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Effect of stress sensitivity on displacement efficiency in CO_2 flooding for fractured low permeability reservoirs

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Abstract: Carbon dioxide flooding is an effective means of enhanced oil recovery for low permeability reservoirs. If fractures are present in the reservoir, CO_2 may flow along the fractures, resulting in low gas displacement efficiency. Reservoir pore pressure will fluctuate to some extent during a CO_2 flood, causing a change in effective confining pressure. The result is rock deformation and a reduction in permeability with the reduction in fracture permeability, causing increased flow resistance in the fracture space. Simultaneously, gas cross flowing along the fractures is partially restrained. In this work, the effect of stress changes on permeability was studied through a series of flow experiments. The change in the flowrate distribution in a matrix block and contained fracture with an increase in effective pressure were analyzed. The results lead to an implicit comparison which shows that permeability of fractured core decreases sharply with an increase in effective confining pressure. The fracture flowrate ratio declines and the matrix flowrate ratio increases. Fracture flow will partially divert to the matrix block with the increase in effective confining pressure, improving gas displacement efficiency.

Key words: Stress sensitivity, flowrate distribution, matrix, fracture, CO_2 flooding, displacement efficiency

1 Introduction

Economic development results in an increasing demand for crude oil. High water cut production is the norm in Chinese large oilfields, necessitating the development of marginal oilfields, especially low permeability reservoirs. Since the 1990s, the reserves of oil and gas in low permeability reservoirs have accounted for a growing proportion of the total proved reserves. Therefore, it is extremely important to continue to develop low permeability reservoirs. However, conventional waterflooding is not effective in low permeability reservoirs and encounters such problems as poor injectivity, low producibility and low recovery ratio (Huang, 1998). Gas injection, one of most effective methods of enhanced oil recovery for low permeability reservoirs, has recently received more attention (Rao, 2001; Kulkarni, 2004; Moritis, 2004). In addition, the high dependence on fossil fuels has increased the emission of global greenhouse gases, which has severely threatened the environment. Consequently, emission reduction of greenhouse gases has become extremely urgent (UN, 1992; 1998). Carbon dioxide, one of the major greenhouse gases, can be injected into low permeability reservoirs to improve oil recovery profitably (Asghari and Al-Dliwe, 2005; Damen et al, 2005; Jessen et al, 2005; Bachu et al, 2007).

Natural and artificial fractures often exist in low permeability reservoirs. Gases injected into reservoirs are prone to cross flow along high permeability zones or fractures, causing early breakthrough of gas (Schechter, 2004). Simultaneously, reservoir pore pressure will fluctuate during the process of gas injection, which contributes to changes in effective confining pressure. As a result, permeability will change, especially in fractured low permeability reservoirs. The decrease in permeability coupled with multiphase flow can cause substantial decreases in well productivity in stress sensitive formations (Ross et al, 1982; Streit and Richard, 2004; Hovorka et al, 2006; Bagheri and Settari, 2006). There has been much research in this area. The fracture opening is strongly dependent on the normal stress across the fracture (Goodman and Onishi, 1974). Both laboratory and field results showed that fractures close rapidly under the action of an applied normal load and that the normal force-closure curve is nonlinear (Goodman and Dubois, 1972; Pratt et al, 1974). Some experiments and theories on the relationship between fracture properties and confining stress were

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extensively investigated (Gale, 1981). Fracture properties influencing fluid flow mainly include fracture surface roughness, surface geometry, and surface filling (Engelder and Scholz, 1977). Currently, the effect of applied stress on fluid flow and flowrate distribution is the subject of some research (Muralidharan, 2004; Diyashev, 2005). Although the effect of applied stress on fluid flow in fractured rocks has been investigated, studies of the applicability of this effect and gas flowrate distribution in gas flooding are sparse. This paper presents the effect of permeability sensitivity on gas flooding efficiency. Concretely, reservoir permeability reduction resulting from reservoir pore pressure fluctuation was studied. Gas flooding experiments under different effective pressures were performed, which provided reference for CO_2 flooding in fractured reservoirs.

