, miscible oil phase zone and trailing phase zone of gas injection. Through the indoor physical simulation experiment, it studies the starting mode of each phase zone of different cores in the process of CO_2 miscible flooding under formation conditions, and determines the threshold pressure gradient and analyzes the factors that influence the threshold pressure gradient in different displacement zones.

Materials and Approaches

Instrument

The experimental equipment is SYS-III multistage ultra-high temperature two-phase displacement system which is produced in Nantong Huaxing Oil Instrument Company. The thermostat is divided into several spaces that can meet the experimental requirements with different temperatures. The maximum driving and confining pressure both are 10000psi, and the maximum temperature is 150 ℃. It can be carried out various displacement experiments on the conditions of formation. The auxiliary equipments include the RUSKA mercury-free PVT instrument (model 2730) and the ISCO-260D high precision displacement pump produced in the United States.

Materials

The experimental pressure is formation pressure (24.5MPa) and the experimental temperature is formation temperature (98 ℃). The experimental cores take from Black 79 block of Jilin oilfield, and the specific parameters are given in Table 1. The formation oil and water are made up according to the actual data of some well which is on the basis of the oilfield requirements. The other experimental fluids are made up according to the experimental requirements, and the relevant parameters can be seen in Table 2.

Table 1 The data of experimental cores

Core Number	Sampling Well Number	Diameter (cm)	Length (cm)	Porosity (%)	Permeability ($\times10^{-3}\mu m^2$)
H-30	Hei-167	2.522	6.890	19.5	36.20
H-44	Hei-84	2.520	6.926	16.7	5.96
H-39-2	Hei-84	2.520	7.810	9.8	0.487

Table 2 The data of experimental fluids

Fluid Number	Experimental Fluid	Density (g/cm^3)	Viscosity (mPa.s)	Saturation Pressure (MPa)	Gas-oil ratio (m^3/m^3)
1	original oil	0.7615	1.85	7.1	30
2	frontal fluid of gas injection	0.7554	1.51	-	50
3	miscible fluid	0.7502	0.725	-	150
4	trailing fluid of gas injection	0.5652	0.046	-	-

The frontal fluid of gas injection is prepared by the proportion of 1m^3 formation oil to 20m^3 CO_2. The miscible fluid is prepared by the proportion of 1m^3 formation oil to 120m^3 CO_2. The trailing fluid of gas injection is prepared to measure the threshold pressure square gradient when the CO_2 flowing through different permeability cores (containing residual oil).

Methods

The experimental principle is to use the relationship of differential pressure and flow rate, obtaining the curve of pressure gradient and flow rate by changing the fluid pressure of the cores and measuring its flow rate when the fluid flowing through the cores. So the intercept value is the threshold pressure gradient which is obtained by extending the linear segment of the curve to the pressure gradient axis.

The experimental steps are as follows: (1) connect the experimental devices according to the experimental design and rise to the formation temperature; (2) put the core into the core holder and load the confining pressure and back pressure until reaching the experimental requirements; (3) saturated with the formation water, and make bound water by flooding experimental fluid, and stabilize the pressure; (4) open the experimental fluid accumulator and regulate the inlet pressure; (5) stabilize each pressure for 30 minutes according to the order from small to big, and record outlet fluid flow rate and its corresponding actual pressure; (6) measure three times repeatedly, and it is qualified when the flow rate error is less than 4% .

The experimental notes: (1) pressure test and leakage detect after connecting the experimental devices, and pay attention to prevent the leakage during the experiment, especially the fluid leakage under the high temperature; (2) make sure that the air can be circulated when carrying on experiments, and operate the valve lightly, and unload the back pressure and the confining pressure slowly in order to avoid the damage of the equipments at the end of experiment.

Results and Discussion

Threshold Pressure Gradient

It can be seen from Figure 1, the curve of pressure gradient and flow rate of Core H-30 is divided into non-linear segment and linear segment. The flow rate of outlet fluid is 0.018 ml/min when the pressure gradient is 0.0726MPa/m, and the curve has an inflection point. When the pressure gradient is less than 0.0726MPa/m, the pressure gradient and flow rate present a nonlinear variation, and the change is steady. The original oil begins to flow in large pores, and the effective seepage capacity of fluid is small. At the moment, the original oil in pores shows nonlinear flow which does not accord with the Darcy law. As the pressure gradient is bigger than 0.0726MPa/m, the pressure gradient and flow rate display a linear growth, and the liquid flow accords with the Darcy law.

