Experiments on Seepage Flow Patterns in Fine Controlled Fractured Thin and Poor Reservoir

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Abstract. Experiments on seepage flow patterns in fine controlled fractured thin and poor reservoir were carried out based on artificial core plate models. Pressure gradient distribution is revealed based on pressure data obtained by pressure transducers in artificial core plate models, and sketch maps of seepage flow sections are drawn to study on seepage flow patterns qualitatively and quantitatively. Experiments show that seepage flow patterns in thin and poor reservoir are influenced by permeability, heterogeneity and cracks of fine controlled fracturing, horizontal cracks generated by fine controlled fracturing have greater influence on seepage flow patterns as thin and poor reservoirs have strong homogeneity and low permeability. Fine controlled fracturing can reduce the negative influence of low permeability and strong heterogeneity and expand fluid flow range. Thin and poor reservoirs can be divided into three sections by types of seepage flow for fluid flowing through, i.e. the no-flow section, the nonlinear seepage flow section, and the quasi-linear seepage flow section. The no-flow section is reduced by at least 72% by fine controlled fracturing, and area for fluid flowing through increases correspondingly, and the proportion of quasi-linear percolation area which is more conducive to fluid flow raise by over 87%.

1. Introduction
The main object of water flooding in old oilfield at high water-cut stage has changed from reservoirs with good physical properties and large thickness to thin and poor reservoirs. Thin and poor reservoirs refer to reservoirs with small thickness, poor physical properties and strong heterogeneity. Fine controlled fracturing is new approach to improve the usage of thin and poor reservoirs which refer to fracturing in single sand body connected injection and production wells with fracturing layers and crack radius under fine control. Seepage flow pattern is the intermediate process between the undertaking mechanism and the production condition, and seepage flow patterns in fine controlled fracturing thin and poor reservoirs are basic problems to be further studied on.

The seepage flow in fine controlled fracturing thin and poor reservoir is equivalent to fluid flow in heterogeneous reservoir with low permeability under horizontal fracture. Distribution and variation of pressure gradient is a dynamic reflection of seepage flow and can be used to characterize seepage flow patterns in fine controlled fracturing thin and poor reservoirs. There have been plenty studies on fluid flow characteristics in porous media, experiments of relationship between pressure difference and fluid volume [1-3] or determination of relative permeability curves [4-5] are regularly carried out, but studies on seepage flow patterns in thin and poor reservoirs are not systematic and perfect. The conventional one-dimensional physical models are widely used and developed, but it can't simulate the
influence of heterogeneity and injection-production relationship [6-7]. Three dimensional artificial core plate models can simulate heterogeneous reservoirs with poor physical properties and fracturing cracks[8], so as to study on seepage flow patterns in fine controlled fracturing thin and poor reservoirs.

2. Experiments

2.1. Experimental conditions
The experimental conditions such as geometric, physical and time proportion should be reduced to reasonable scale [9-11].

| Experimental conditions | Parameters of typical injection and production unit in fine controlled fracturing thin and poor reservoir |
|-------------------------|--------------------------------------------------------------------------------------------------|
| Length of plate model   | Length of injection and production unit 140m                                                    |
| Diagonal length of plate model | Well spacing 200m                                      |
| Thickness of plate model | Thickness of thin and poor reservoir 7.5m                                                      |
| Permeability of plate model | Permeability of thin and poor reservoir 10-50×10^{-3}μm² |
| Porosity of plate model  | Porosity of thin and poor reservoir 0.195                                                        |
| Crack radius in plate model | Crack radius of fine controlled fracturing 50m                                                  |
| Pressure difference     | Pressure difference 20 MPa                                                                       |
| Oil viscosity           | Oil viscosity 6.7 mPa*s                                                                           |
| Water viscosity         | Water viscosity 1.0 mPa*s                                                                          |
| Oil density             | Oil density 0.88 g/cm²                                                                            |

Artificial core plate models of fine controlled fractured thin and poor reservoir are designed and made based on permeability and porosity, and take heterogeneity between injection and production points into account at the same time. Thin and poor reservoirs have the characteristics of poor physical properties and strong heterogeneity, and the conductivity of cracks generated by fine controlled fracturing is much larger than conductivity of reservoir.

Figure 1. Design of sand packing moulds for artificial core plate model of fine controlled fractured thin and poor reservoir.
Sand packing method is carried out to made plate models. Plate models are divided into different sand packing zones to simulate different physical properties (Figure 1).

Figure 2. Arrangement of pressure transducers, injection and production points for artificial core plate model of fine controlled fractured thin and poor reservoir.

Twelve pressure transducers are symmetrically arranged on plane in the vertical middle position of artificial core plate models (Figure 2).

Figure 3. Front view of some artificial core plate model.

Figure 3 shows the front view of certain artificial core plate model, its appearance, size and seal meet the experimental requirements.