2 Experimental methods

2.1 Test samples

Physical parameters of the artificial sandstone cores used in tests are listed in Table 1. Each core, with a matrix permeability of 3×10^{-3}-300×10^{-3} μm^2, contains a single fracture oriented parallel to the core axis. Sketches of a fractured core are shown in Figs. 1 and 2.

Table 1 Parameters of core samples

Core No.	Diameter cm	Length cm	Permeability 10^{-3}μm^2
HW1	2.520	8.138	306.060
MK3	2.500	8.040	31.189
PC2	2.510	6.130	3.401

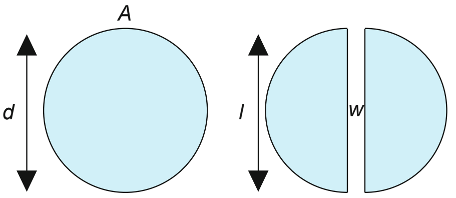

Fig. 1 Schematic layout of cross sections for matrix core and fractured core

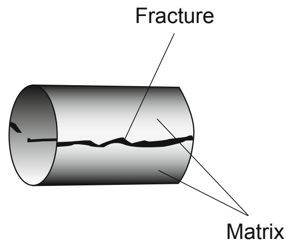

Fig. 2 Schematic layout of fractured core

2.2 Experimental procedures

2.2.1 Experimental setup

Fig. 3 shows a scheme of the experimental setup. The injection system included a constant pressure, constant speed pump and a high pressure gas bottle with CO_2 of 99.99% purity. A hand pump provided confining pressure for the system. Fluid flowrate and gas flowrate were measured with a volumetric cylinder and a gas flowmeter, respectively.

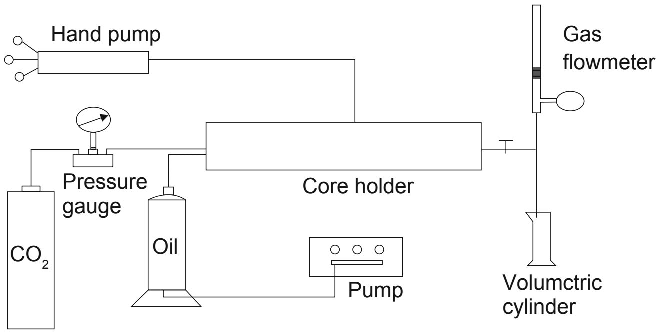

Fig. 3 Schematic layout of experimental setup

2.2.2 Permeability-stress sensitivity experiment

Permeability stress sensitivity with CO_2 in a matrix core and a fractured core was investigated. The effective confining pressure (or effective stress) is defined as the confining pressure minus the pore pressure. It can be simulated through the difference between confining and pore pressures. Average permeabilities of the matrix core and the fractured core were measured under effective confining pressures of 3, 5, 10, 15, 20, and 30 MPa, respectively.

2.2.3 Gas flooding experiment

A 1:4 mixture of Changqing crude oil and kerosene was used as simulated oil. The viscosity of this oil was 1.775 mPa·s at 45 ºC and atmospheric pressure. After being thoroughly dried and weighed, fractured cores were evacuated in a vacuum flask for at least 12 hours and then saturated with the simulated oil. After saturating the core samples, several days were allowed for ageing within the rock. The volume of simulated oil necessary to saturate the cores was determined from the gain in weight. Finally, one of the saturated cores was inserted in the core holder. An initial confining pressure of 3 MPa was applied. This was followed by core flooding with carbon dioxide at a gas injection pressure of 0.2 MPa. Subsequently, carbon dioxide was displaced from the fractured core by more than three pore volumes of simulated oil at a low flowrate until no more gas was produced. The experiments were repeated at effective confining pressures of 5, 10, 15, 20, and 30 MPa, respectively. Corresponding displacement efficiencies were recorded.

The displacement efficiency is mainly affected by the pressure gradient in immiscible flooding. The inlet pressure is designed to be 0.2 MPa to achieve an average pressure gradient of 2.690 MPa/m, which is much higher than that in the field. In addition, it should be noted that resaturation with the simulation oil in this manner is incomplete, meaning there is residual gas remaining in the cores after displacement. However, the residual gas saturation is low enough to be neglected due to the significant difference in viscosity between oil and CO_2. Moreover, the same fractured core was adopted to maintain the similarity in the properties of the fracture. Additionally, the saturation volumes are approximately judged by weighing cores. Based on the above considerations, the method of resaturation with simulation oil was utilized.