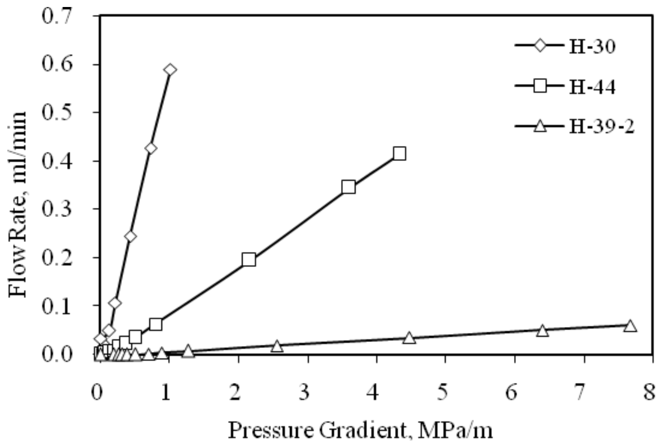

Fig. 1 The Relationship between Pressure Gradient and Flow Rate of Original Oil Phase Zone in Different Cores

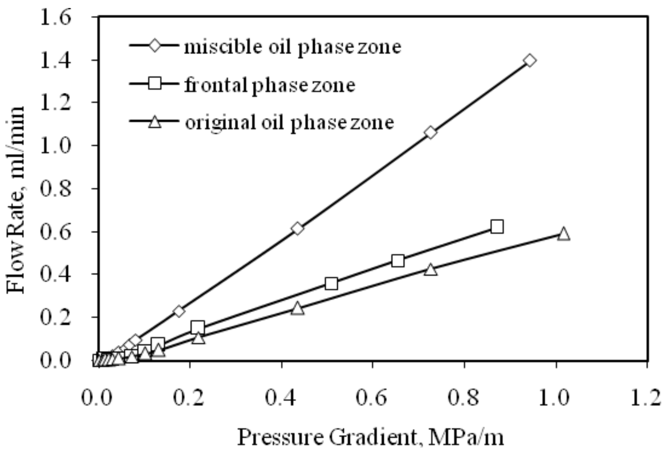

Fig. 2 The Relationship between Pressure Gradient and Flow Rate of Different Displacement Zones in Core H-30

It also shows that, with the decrease of core permeability, the slope of linear segment is gradually decreasing in the curve of pressure gradient and original oil flow rate. And the value which is the intersection of linear segment and pressure gradient axis is gradually increasing. The smaller the core permeability is, as the original oil flowing in the core, the bigger the flow resistance is, the bigger the threshold pressure gradient is. The non-linear flow phase of original oil increases with the permeability decreasing. The pressure gradient is needed gradually increasing when the flow of original oil converts from non-linear to linear. The curvature of curve is gradually decreasing, and the threshold pressure gradient increases significantly.

The frontal phase zone of gas injection refers to the displacement zone which is formed by mixing CO_2 and formation oil or mixing CO_2 with fluid containing light hydrocarbons and formation oil. Its main characteristic is that the formation oil is dissolving CO_2. The miscible oil phase zone refers to the fluid zone that the formation oil has dissolved plenty of CO_2, and the formation oil and CO_2 present a state of single-phase fluid. The trailing phase zone of gas injection refers to the zone that the CO_2 displaces the residual formation oil which is the remaining oil that has not mixed with CO_2 to form miscible oil and has not been flooded by CO_2. The experiments study and measure the threshold pressure gradients in different displacing phase zones of cores with different permeability, and the experimental results are presented in Table 3.

Table 3 The experimental data of threshold pressure gradient

Core Number	H-30	H-44	H-39-2
Permeability ($\times 10^{-3}\mu m^2$)	36.20	5.96	0.487
	Threshold Pressure Gradient (MPa/m)		
1. original oil phase zone	0.0435	0.1426	0.3928
2. frontal phase zone of gas injection	0.0336	0.1101	0.3005
3. miscible oil phase zone	0.0175	0.0508	0.1425
	Threshold Pressure Gradient Square (MPa^2/m)		
4. trailing phase zone of gas injection	0.0069	0.011	0.0632

Displacement Phase Zone

In the three displacing phase zones, with the permeability of Core H-30 is unchanged, the influence of core permeability can be excluded on the threshold pressure gradient. As is shown in Figure 2, the slopes of the curves are arranged from small to large as following order: original oil phase zone, frontal phase zone of gas injection and miscible oil phase zone. It displays that, at the same pressure gradient, the outlet flow rates are ranked from small to large as following order: original oil phase zone, frontal phase zone of gas injection and miscible oil phase zone.