2.2. Experimental apparatuses
The self-designed physical simulation apparatuses of artificial core plate models (Figure 4) consist of four parts, injection and control system, artificial core plate model auxiliary system, pressure measurement and recording system, and production and measurement system.
1- Injection and Controlling System; 2- Artificial Core Plate Model Auxiliary System; 3- Pressure Measurement and Recording System; 4- Production and Measurement System; 5-High Pressure Pump; 6-Pressure Stabilizing Device; 7- Injection Fluid Tank; 8- Micro Flowmeter; 9- Electronic Balance; 10- Pressure Inspection Instrument; 11- Recording System

Figure 4. The self-designed physical simulation apparatuses of artificial core plate models.

2.3. Experimental process
Different artificial core plate models are designed and made in order to study on the seepage flow patterns in fine controlled fracturing thin and poor reservoir. Experiments were carried out by plate models named 10-20mD and 10-50mD to characterize two types of heterogeneity in thin and poor reservoir, the permeability of injection point zone is set to $10 \times 10^{-3} \mu m^2$, and the permeability of production point zone is set to $20 \times 10^{-3} \mu m^2$ and $50 \times 10^{-3} \mu m^2$, the analysis focuses on two cases of permeability contrast of 2 and 5. Experiments were carried out by other plate models with cracks named LF10-20mD and LF10-50mD to characterize the effect of fine controlled fracturing.

Make sure that the viscosity, density and other properties of formation oil and formation water can meet the experimental conditions, plate models are saturated with treated fluids to simulate oil-bearing and water-cut conditions of thin and poor reservoir. Filtered formation water is injected under constant pressure difference of 0.42 MPa to simulate production under constant pressure. The pressure value at each measurement point is obtained after the flow rate of production point is stable.

3. Results and Discussions

3.1. Distribution of pressure gradient
Pressure gradient data can be filled with pressure data with extrapolation interpolation algorithm processing after planar mesh generation. Pressure gradient distribution map of different plate models can be drawn to analyze seepage flow patterns in fine controlled fracturing thin and poor reservoirs.
Pressure gradient distribution maps of artificial core plate models (Figure 5 and Figure 6) show that, the pressure gradient contours are approximately elliptical with the well points as the centre of the ellipse and connection line of injection and production points as long axis, and the integral form of pressure gradient contours of different plate models are similar. The pressure gradient is very high around well points, and the pressure gradient of diagonal corner is very low.

The variation of pressure gradient around wellbore increases as increased heterogeneity degree determined by different permeability of different plate models. The area of high pressure gradient around the wellbore is decreased due to the increasing of permeability of production zone, the distribution of contours is sparser, the pressure drop of the same distance becomes smaller, and the propagation distance of the same pressure becomes larger. At the same time, Low pressure gradient region of plate models becomes smaller.

Pressure gradient distribution maps of artificial core plate models with cracks (Figure 7 and Figure 8) show that, the pressure gradient contours are approximately elliptical with the well points as the center of the ellipse, crack edge as the boundary and connection line of injection and production points as the long axis. The strip around crack edge is high pressure gradient zone, and the pressure gradient of diagonal corner is also very low. Certain area of low pressure gradient is formed inside cracks as permeability of cracks is far higher than other parts. Fluid flows through cracks for a short time with almost no pressure consumption, and the pressure gradient is almost unchanged.

Pressure gradient slightly change as permeability and heterogeneity of different plate models change. The high pressure gradient at crack edge is obviously reduced, the pressure gradient reduction at injection point is less than that of production point, low pressure gradient region of plate models slightly reduce at the same time.
3.2. Variation of seepage flow sections
The typical seepage flow pattern chart of thin and poor reservoir can be established based on experiments on seepage velocity and pressure gradient by typical natural cores.

Figure 9. The typical seepage flow pattern chart of thin and poor reservoir.
Plate models can be divided into three sections by types of seepage flow for fluid flowing through, i.e., the no-flow section, the nonlinear seepage flow section and the quasi-linear seepage flow section as pressure gradient change.

Figure 10. Sketch map of seepage flow section of 10-20mD plate model.  Figure 11. Sketch map of seepage flow section of 10-50mD plate model.

Sketch map of seepage flow section of artificial core plate models (Figure 10 and Figure 11) shows that three seepage flow sections appear in plate models at the same time. There is no-flow section in the diagonal corner which means that there is some area where the injected fluid can't flow through in the middle point of connection line of injection wells in thin and poor reservoirs. The ratio of no-flow section is the smallest, and the ratio of nonlinear seepage flow section is the largest in plate model. Form and ratio of different seepage flow sections change as heterogeneity of plate models enhance caused by permeability of production points increasing.

Table 2. Seepage flow sections of artificial core plate models.

| Plate model | No-flow section | Nonlinear seepage flow section | Quasi-linear seepage flow section |
|-------------|-----------------|---------------------------------|-----------------------------------|
|             | Ratio/%         | Change extent/%                 | Ratio/%                           | Change extent/% |
| 10-20mD     | 16.612          | /                               | 48.163                            | /               |
| 10-50mD     | 14.393          | -13.358                         | 49.574                            | -2.929          |
|             |                 |                                 | 36.033                            | 2.234           |

Ratio of no-flow section in 10-20mD plate model is up to 16.612%, ratio of no-flow section decreases as permeability of production points increase. Ratio of no-flow section in 10-50mD plate model is 14.393%, reduce extent is 13.358% compared with 10-20mD plate model. On the contrary, ratio of seepage flow section included nonlinear seepage flow section and quasi-linear seepage flow section overall increase. Ratio of nonlinear seepage flow section increase from 48.163% to 49.574%,
and ratio of quasi-linear seepage flow section which is more conducive to fluid flow increase gradually from 35.225% to 36.033%.