2.3 Estimation of permeability and flowrate distribution of fractured core

Flow sketch maps of the matrix core and the fractured core are shown in Figs. 4 and 5.

Fig. 4 Schematic layout of flow in matrix core

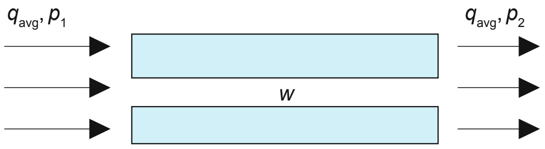

Fig. 5 Schematic layout of flow in fractured core

If the gas is assumed to behave as an ideal gas and be of constant viscosity, the permeability of the matrix block can be calculated as below:

$$K_m = \frac{10\mu_0 q_m p_0 L}{3A(p_1^2 - p_2^2)} \tag{1}$$

The average permeability of the fractured core can be obtained as below:

$$K_{avg} = \frac{10\mu_0 q_{avg} p_0 L}{3A(p_1^2 - p_2^2)} \tag{2}$$

Single fracture permeability is (Bradley, 1987):

$$K_f = 8.44 \times 10^9 w^2 \tag{3}$$

where K_m is matrix permeability, $10^{-3}\mu m^2$; K_{avg} is the average permeability of the fractured core, $10^{-3}\mu m^2$; μ_0 is the viscosity of CO_2 under standard conditions; q_m is the flowrate through the matrix block, cm^3/min; q_{avg} is the average flowrate through the fractured core; p_0 is the atmospheric pressure, MPa; p_1 and p_2 are the inlet and outlet absolute pressures, respectively, MPa; A is the cross section area; L is the core length, cm; w is the fracture aperture, cm; and K_f is the fracture permeability, 10^{-3} μm^2.

In fractured rocks, the average flowrate is equal to the sum of the single fracture's flowrate and the matrix block's flowrate.

$$q_{avg} = q_f + q_m \tag{4}$$

From Darcy's law, we have

$$\frac{K_{avg}A}{\mu_o} \cdot \frac{3(p_1^2 - p_2^2)}{10 p_0 L} = \frac{K_f A_f}{\mu_o} \cdot \frac{3(p_1^2 - p_2^2)}{10 p_0 L} + \frac{K_m A_m}{\mu_o} \cdot \frac{3(p_1^2 - p_2^2)}{10 p_0 L}$$

Then,

$$K_{avg} A = K_f A_f + K_m A_m \tag{5}$$

$$K_f = \frac{K_{avg} A - K_m (A - wl)}{wl} \tag{6}$$

The combination of Eq. (3) and Eq. (6) gives,

$$8.44 \times 10^9 w^3 l - K_{avg} A + K_m (A - wl) = 0 \tag{7}$$

The fracture aperture can be calculated from the above equation. By combining Darcy's law and Eq. (4), flowrates through the matrix block and fracture can be obtained.

The flowrate through the matrix block is:

$$q_f = 2.532 \times 10^9 \frac{w^3 l (p_1^2 - p_2^2)}{\mu_0 p_0 L} \tag{8}$$

The flowrate through a single fracture is:

$$q_f = 2.532 \times 10^9 \frac{w^3 l (p_1^2 - p_2^2)}{\mu_0 p_0 L} \tag{9}$$

where l is the fracture width, cm; q_f is the flowrate through the fracture, cm^3/min.

3 Experimental results

3.1 Permeability stress sensitivity for fractured cores

3.1.1 Effect of stress sensitivity on permeability for fractured cores

Experiments of stress-sensitive permeability were performed on three groups of core samples. Each group included a matrix core and a fractured core, in which the permeability of the matrix core is equal to the permeability of the matrix block in the fractured core. The results are shown in Figs. 6-8.

