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Research Article

Experimental Study on Well Pattern Adjustment using Large-Scale Natural Sandstone Flat Model with Ultra-Low Permeability

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Abstract: Aimed at ultra-low permeability reservoirs, the recovery effect of inverted nine-spot equilateral well pattern is studied through large-scale natural sandstone flat model experiments. Two adjustment schemes were proposed based on the original well pattern. This essay has put forward the concept of pressure sweep efficiency for evaluating the driving efficiency. Pressure gradient fields under different drawdown pressure were measured. Seepage area of the model was divided into immobilized area, nonlinear seepage area and quasi-linear seepage area combining with the nonlinear seepage experiment of the small twin core. The results showed that the ultra-low permeability sandstone flat model was characterized as nonlinear seepage law and threshold pressure gradient obviously. For one quarter of the inverted nine-spot equilateral well pattern, the middle region is difficult to develop. The recovery effect can be improved by adjusting production wells or adding injection wells. And the best solution is transforming the corner production well into injection well.

Keywords: Low permeability reservoirs, large-scale sandstone outcrops model, pressure sweep efficiency, threshold pressure gradient, well pattern adjusting

INTRODUCTION

The investigation of the well patterns is one important aspects of an oil and gas field development which is a complex and systemic engineering. Whether it can be properly dealt with will not only affect the long term stability of an oil and gas field, but also affect the economic profit that the oil and gas company can make (Peng *et al*., 2002). The effects of many factors on waterflooding in ultra-low permeability oil field, such as the stronger heterogeneity of reservoirs, the bigger threshold pressure difference and driving pressure gradient, the natural fracture development and the declining productivity index after water breakthrough are getting increasingly strong (Li *et al*., 2002). The reasonable well pattern disposition is a key factor that low permeability oil fields are developed successfully (Li and Tang, 1998). Most of the researchers studied well patterns through theoretical analysis, field testing and numerical simulation (Muskat, 1946; Tong, 1983; Zhang *et al*., 2000; Hou *et al*., 2000). And their conclusions were different. For better simulating reservoirs, some researchers studied through artificial sand filling model experiments (Geertsma *et al*., 1956; Gaucher and Lindley, 1960; Craig *et al*., 1957; Rapoprt, 1995; Butler, 1987; Sugianto and Butler, 1990; Zhou and Wang, 1994; Shen *et al*., 2004; Wang *et al*., 2005). However, artificial sand filling model is difficult to represent the actual reservoir with ultra-low permeability. Nine-spot and equilateral well pattern is the commonest form in low permeability oil fields, especially at the beginning of exploitation in china (Wang, 2007). In this study, a large-scale sandstone flat model made of natural outcrops was established to study the inverted nine-spot equilateral well pattern and its adjustment well patterns. The pressure gradient fields and fluid recovery rate were measured. And according to nonlinear seepage curve of the model's small twin core, the seepage area of the model was divided into different flow areas. This research not only enriches the well pattern research methods, but also provides theoretical basis for effective development of ultra-low permeability reservoirs.

MATERIALS AND METHODS

Physical model preparation: Quotation (Xue *et al*., 2011; Xu *et al*., 2012): By constant-rate mercury injection, when porosity and permeability of the natural sandstone outcrops are close to those of the ultra-Low Permeability Reservoir, their throat radiuses are similar to each other. This proves that natural sandstone outcrops can be used to simulate the ultra-low permeability reservoir in the experiments.

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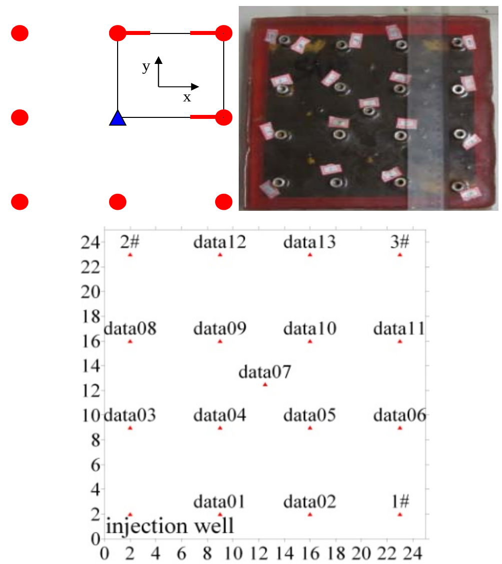


