IOP Conference Series: Materials Science and Engineering

PAPER • OPEN ACCESS

Calculating Methods of the Oil Production for Areal Well Patterns Based on the Sensitivities of the Permeability and Pressure

Calculating Methods of the Oil Production for Areal Well Patterns Based on the Sensitivities of the Permeability and Pressure

Baofeng Wu*, Xianbao Zheng

Exploration and Development Research Institute, Daqing Oilfield Company Ltd, Daqing 163712, China
*E-mail: wubaofeng@petrochina.com.cn

Abstract. Based on the characteristics of the low-permeability oil reservoirs and analyses of the laboratory expertments and investigation, the calculating methods for 4-spot, 5-spot and inverted 9-spot areal well patterns with the permeability and pressure sensitivity are deduced with the help of the methods of flow line integration and unit analysis. Comparing with M. Muskat method, the accuracy and reliability of this method are confirmed. The effects of the pressure-sensitivity on the productivity for the oil reservoirs with different permeabilities are researched. And moreover the influences of the pressure-sustained degree on the productivity of extra-low-permeability reservoirs are also figured out. The calculating methods for the production of areal well patterns based on the pressure sensitivity have provided effective ways for the productivity design and development index prediction.

1. Introduction

There are many researches on the pressure sensitivity of low permeability reservoir permeability at home and abroad, but mainly laboratory core experiments are carried out to analyze the change of reservoir permeability with pressure and further study the seepage law of deformed media [1]. Laboratory experiments and field practice show that pressure sensitivity is common in low permeability reservoirs [2]. Due to the lack of corresponding reservoir engineering methods, pressure sensitivity is not considered in well pattern design and development index calculation. Pressure sensitivity is an irreversible process. Different pressure sensitivity index is adopted for injection wells and production wells respectively [3]. In this paper, the flow-tube integral and element division methods are used to establish the oil production calculating methods of area well pattern based of fou-point method, five- point method and inverse nine-point method on the pressure sensitive, which provides an effective method for productivity design and development index prediction of low permeability oilfield.

2. Production Calculation Method

2.1. Calculation of Single Flow Pipe Production

Hypothetical conditions for flow pipe calculation: (1) The reservoir is homogeneous, isotropic and isotropic, (2) The Fluid is single phase and incompressible, (3) Oil and water wells are connected by a series of flow pipes (Fig.1).

Under the above assumptions, Darcy's law is obeyed for the flow rate of each flow pipe [4], flow at a section can be expressed as:

$$q_s = -\frac{K(p)}{\mu} A(\xi) \frac{\mathrm{d}p}{\mathrm{d}\xi} \tag{1}$$

q_s-flow through flow pipe, t/d; $k(p)$-reservoir permeability, μm^2; $A(\xi)$ - cross-sectional area in the ξ of the flow tube, m^2; μ- fluid viscosity, mPa·s; ξ——streamline length from injection well to flow pipe at any position, m.

According to the results of laboratory experiments and investigations, there is a negative exponential relationship between permeability and pressure change.

$$K(p) = K_i e^{-\alpha(p_i - p)} \tag{2}$$

K_i-initial permeability of reservoir, μm^2; α-pressure sensitivity index of reservoir, 1/MPa; P_i- initial formation pressure, MPa; P- formation pressure at any position of formation, MPa.

Substitute formula (2) into formula (1)

$$q_s = \left(\frac{K_i}{\alpha_o}[e^{-\alpha_o(p_i-p_0)} - e^{-\alpha_o(p_i-p_{wf})}] + \frac{K_i}{\alpha_w}[e^{-\alpha_w(p_i-p_k)} - e^{-\alpha_w(p_i-p_0)}]\right) \Big/ \left(\mu \int_L \frac{\mathrm{d}\xi}{A(\xi)}\right) \tag{3}$$

α_o-pressure sensitive index of reservoir near production wells, 1/MPa; α_w-pressure sensitive index of reservoir near water wells, 1/MPa.

Near oil wells, formation pressure is a process of pressure drop, resulting in the decrease of reservoir permeability; near water injection wells, formation pressure can be regarded as a process of pressure rise. Considering pressure sensitivity is an irreversible process, water injection wells and production wells take different pressure sensitivity index respectively.

There are five-point method, four-point method and inverse nine-point method commonly used for area water injection in oilfields. In this paper, three methods for calculating production of area well pattern based on pressure sensitivity are derived respectively.

2.2. Five-point well Pattern

For five-point well pattern, one oil well is affected by four water wells. Similarly, one water well supplies water for four oil wells (Fig. 2). The shaded part of Figure 2 is taken as the calculation unit, which can be approximated to an isosceles right triangle. Oil and water wells are subjected to eight calculation units respectively.