The reason why having this phenomenon is mainly because the gas oil ratios (the CO_2 contents) are different in each displacement zone, which is directly affecting the physical properties of the fluid. With the gas oil ratio increasing, the fluid viscosity decreases significantly, and the density declines slightly and the flow ability is stronger. Therefore, the differential pressure is smaller than the fluid needs to flow from non-linear to linear, and the threshold pressure gradient is smaller.

Permeability

In Figure 3, after the regression with the scatter values of three cores in the miscible oil phase zone, the threshold pressure gradient and the permeability present a relationship of power function. The equation is as follows: $Y=0.1061X^{-0.4821}$, and the correlation coefficient is $R^2=0.9894$. With the decreasing of core permeability, the threshold pressure gradient increases. When the core permeability is less than $1\times 10^{-3}\mu m^2$, the threshold pressure gradient increases significantly, more than 0.14MPa/m. When the core permeability is more than $30\times 10^{-3}\mu m^2$, the threshold pressure gradient is very small that is less than

0.02MPa/m, and changes smoothly. Only need a small pressure gradient to change the flow from non-linear to linear.

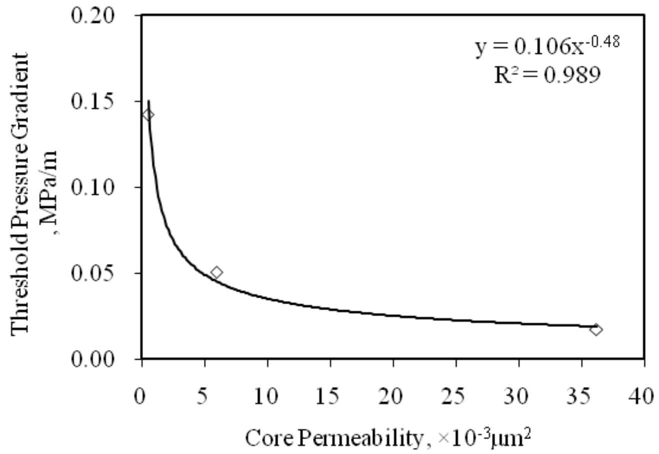

Fig. 3 The Relationship between Core Permeability and Threshold Pressure Gradient of Miscible Oil Phase Zone

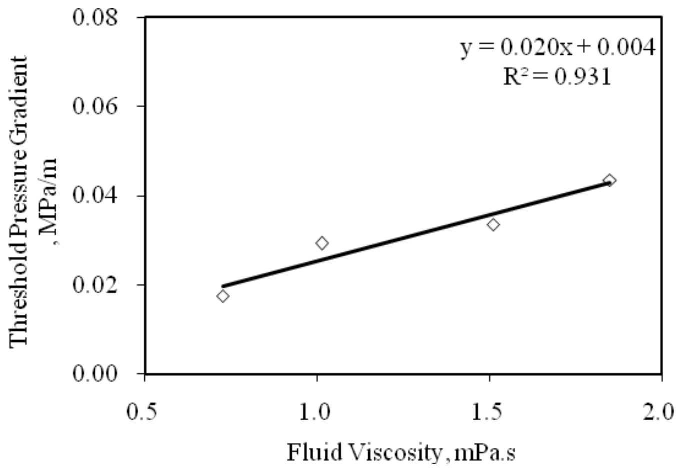

Fig. 4 The Relationship between Fluid Viscosity and Threshold Pressure Gradient of Core H-30

The core permeability has great influence on the threshold pressure gradient of each displacement zone. The size, structure and distribution of pore and throat can affect the seepage velocity of the fluid .The porosity of low permeability reservoir is very small and the throat is very thin. The connectivity of pore and throat is poor and the ratio of pore and throat is big. And the contribution of permeability is mainly according to the thick pore and throat which have a small proportion of pore volume. But the small pore, the thin throat and the poor connectivity are the important factors that cause the low permeability reservoir having non-Darcy seepage. Therefore, the smaller the core permeability is, the stronger the heterogeneity is, the bigger the differential pressure that the fluid needs is, the bigger the pressure gradient that the fluid needs to change from non-linear to linear is, and the bigger the threshold pressure gradient is.

Viscosity

Because the absolute permeability of one core is the same, the main factor which influences the threshold pressure gradient of Core H-30 changes to the fluid viscosity of different displacement zones. By studying the single factor, it can be obtained a more accurate relationship between threshold pressure gradient and fluid viscosity. On the basis of Figure 4, as the fluid viscosity increasing, the threshold pressure gradient of H-30 increases gradually. It can be concluded that the main factor which influences the threshold pressure gradient of the same core is the fluid viscosity. When the viscosity is 0.725MPa.s, the threshold pressure gradient of Core H-30 is 0.0175MPa/m. As the viscosity increases to 1.85MPa.S, the threshold pressure gradient of Core H-30 is 0.0435MPa/m.