(a) Schematic of model (b) Physical model (c) Measure points

Fig. 1: The model

Flat model in this experiment is made of natural sandstone outcrops. For effective recovery of low/ultra-low permeability oil fields, the physical models should be made of natural sandstone outcrops characterized as fracture. In this essay, it is micro-fractured nonhomogenous reservoir when kx/ky is around 3 (Fig. 1), so the physical models are taken from such sandstone outcrops which is with $3.21\times10^{-3}\mu m^2$ (kx) and $0.8\times10^{-3}\mu m^2$ ky.

For effective simulating the whole well pattern, 1/4 unit of inverted nine-spot equilateral well pattern is taken for experimental simulation. The real lines in Fig. 1 represent the streamlines and as well as the borderline of the physical model. Induced fractures are represented by bold real lines. Injection well is represented by the triangle. Production wells are represented by the circles. The length×width×height of the model is 250 mm×250 mm×30 mm.

Methods: Devices used in this experiment and made by Research Institute of Porous Flow and Fluid Mechanics, Chinese Academy of Sciences, consist of sandstone flat model, injection system, pressure measuring system and micro-flow measuring system.

Sandstone flat model: made up of natural sandstone outcrops.

Injection system: made up of pressure source, pressure stabilizing device and intermediate container and able to inject fluid to flat model under different pressure.

Pressure measuring system: consist of multiple data collector and 13 pressure difference transducers. Multiple data collector transforms the pressure data, measured by pressure difference transducers, which are placed scatteredly on the flat model, to view data and then transmits to computer.

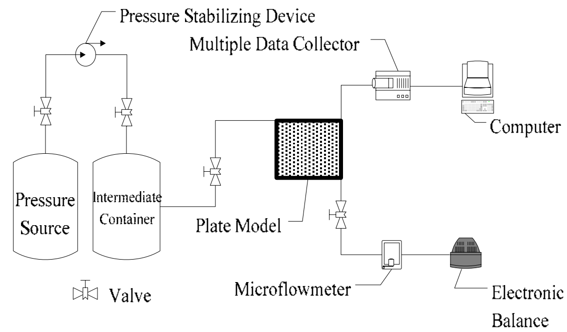


Fig. 2: Schematic of experimental setup

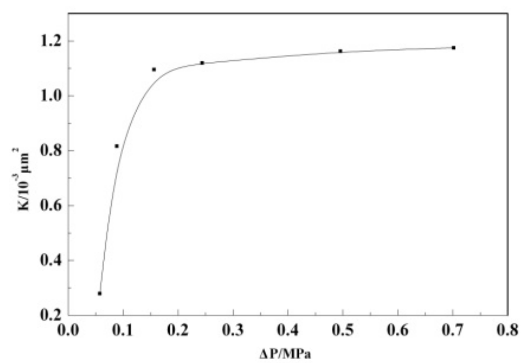


Fig. 3: Water permeability of the model's twin core

Micro-flow measuring system: composed of microflowmeter (Fig. 2).

To carry out experiments on the model as the following steps:

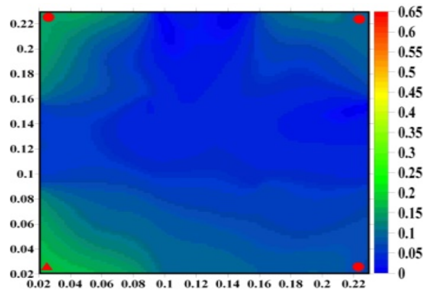
First, vacuumize the models and prepare mineralized water saturated as 100.0×10^3mg/L.