Production of oil well:

$$q_o = 8q_e \tag{4}$$

Injection of water well:

$$q_w = 8q_e \tag{5}$$

q_e-flow of calculating unit, m^3/d.

For each unit (Fig. 3), a flow tube is selected, and the cross-sectional area of the flow element starting from end A is equal to that of the flow element starting from end B. $\alpha_1=\beta_1=\pi/4$, $\Delta\beta=\Delta\alpha$, $A_1(\xi)=A_2(\xi)=2h\xi\tan(\Delta\alpha/2)$. According to the symmetry, the flow rate of single-flow pipe is obtained, and the flow rate of calculation unit is obtained by integrating the single-flow pipe according to the angle [5].

r_w-wellbore radius of oil and water wells, m; l-distance between oil and water wells, m; h-reservoir thickness, m.

$$q_e = \int_0^{\frac{\pi}{4}} \left(\frac{k_i h}{\mu}\left[\frac{e^{-\alpha_o(p_i-p_0)} - e^{-\alpha_o(p_i-p_{wf})}}{\alpha_o} + \frac{e^{-\alpha_w(p_i-p_k)} - e^{-\alpha_w(p_i-p_0)}}{\alpha_w}\right] \Big/ \left(2\ln\frac{l}{2r_w\cos\alpha}\right)\right)\mathrm{d}\alpha \tag{6}$$

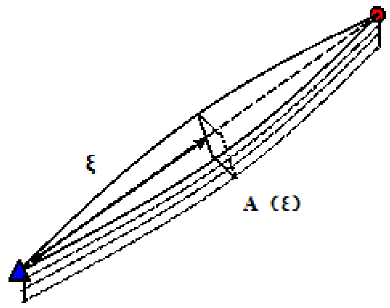
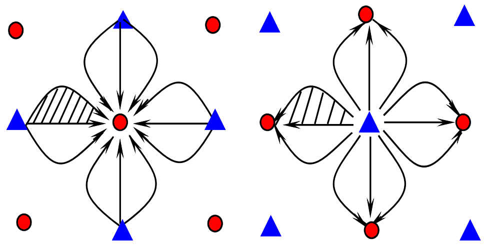


Figure 1. Schematic diagram of the single stream tube



(a)calculating unit of oil well (b)calculating unit of water well

Figure 2. Schematic diagram of the unit division for the oil-water wells of five-spot well pattern

2.3. Four-point Well Pattern

For four-point well pattern, one oil well is affected by three water wells, one water well is supplied for six oil wells (fig.4). Shadow part of Fig. 4 is taken as calculation unit, which can be approximated to a right triangle, oil wells are affected by six units, and water wells are affected by twelve units.

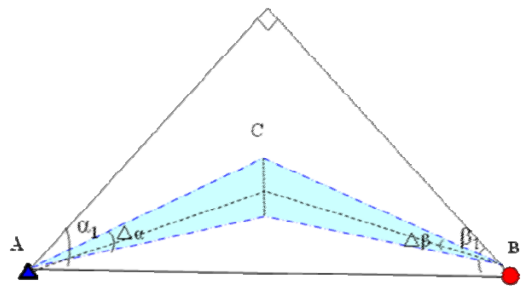
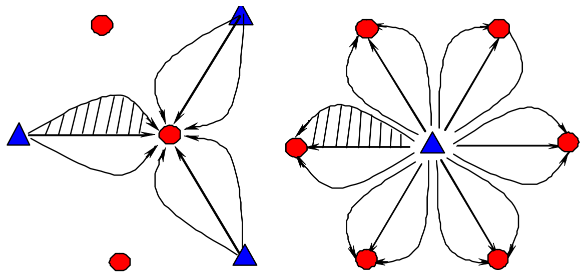


Figure 3. Schematic diagram of the stream tube division for calculating unit of 5-spot well pattern



(a)calculating unit of oil well (b)calculating unit of water well

Figure 4. Schematic diagram of the unit division for the oil and water wells of 4-spot well pattern

Production of oil well:

$$q_o = 6q_e \tag{7}$$

Injection of water well:

$$q_w = 12q_e \tag{8}$$

For each unit(Fig.5), choose a flow tube, because the cross-section of the flow element starting from end A is different from that of the flow element starting from end B,$\alpha_2=\pi/6$, $\beta_2=\pi/3$,$\Delta\beta=2\Delta\alpha$. The cross-section of the flow tube $A_1(\xi)=2h\xi\tan(\Delta\alpha/2)$, $r_w<\xi<l\sin2\alpha/\sin3\alpha$; $A_2(\xi)=2h\xi\tan\Delta\alpha$, $r_w<\xi<l\sin\alpha/\sin3\alpha$.