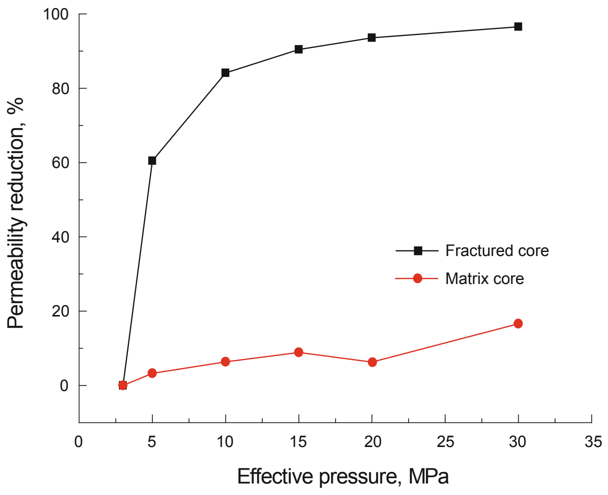

Fig. 6 Permeability reduction ratio of core PC2

As shown in Figs. 6 to 8, the effect of effective confining pressure on permeability is present in both matrix cores and fractured cores. The permeability retention ratio or normalized permeability is calculated by dividing the permeability at given effective pressure by standard permeability that is

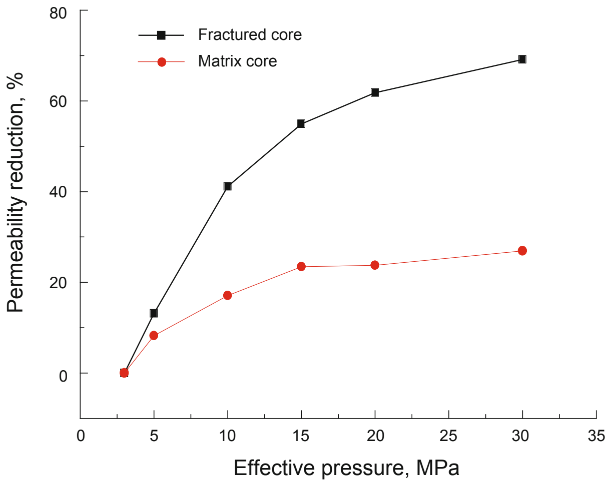

Fig. 7 Permeability reduction ratio of core MK3

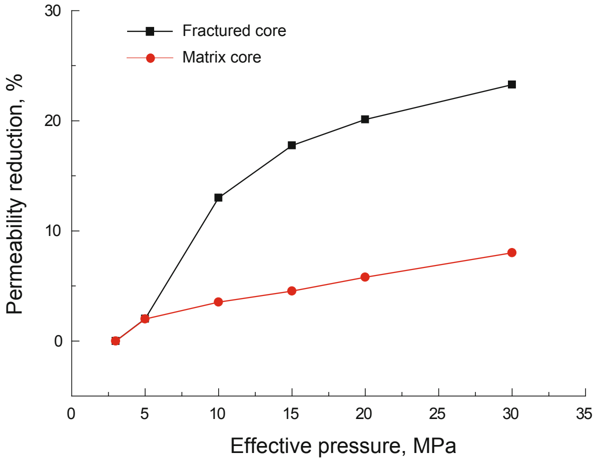

Fig. 8 Permeability reduction ratio of core HW1

measured at 3 MPa effective pressure, and the permeability reduction ratio is defined by 100% minus the permeability retention ratio. Moreover, the permeability is reduced in both cases with the increase in the effective stress. However, the decrease in the permeability of fractured cores is much more significant compared with matrix cores. Specifically, the permeability reduction of fractured cores PC2, MK3 and HW1 are about 90%, 60% and 20%, respectively.

Table 1 gives the parameters of cores. The permeability of matrix core PC2 is the smallest (3.04×10^{-3} μm), followed by MK3, and then HW1. In order to describe the difference in permeability between the fracture and the matrix block in fractured core, the concept of permeability contrast is introduced, originally proposed to characterize the difference in permeability between the high permeability layers and the low permeability layers in a heterogeneous reservoir. Obviously, the permeability contrast of fractured core PC2, MK3, and HW1 increases in turn. The results indicate that the bigger the permeability contrast, the bigger the permeability reduction as well as the rate of permeability reduction. In addition, the permeability reduction mainly happens with an initial increase in effective confining pressure. As the effective confining pressure increases to definite values or greater, the permeability reduction will be trivial.