Second, experimentize on the nonlinearity of the model: to simulate the production of the ultra-low permeability reservoir with low pressure and velocity of flow. Inject water to injection well under certain pressure and measure the outflow after the pressure at all points is stabilized. Write down the pressure till it become unchanged. Then increase the pressure gradually and repeat the process and take record of all the data.

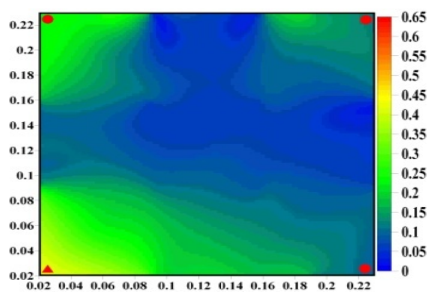
Finally, process the data: to draw a chart of pressure gradient field of the model and analyze the characteristics of the deliverability and provide well pattern adjustment schemes.

RESULTS AND DISCUSSION

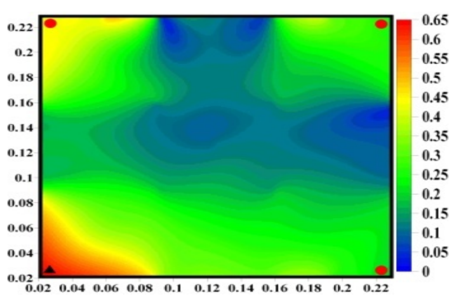
Single phase seepage curve of the small core: Figure 3 shows the water permeability pressure gradient relation curve of the model's small twin core. It shows that there is threshold pressure gradient during the seepage of low



(a) 0.02MPa



(b) 0.04MPa

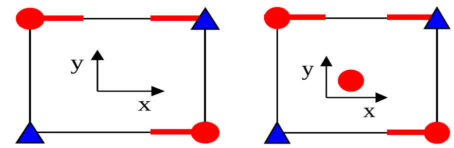


(c) 0.07MPa

Fig. 4: Pressure gradient fields of inverted nine-spot equilateral well pattern

permeability reservoir. And the threshold pressure gradient of single phase seepage in the small twin core is 0.048MPa/m measured with the methods described in literature (Lv *et al*., 2002). Moreover, Fig. 3 shows that seepage through porous media with ultra-Low permeability is characterized with nonlinearity. When the pressure gradient is less than 0.16MPa/m, core permeability increases gradually with pressure gradient increasing and the seepage is characterized with nonlinearity. When the pressure gradient is higher than 0.16MPa/m, the permeability becomes stabilized and the seepage is characterized with quasi-linearity.

Pressure gradient fields and adjustment schemes: The change of pressure reflects the flow of oil reservoir. Based on the theory of nonlinear fluid flow, seepage area can be divided into immobilized area, nonlinear seepage area and quasi-linear seepage area (Lv *et al*., 2002; Yang *et al*., 2010).



(a) Adjustment scheme 1 (b) Adjustment scheme 2

Fig. 5: Adjustment scheme

According to the experiment above, a chart of pressure gradient field is drawn for analysis. And with the help of single phase seepage curve of the small core, seepage areas of the well pattern are divided. Then theoretically where and how the water flows in the model can be reflected. Here define the pressure sweep efficiency as the percentage of seepage area accounts for the area of the model as below:

$$P_e = \frac{Model\ Area - Immobilization\ Area}{Model\ Area} \times 100\%$$

The pressure sweep efficiency is a non-dimensional parameter, which reflects the relation between the drawdown pressure and the seepages.

Figure 4 is the gradient fields under different drawdown pressure, of which the high pressure gradient highlighted in red, while the low one highlighted in blue. From Fig. 4, it is not difficult to see that with the increase of the drawdown pressure, the pressure gradient of the whole model increases especially around the wells. And low pressure gradient appears at the middle of the model, which should be the area that is hard to exploit. The area in which the pressure gradient is lower than 0.048 MPa/m is called immobilized area here. And the area in which the pressure gradient is between 0.048 MPa/m and 0.16 MPa/m is called non-linear seepage area. Finally, the area in which the pressure gradient is higher than 0.16 MPa/m is called quasi-linear seepage area.