The area is substituted into the flow calculation formula of single-flow pipe, and the flow of calculation unit is obtained by integrating the flow of single-flow pipe according to the angle.

$$q_e = \int_0^{\frac{\pi}{6}} \left(\frac{k_i h}{\mu} \left[\frac{e^{-\alpha_o(p_i-p_0)} - e^{-\alpha_o(p_i-p_{wf})}}{\alpha_o} + \frac{e^{-\alpha_w(p_i-p_h)} - e^{-\alpha_w(p_i-p_0)}}{\alpha_w} \right] \Big/ \left(\ln\frac{l\sin2\alpha}{r_w\sin3\alpha} + \frac{1}{2}\ln\frac{l\sin\alpha}{r_w\sin3\alpha} \right) \right) d\alpha \tag{9}$$

2.4. Inverse Nine-point well Pattern

The geometric characteristics of side and corner wells in the inverse nine-point well pattern are completely different, and the basic calculation units that the side and corner wells form with the water wells are different (Fig. 6). The corner wells are affected by four injection wells, eight calculation units of corner wells; the edge wells are affected two injection wells and four calculation units of edge wells. At the same time, four edge wells and four corner wells are supplied by one water well.

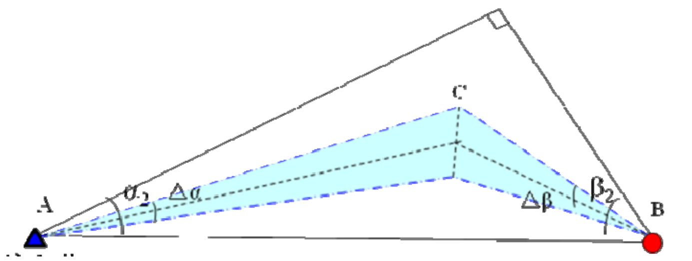
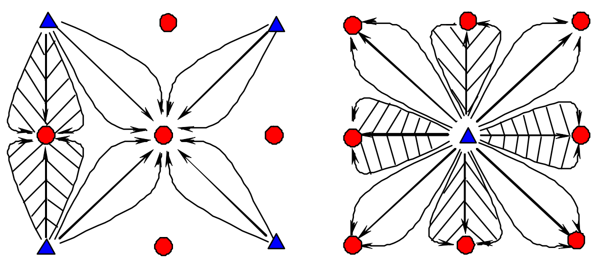


Figure 5. Schematic diagram of stream tube division for calculating unit by 4-spot well pattern



(a) calculating unit of oil well (b) calculating unit of water well

Figure 6. Schematic diagram of the unit division of oil-water wells for inverted 9-spot well pattern

Flow rate of edge well:

$$q_o = 4q_{e1} \tag{10}$$

Flow rate of corner well:

$$q_o = 8q_{e2} \tag{11}$$

Flow rate of water well:

$$q_w = 8(q_{e2} + q_{e1}) \tag{12}$$

q_{e1}- unit flow of edge well, m^3/d, q_{e2}-unit flow of corner well, m^3/d.

For each edge well calculation unit (Fig. 7), a flow tube is selected. The cross-sectional area of the flow tube element starting from end A is different from that of the flow tube element starting from end B, α_3=arctan(1/2), β_3=π/2, $\Delta\beta=(\beta_3\Delta\alpha)/\alpha_3$.

Unit flow of edge well:

$$q_{e1} = \int_0^{\alpha_3} \left(\frac{k_i h}{\mu}\left[\frac{e^{-\alpha_o(p_i-p_0)} - e^{-\alpha_o(p_i-p_{wf})}}{\alpha_o} + \frac{e^{-\alpha_w(p_i-p_h)} - e^{-\alpha_w(p_i-p_0)}}{\alpha_w}\right] \Big/ \left(\ln\frac{l\sin\beta}{r_w.\sin(\alpha+\beta)} + \frac{2\alpha_3}{\pi}\ln\frac{l\sin\alpha}{r_w\sin(\alpha+\beta)}\right)\right)d\alpha \tag{13}$$

α3-Maximum angle at injection end of edge well unit, (°); β3-Maximum angle at production end of edge well unit, (°).

For each corner well calculation unit (Fig. 8), a flow tube is selected. The cross-section of the flow tube element at end A is different from that of the flow tube element at end B. α_4=π/4-arctan(1/2), β_4=π/4, $\Delta\beta=(\beta_4\Delta\alpha)/\alpha_4$.

Unit flow of corner well:

$$q_{e2} = \int_0^{\alpha_4} \left(\frac{k_i h}{\mu}\left[\frac{e^{-\alpha_o(p_i-p_0)} - e^{-\alpha_o(p_i-p_{wf})}}{\alpha_o} + \frac{e^{-\alpha_w(p_i-p_h)} - e^{-\alpha_w(p_i-p_0)}}{\alpha_w}\right] \Big/ \left(\ln\frac{\sqrt{2}l\sin\beta}{r_w.\sin(\alpha+\beta)} + \frac{4\alpha_4}{\pi}\ln\frac{\sqrt{2}l\sin\alpha}{r_w\sin(\alpha+\beta)}\right)\right)d\alpha \tag{14}$$

α4-Maximum angle at injection end of corner well unit, (°); β4-Maximum angle at production end of corner well unit (°).