3.1.2 Effect of stress sensitivity on flowrate distribution for fractured cores

The flowrate distribution in the fracture versus the matrix block in fractured core can be obtained by flowing CO_2 at different effective pressures. The results are demonstrated in detail below (Figs. 9-12). The fracture flowrate ratio is equal to the value of the fracture flowrate divided by the average flowrate or the total flowrate of the fractured core, and the matrix flowrate ratio is equal to the value of the matrix flowrate divided by the average flowrate or the total flowrate of the fractured core.

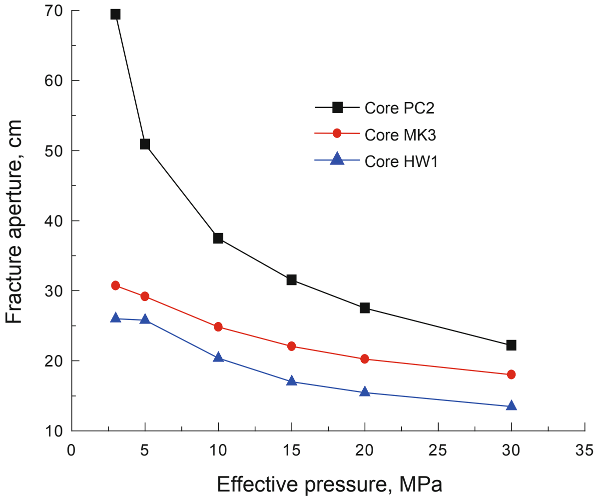

Fig. 9 Relationship between fracture aperture and effective pressure

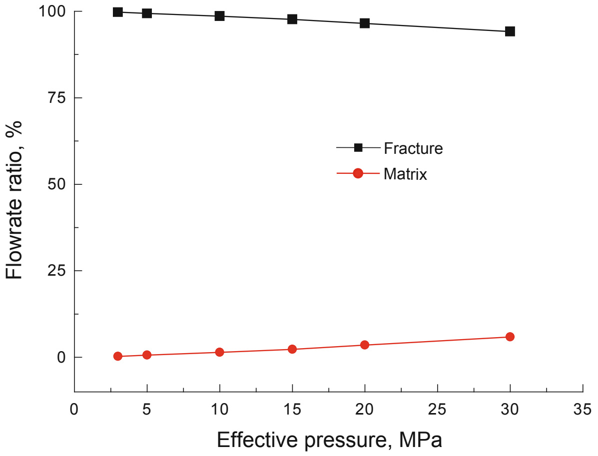

Fig. 10 Flowrate distribution in core PC2

In Fig. 9, the fracture aperture has a similar trend with fracture permeability at different effective confining pressures. The reason is that the fracture aperture is a function of fracture permeability. As shown in Fig. 10 through Fig. 12, the fracture flowrate ratio gradually decreases and the matrix block flowrate ratio gradually increases with an increase in effective confining pressure. For core PC2, with high permeability contrast between the fracture and matrix, the fracture flowrate is dominant at the initial effective pressure. For core MK3, the fracture flowrate still dominates, but the difference between the fracture and matrix block decreases compared with core PC2. For core HW1, with a large matrix block permeability and low permeability contrast, the fracture flowrate is smaller than the matrix flowrate. In general, the fracture flowrate ratio gradually decreases and the matrix flowrate ratio gradually increases with an increase in effective confining pressure. Furthermore, the matrix flowrate is approximately equal to the fracture flowrate, even exceeding it with the increase in effective confining pressure.