From Table 1, it's known that seepage of low permeability oil reservoir is obviously characterized as nonlinearity. As the drawdown pressure increases, the immobilized area reduces and quasi-linear seepage area expands. At the same time, the nonlinear seepage area fluctuates as expanding first and then reducing. And with the increase of the drawdown pressure, the pressure sweep efficiency increases correspondingly, which proves that the increase of the drawdown pressure is helpful for the exploitation of the oil reservoir.

In Fig. 4, the most part of immobilization seepage area is at the middle of the model. The only solution is increasing the pressure gradient of the middle area. Therefore, it can be solved by adding production well to the middle or transforming 3# (the corner production well at the upper right of the model) into injection well. There are two adjustment schemes as follows.

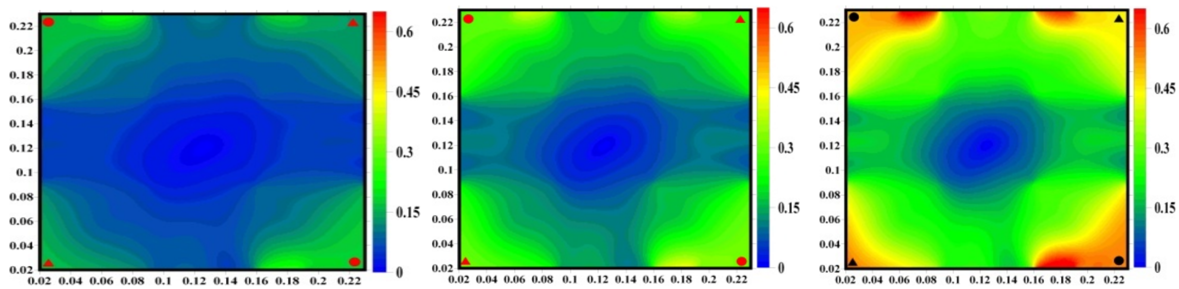
The first adjustment scheme is shown in Fig. 5. On the basis of original inverted nine-spot equilateral well pattern, the corner well (3#) is transformed into injection well.

Table 1: Seepage areas under different drawdown pressure

Pressure difference/MPa	Immobilization area/%	Nonlinear seepage area/%	Quasi-linear seepage area/%	Pressure sweep efficiency/%
0.02	45	55	0	55
0.04	16	73	11	84
0.07	5	36	59	95

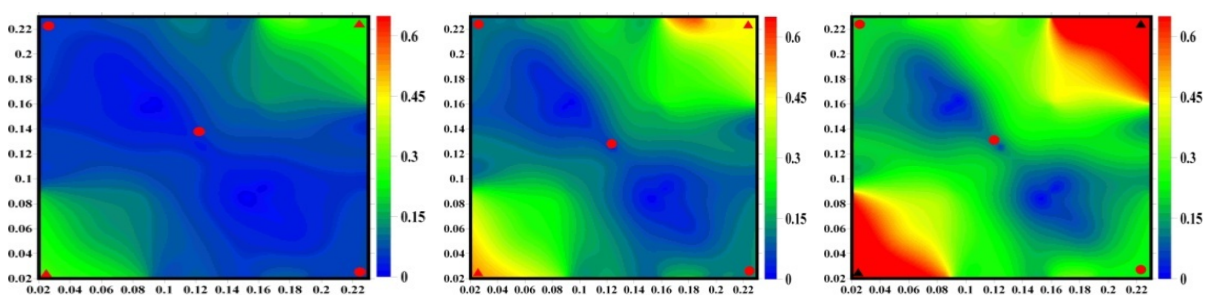
Table 2: Seepage areas under different drawdown pressure

Well pattern	Pressure difference /mpa	Immobilization Area/%	Nonlinear seepage area/%	Quasi-linearseepage area/%	Pressure sweep efficiency/%
Scheme one	0.02	25	64	11	75
	0.04	9	53	38	91
	0.07	2	8	90	98
Scheme two	0.02	24	69	7	76
	0.04	11	49	40	89
	0.07	2	11	87	98



(a) 0.02MPa (b) 0.04MPa (c) 0.07MPa

Fig. 6: Pressure gradient fields of adjustment scheme one



(a) 0.02MPa (b) 0.04MPa (c) 0.07MPa

Fig. 7: Pressure gradient fields of adjustment scheme one

The second adjustment scheme is shown in Fig. 6. On the basis of adjustment scheme one, adjustment scheme two is added a production well to the middle of the model.