In the inverse nine-point pattern, because the ratio of water wells, angle wells and edge wells is 1:1:2, the injection-production volume of the whole well group is equal as a whole.

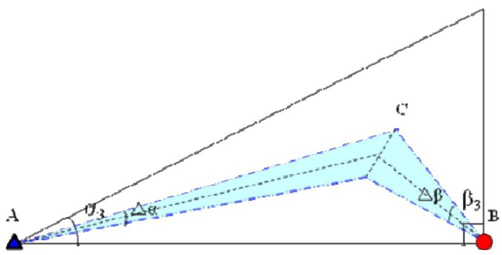


Figure 7. Schematic diagram of the stream tube division for the unit by edge wells of inverted 9-spot well pattern

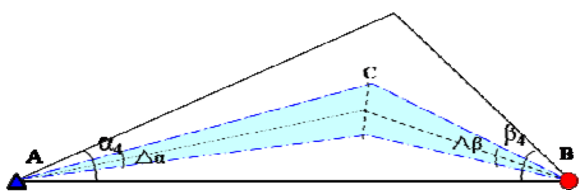


Figure 8. Schematic diagram of the stream tube division for the calculating unit by the corner wells of inverted 9-spot well pattern

3. Validation of Area Well Pattern Production Calculation Method

The simulator is developed based on production calculation for the pressure sensitive area pattern established in this paper. In order to prove the correctness of the calculation method and program, the simulation calculation was carried out and compared with the calculation results of the M. Muskat method [6]. Relevant parameters were as follows: original formation pressure is 17 MPa, the effective thickness is l0 m, injection well flow pressure is 23 MPa, oil well flow pressure is 5 MPa, wellbore radius is 0.1 m, fluid viscosity is 4 mPa.s, the oil well spacing is 300 m. When α=0, The method in this paper, the calculation results and the M. Muskat pattern production formula calculation results are basically identical (table 1).

Table 1. Calculated results of the oil production for four-and five-spot well patterns

permeability ($10^{-3}\mu m^2$)	Five-piont		Four-point	
	Method in this paper (m^3/d)	M. Muskat method (m^3/d)	Method in this paper (m^3/d)	M. Muskat method (m^3/d)
0.5	0.82	0.83	0.57	0.55
1.0	1.65	1.65	1.14	1.09
1.5	2.47	2.48	1.71	1.64
2.0	3.29	3.31	2.27	2.19
3.0	4.94	4.96	3.41	3.28
5.0	8.23	8.27	5.68	5.47
10.0	16.46	16.53	11.36	10.95

4. Conclusions

(1) The production calculating methods for 4-spot, 5-spot and inverted 9-spot areal well patterns is established based on permeability and pressure sensitivity. Through comparing and checking out, the method presented in this paper is correct and reliable. It makes pressure sensitivity reflected in productivity design and development index calculation.

(2) Studies on the influence of pressure sensitivity on productivity of reservoirs with different permeability show that when the permeability is lower than $2\times10^{-3}\mu m^2$, the productivity decreases over 9.98% of the proportion. Therefore, the influence of permeability pressure sensitivity should be considered during the development of ultra-low permeability reservoirs.

(3) The influence study of pressure maintenance level on production capacity of oil wells shows that the development pressure maintenance level of ultra-low permeability oilfields should be controlled at more than 75%.

5. Reference

[1] Ji Bingyu, Li Li, Zheng Xianbao. A NewProduction Model by Con-sidering the Pressure Sensitivity of Permeability in Oil Resetvolts[R]. SPE 155951, 2012.
[2] Li Zhuanhong, Ren Xiaojuan, Zhang Ningsheng, etc. Stress sensitivity of super-low permeability reservoirs and its influence on the productivity of oil well [J]. Journal of Xian Shi you University (Natural Science Edition) Ju1. 2005 V01.20No.4
[3] Gorbrov AT. Abnormal field development [M]. Beijing: petroleum industry press, 1987.32-60.
[4] B.C. orlov. Design and analysis of waterflood development in oil field [M]. Beijing: petroleum industry press, 1982.60-67.
[5] Ji Bingyu, Li Li, Wang Chunyan,. Oil production calculation method of non-darcy flow area pattern in low permeability reservoir [J]. Petroleum Journal, 2008, 29(2):256-261.
[6] P.T. fazreyev. Area waterflooding of oilfield [M]. Beijing: petroleum industry press, 1989.72-86.