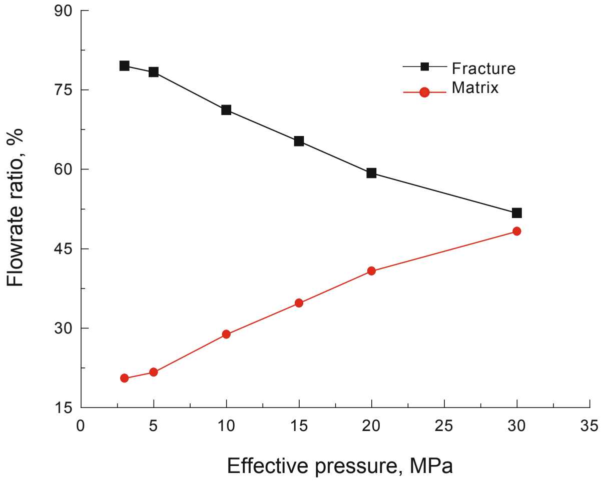

Fig. 11 Flowrate distribution in core MK3

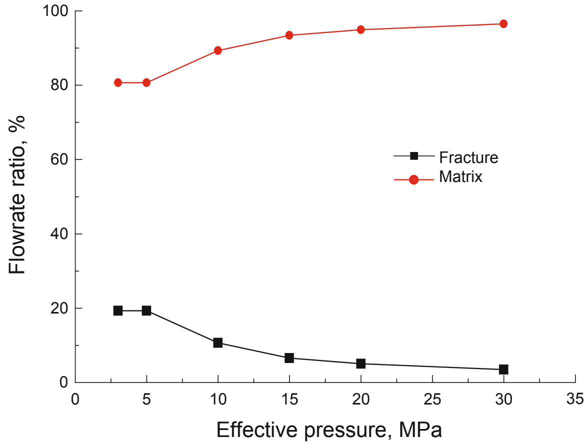

Fig. 12 Flowrate distribution in core HW1

3.2 Effect of stress sensitivity on CO_2 displacement efficiency for fractured cores

It is well established that CO_2 flooding is one of the best enhanced oil recovery methods. However, due to natural fractures or heterogeneity in reservoirs, gas injected into reservoirs is prone to early breakthrough along fractures or high permeability layers. The performance of gas flooding is poor in these reservoirs. The results of stress-sensitive permeability experiments indicate that the gas flowrate distribution can be changed with changing effective confining pressure. Whether the change of flowrate distribution in the fractured core can improve oil recovery for gas injection or not is the question at hand. CO_2 flooding experiments conducted at different effective confining pressures can provide insight into this question.

The results shown in Fig. 13 indicate that gas displacement efficiency first rises and then decreases with an increase in effective confining pressure. For core PC2 with maximum permeability contrast, gas displacement efficiency is the highest when the effective pressure is within the range of 20 to 25 MPa. For core MK3, gas displacement efficiency is the highest when the effective pressure is approximately 20 MPa. For the core HW1 with smaller permeability contrast compared with the above cores, the gas displacement efficiency reaches peak values when the effective pressure is in the range of 10 to 15 MPa. This indicates that the increase in effective pressure reduces the fracture aperture and the permeability contrast, which inhibits early gas breakthrough, increases gas sweep efficiency, and improves gas displacement efficiency. However, as effective pressure increases, gas displacement efficiency will decrease because the fracture gradually closes and the matrix block begins to partially deform at high effective pressure values. Comparing the cores with different permeability contrast, gas displacement efficiency is smaller for cores with high permeability contrast at lower effective pressures, but bigger at higher effective pressures.

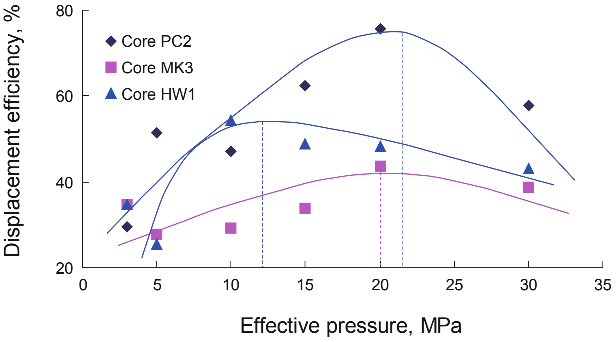

Fig. 13 CO_2 displacement efficiency at different effective pressures

4 Discussion

The permeability reduction in fractured cores is bigger than that in matrix cores. The reason is that the permeability reduction of matrix cores depends on the pore structure deformation. However, the permeability reduction of fractured core depends on fracture properties. As effective confining pressure increases, the fracture is much easier to deform than the pore structure and the fracture aperture reduces sharply. High permeability contrast, which indicates low matrix permeability, makes the fracture space reduce significantly with an increase in effective confining pressure. As the effective confining pressure increases, the permeability contrast of the fractured core decreases. The fracture permeability approaches the matrix permeability as the effective confining pressure increases. Additionally, the permeability reduction rate gradually declines. Note that the fracture aperture is not completely healed even at a high effective pressure, but rather remains a flow channel in fractured cores.