Figure 12. Sketch map of seepage flow section of LF10-20mD plate model.  Figure 13. Sketch map of seepage flow section of LF10-50mD plate model.

Sketch map of seepage flow section of artificial core plate models with cracks (Figure 12 and Figure 13) shows that three seepage flow sections still appear in plate models with cracks. There is still small area of no-flow section in the diagonal corner which means that there is some small area where the injected fluid can't flow through in the middle point of connection line of injection wells or in the middle point of connection line of production wells in fine controlled fractured thin and poor reservoirs. The ratio of quasi-linear seepage flow section is the largest in plate model, and the ratio of no-flow section is the smallest. Form and ratio of different seepage flow sections change as heterogeneity of plate models enhance caused by permeability of production points increasing.

Table 3. Seepage flow sections of artificial core plate models with cracks.

| Plate model | No-flow section | Nonlinear seepage flow section | Quasi-linear seepage flow section |
|-------------|-----------------|-------------------------------|-----------------------------------|
|             | Ratio/% | Change extent/% | Ratio/% | Change extent/% | Ratio/% | Change extent/% |
| LF10-20mD   | 4.058    | / | 29.425 | / | 66.517 | / |
| LF10-50mD   | 4.013    | -1.109 | 28.405 | -3.467 | 67.582 | 1.601 |

Ratio of no-flow section in LF10-20mD plate model is 4.058%, ratio of no-flow section decreases as permeability of production points increase, ratio of no-flow section in LF10-50mD plate model is 4.013%, reduce extent is 3.358% compared with LF10-20mD plate model. On the contrary, ratio of seepage flow section included nonlinear seepage flow section and quasi-linear seepage flow section overall increase. Ratio of nonlinear seepage flow section reduce from 29.425% to 28.405%, and ratio of quasi-linear seepage flow section which is more conducive to fluid flow increase gradually from 66.517% to 67.582%.

Table 4. Seepage flow sections of artificial core plate models without and with cracks.

| Plate model | No-flow section | Nonlinear seepage flow section | Quasi-linear seepage flow section |
|-------------|-----------------|-------------------------------|-----------------------------------|
|             | Ratio/% | Change extent/% | Ratio/% | Change extent/% | Ratio/% | Change extent/% |
| 10-20mD     | 16.612 | / | 48.163 | / | 35.225 | / |
| LF10-20mD   | 4.058 | -75.572 | 29.425 | -38.905 | 66.517 | 88.835 |
| 10-50mD     | 14.393 | / | 49.574 | / | 36.033 | / |
| LF10-50mD   | 4.013 | -72.118 | 28.405 | -42.702 | 67.582 | 87.556 |

Change of seepage flow patterns before and after fine controlled fracturing can be analyzed by comparing experimental data of the seepage flow sections of artificial core plate models without and with cracks. Ratio of no-flow section of plate models with cracks greatly decreases compared with ratio of no-flow section of plate models without cracks, which means ratio of no-flow section in thin and poor reservoir greatly decreases after fine controlled fracturing. The decrease in ratio of no-flow...
section is 75.572% when the permeability of injection point is $10 \times 10^{-3} \mu m^2$ and production point is $20 \times 10^{-3} \mu m^2$. The decrease is still more than 72% when the permeability of production point is increased to $50 \times 10^{-3} \mu m^2$. Ratio of nonlinear seepage flow section decrease, and the decrease is 38.905% and 42.702%. The proportion of quasi-linear seepage flow section which is more conducive to fluid flow raise greatly as seepage flow section becomes larger, and the increase is more than 87%. It shows that cracks can greatly reduce the ratio of no-flow section in plate models, and the ratio of no-flow section in thin and poor reservoirs can be greatly reduced by fine controlled fracturing.

4. Conclusions
In this paper, experiments on seepage flow patterns in fine controlled fractured thin and poor reservoir were carried out based on artificial core plate models, and sketch maps of seepage flow sections are drawn to study on seepage flow patterns of fine controlled fractured thin and poor reservoir.

• Seepage flow patterns in thin and poor reservoirs are influenced by permeability, heterogeneity and cracks generated by fine controlled fracturing.
• The effect of permeability is greater than the negative impact of heterogeneous when the overall permeability of the plate model is at a very low level.
• Cracks generated by fine controlled fracturing have greater influence on seepage flow patterns, fine controlled fracturing can reduce the negative influence of low permeability and strong heterogeneity.
• Thin and poor reservoirs can be divided into three sections i.e. the no-flow section, the nonlinear seepage flow section, and the quasi-linear seepage flow section. The no-flow section is reduced by at least 72% by fine controlled fracturing, and the proportion of quasi-linear percolation area which is more conducive to fluid flow raise by over 87%.

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