The effect after being adjusted can be shown by the comparison of the pressure gradient fields, the pressure sweep efficiency and fluid recovery rate. Figure 7 and 8 are the pressure gradient fields under different drawdown pressure.

From Table 2, with the increase of the drawdown pressure, immobilization seepage area and non-linear seepage area reduced sharply, while the quasi-linear seepage area always increases. And the pressure sweep efficiency increases correspondingly just like the original well pattern, which proves that the increase of the drawdown pressure is helpful for the exploitation once again. Additionally, under the same drawdown pressure, the pressure sweep efficiency of the original well pattern is lower than the other two adjustment well patterns. And the pressure sweep efficiency of the adjustment scheme one is not far from that of the adjustment scheme two. Therefore, the two adjustment

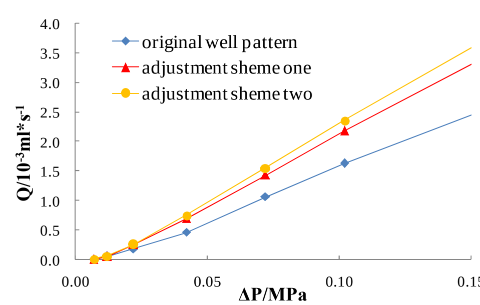


Fig. 8: The fluid recovery rate of the model

schemes are proved to be better than the original well pattern in terms of pressure sweep efficiency. They can be further evaluated through measuring the fluid recovery rate.

Fluid recovery rate analysis: The experiment has simulated the reservoir's production under constant pressure and the flow rate measured under different drawdown pressure. In low drawdown pressure case, the flow rate of low permeability reservoir's production well is very small, even smaller than 0.01×10^{-3} ml/s. Therefore high-precision microflow meter instead of the conventional tools is used in the experiment in order to get accurate data. The fluid recovery rates (Q) of the original well pattern and the two adjustment schemes are measured as shown in Fig. 8.

According to Fig. 8, there is no flow rate when the pressure is too low; therefore threshold pressure gradient is proved to be existing once again. Additionally, the curves illustrate that the fluid recovery rate of adjustment scheme one is the highest and that of the original well pattern is the lowest. Maybe the reason is that the production well at the middle of the model remedies the major defect of the original well pattern in which the pressure gradient is very low at the middle. However, those of the two adjustment well pattern are not far from each other. And it obvious that the middle well in adjustment scheme two may lead to producing water early and even volcanically water flooding in oilfields. Therefore the scheme one is more suitable to oilfield exploitation than the scheme two although scheme two has bigger injection-to-production well ratio.

CONCLUSION

The comprehensive analysis of the recovery efficiency of inverted nine-spot equilateral well pattern and its two adjustment well patterns is presented in the study through the large-scale natural sandstone outcrops flat model experiments which proved the existence of nonlinear flow and threshold pressure gradient. Combining with the nonlinear flow experiments results of the small twin core, the seepage area of the model was divided into immobilized area, nonlinear seepage area and quasi-linear seepage area. Additionally, the flat model experiments demonstrated that the proportion of immobilized area can be reduced effectively correspondingly with the increase of drawdown pressure.

There are two adjustment schemes, just transforming the corner production well into injection well and adding a production well to the middle of the model on the basis of the former scheme. The researches on pressure gradient fields, pressure sweep efficiency and fluid recovery rate indicate that the recovery efficiency of the two schemes is both better than the original well pattern. Additionally, the scheme one is more suitable for the development of the fields. Consequently, it is not the perfect solution to merely increase the injection-to production well ratio.

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