Simultaneously, flow resistance in the fracture will become larger with the reduction in the fracture aperture. The fracture walls will be in contact over part of their surface, and the flow path will be more tortuous. If the injection pressure remains invariable, the fracture flowrate ratio will decline and the matrix flowrate ratio will increase with an increase in effective confining pressure. It is obvious that parts of the fracture flowrate divert into the matrix block. Changes of effective pressure will affect the flowrate distribution in the fracture and matrix block. From another perspective, the effect of effective pressure on flowrate distribution can restrict early gas breakthrough in the fracture and broaden the gas sweep area into the matrix block. It is very important for CO_2 flooding to restrain gas cross flow. Whether the increase in effective pressure can partially improve oil recovery from gas flooding or not is a key question. The results of gas flooding experiments indicate the flowrate redistribution effect would seem to improve oil recovery for gas flooding. There will be more gas entering into the matrix block with an increase in effective pressure in fractured cores.

Stress sensitivity of permeability characterizes the influence of effective confining pressure on permeability. It certainly causes a detrimental effect on reservoir production. Due to the existence of natural fractures or heterogeneity, the difference between the fracture and matrix block or the permeability contrast is big. Gases injected into a reservoir mostly cross flow into the production well along high permeability fractures during gas flooding, resulting in poor performance. It is proposed that a higher pressure maintenance level can partially improve sweep efficiency during gas flooding. In detail, an increase in effective confining pressure can induce definite deformation for fractured cores, which means a low pore pressure maintenance level. The reduction in fracture permeability causes an increase in flow resistance in the fracture. Then the gas injected into reservoirs will partially divert into and increase oil recovery from the matrix block. Of course, the pressure maintenance level is related to the matrix permeability and the permeability contrast of the cores. The pressure maintenance level is relative low for cores with low matrix permeability and large permeability contrast. The pressure maintenance level is relative high for cores with high matrix permeability and small permeability contrast.

5 Conclusions

1) Permeability decreases sharply with an initial increase in effective confining pressure. As the effective confining pressure increases, the reduction in permeability becomes less. The higher the permeability contrast between the fracture and the matrix block, the bigger the reduction in permeability with an increase in effective confining pressure. The permeability reduction of the fractured core depends mainly on the fracture, and the fracture also deforms as the effective pressure is changed.

2) The fracture aperture trends in a similarly manner as fracture permeability at different effective confining pressures.

3) A change in effective confining pressure can cause flowrate redistribution in the fracture and matrix block. As the effective confining pressure increases, the fracture flowrate ratio decreases, and the matrix flowrate ratio increases. This indicates that with an increase in effective confining pressure the fracture flowrate partially diverts into the matrix block.

4) The increase in effective confining pressure can restrain gas channeling in fractured cores, to some extent, which can improve gas sweep efficiency in the matrix block, thereby resulting in improved oil recovery. As the effective confining pressure becomes higher, the permeability reduction in both the fracture and the matrix block will be larger. The effective pressure has a significant effect on reservoir productivity. Gas displacement efficiency will be reduced somewhat. However, the displacement efficiency at a higher effective confining pressure is still bigger than that at lower effective confining pressure.

5) An increased maintenance level of effective confining pressure can improve oil recovery during gas flooding. The pressure maintenance level is relatively high for the reservoirs with low matrix permeability and big permeability contrast, and relatively low for reservoirs with high matrix permeability and small permeability contrast.

The effect of fracture orientation and morphology on fracture flowrate and matrix flowrate will be further investigated, as well as the effect on CO_2 displacement efficiency. The distribution of CO_2 in fractured cores, which are saturated with water or oil, will also be investigated in detail.

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