Combining Figure 2, it can be known, with the increasing of fluid viscosity, the non-linear segment is elongating in the curve of pressure gradient and flow rate. The curvature of the curve decreases, and the non-linearity becomes heavier. As a result, the threshold pressure gradient is increasing. When the fluid viscosity decreases to a certain value, the fluid flow changes from non-Darcy to Darcy in the core, and the threshold pressure gradient is close to zero.

Mobility

It has been analyzed the influences of permeability and viscosity on the threshold pressure gradient respectively, and now analyzes their influences on the threshold pressure gradient by combining the two factors. Permeability divided by viscosity is the mobility (k/μ), which integrates the effect of permeability and viscosity on the threshold pressure gradient. It can be seen from Figure 5, after the regression with the values of threshold pressure gradient and the values of mobility, it presents a power function distribution. The equation is $Y=0.179X^{-0.509}$, and the correlation coefficient is $R^2=0.9355$.

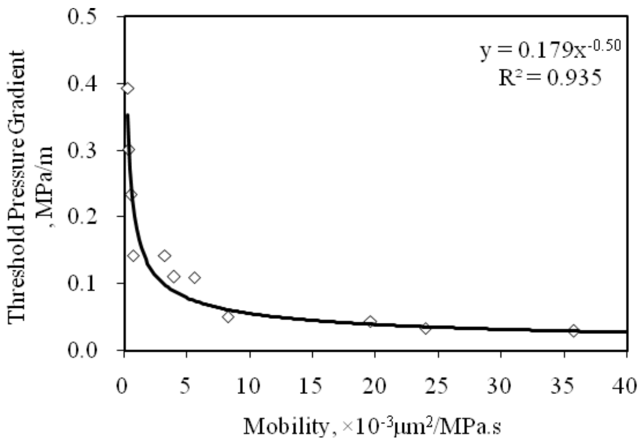

Fig. 5 The Relationship between Mobility and Threshold Pressure Gradient

As the mobility decreasing, the threshold pressure gradient increases gradually. The inflection point of threshold pressure gradient and mobility appears that the mobility is $5\times10^{-3}\mu m^2$/MPa.s and the threshold pressure gradient is 0.1MPa/m. When the mobility is less than $5\times10^{-3}\mu m^2$/MPa.s, the threshold pressure gradient increases sharply. When the mobility is bigger than $5\times10^{-3}\mu m^2$/MPa.s, the threshold pressure gradient decreases gradually, and the changing is smooth. Therefore, in order to reduce the threshold pressure gradient, it can be increased the mobility by improving the effective permeability or decreasing the fluid viscosity. The bigger the mobility is, the stronger the liquidity is, the smaller the pressure gradient that the linear flow needs is, and the easier the fluid flows through the pore and throat.

Conclusion

(1) The experimental studies show that the curve of flow rate and pressure gradient presents a concave distribution in low permeability core, which is divided into non-linear segment and linear segment. There is an inflection point between the two segments and the threshold pressure gradient is found.

(2) Each displacing phase zone has a different fluid viscosity, effective permeability, density and gas oil ratio, which can affect the threshold pressure gradient. The threshold pressure gradients from the same core are arranged from small to large as following: miscible oil phase zone, frontal phase zone of gas injection and original oil phase zone.

(3) Core permeability is one of the important factors that influence the threshold pressure gradient. The threshold pressure gradient and core permeability bases on the power function, and the equation is $Y=0.1061X^{-0.4821}$ and $R^2=0.9894$. In the low permeability reservoir, it can be determined the mathematical expression by defining the corresponding regression coefficient and the index value.

(4) Fluid viscosity is one of the important factors that influence the threshold pressure gradient. The viscosity influences the flow of the fluid. The bigger the viscosity is, the harder the fluid flows in the pores,

and the bigger the threshold pressure gradient is. On the contrary, the easier the fluid flows in the pores, the smaller the threshold pressure gradient is.

(5) The mobility comprehensively considers the effect of permeability and viscosity on the threshold pressure gradient. The threshold pressure gradient and core permeability bases on the power function. The equation is $Y=0.179X^{-0.509}$ and $R^2=0.9355$. On the condition that knowing the fluid viscosity, the threshold pressure gradient can be determined by looking up the chart.

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