Analysis of Initial Productivity Evaluation Method for Horizontal Well in Offshore Block Oilfield

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Abstract. Due to the short testing time and unstable productivity of horizontal wells in offshore fault-block oilfields, it is very important to evaluate the stable productivity of horizontal wells and the comprehensive correction coefficient of productivity by using limited horizontal well testing data. In this paper, the unsteady flow stage of horizontal wells is decomposed, and the productivity equations of vertical radial flow, linear flow and pesudo radial flow stage are obtained respectively. On this basis, the test time correction coefficients under different formation properties and horizontal well length conditions are plotted, unsteady productivity changes in horizontal wells under different fault conditions are compared and analyzed, the productivity correction coefficients under different fault conditions are obtained. The distance between well spacing fault and horizontal well is generally 0.2–1.0, its productivity correction coefficient is 0.68–0.85. The reliability of the charts are verified by testing data and production performance data of an offshore fault block oilfield. The methods and charts can effectively guide the determination of productivity of horizontal well testing method in offshore fault block oilfield.

Keywords: Horizontal well · Productivity · Well testing · Fault · Correction coefficient

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1 Introduction

Horizontal well placement has evolved from the science of drilling wells at 90° from the kickoff point to the art of utilizing technologies that place wells with maximum reservoir contact. And we also known many scholars have studied the productivity of horizontal well.

Merkulov deduced the analytical formula of horizontal well productivity for zonal and circular reservoirs, which is suitable for pseudo-radial and parallel flow [1]. Borisov summarizes the production principle and development process of horizontal wells, and puts forward the equation of steady productivity calculation for horizontal wells [2]. Giger obtained the productivity ratio equation of horizontal well and vertical well in homogeneous isotropic reservoir based on Borisov formula, and compared the productivity of horizontal well and vertical well [3]. Joshi simplified the three-dimensional seepage problem of horizontal wells into two-dimensional seepage problem in vertical and horizontal planes. The steady-state productivity equation of horizontal wells in homogeneous isotropic reservoirs was derived by using potential energy theory [4]. Renard et al. summarized the productivity equations of Joshi and Giger horizontal wells and introduced skin factor to modify the steady-state equation [5, 6].

The above is the main steady-state productivity equation. Mutalik assumed the shape coefficients and corresponding equivalent skin coefficients of horizontal wells at any position in a certain rectangular oil release zone. According to the productivity formula of fractured vertical wells, the productivity formula for predicting quasi-steady state of horizontal wells was given [7]. Babu set up a mathematical model for three-dimensional unsteady seepage flow in horizontal wells for arbitrary box type closed reservoirs [8]. Kuchuk et al. used an approximate infinite diversion method to derive the inflow performance equations of horizontal wells with constant pressure and impermeable top-bottom boundary conditions [9].

Frick et al. deduced an analytical formula for skin factor of horizontal wells, which can be directly added to the productivity formula of horizontal wells. The form of the equation is similar to the traditional productivity formula of vertical wells, and it is suitable for both unstable early stage and quasi-stable flow [10].

Although the steady-state model of horizontal wells is widely used in productivity prediction of horizontal wells, in fact, it is difficult for any reservoir to appear in a steady-state form when well testing. The unstable pressure formula is researched by many scholar.

Gringarten and Ramey introduce the point source function and Green function to solve unstable reservoir seepage problem, based on the theory of point source function, horizontal well testing technology has been developed [11]. Daviau first proposed a horizontal well test analysis model [12]. Goode considered reservoir anisotropy in the horizontal well test model [13]. Kuchuk proposed a horizontal well test model with different boundary between top and bottom of reservoir [14, 15]. Ozkan obtained a dynamic mathematical model of horizontal well with closed boundary, and solved the model in pull space [16].

In the process of horizontal well testing, unstable flow can be divided into three sections: vertical radial flow, linear flow and quasi-radial flow. Because of the short test time at sea, the productivity of quasi-radial flow is still not stable. In evaluating the stable productivity of horizontal well, we must introduce productivity correction coefficient.

2 Unsteady Productivity Equation of Horizontal Well

Suppose a horizontal well is drilled in the middle of the reservoir, the half length of the horizontal well is L, the thickness of the reservoir is h, and the horizontal permeability and vertical permeability are different. The horizontal well location is shown in Fig. 1.

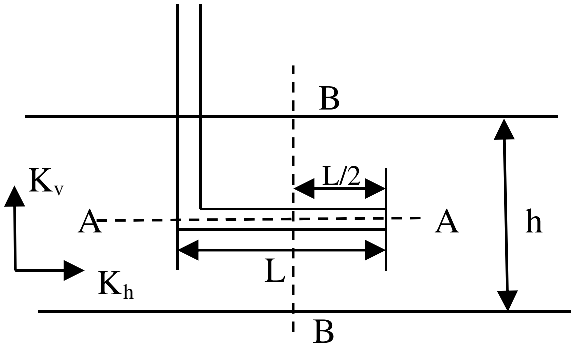

Fig. 1 Horizontal wells in central reservoir schematic diagram

Assuming that the upper and lower boundaries of the strata are closed and the horizontal direction is infinite, the seepage control equation of horizontal wells is:

$$K_h \frac{\partial^2 p}{\partial x^2} + K_h \frac{\partial^2 p}{\partial y^2} + K_v \frac{\partial^2 p}{\partial z^2} = \phi \mu C_t \frac{\partial p}{\partial t} \tag{1}$$

where $z^* = z\sqrt{K_h/K_v}$

The above formula can be turned into the standard equation:

$$\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} + \frac{\partial^2 p}{\partial z^{*2}} = \frac{1}{\eta} \frac{\partial p}{\partial t} \tag{2}$$

Initial and boundary conditions of reservoir:

$$p(x, y, z, t)|_{t=0} = p_{\mathrm{i}}$$

$$\left.\frac{\partial p}{\partial x}\right|_{x\to\infty} = 0 \left.\frac{\partial p}{\partial y}\right|_{y\to\infty} = 0 \left.\frac{\partial p}{\partial z}\right|_{z=0} = \left.\frac{\partial p}{\partial z}\right|_{z=h} = 0 \tag{3}$$

The above is a differential equation for unsteady seepage in horizontal wells with an upper and lower boundary in an infinite reservoir.

Using Newman product method and instantaneous source solutions under various conditions, the formation pressure distribution formulas of the above models are obtained.

$$\begin{aligned}\tilde{p}(x,y,z,t) = p_i - \frac{dv}{\phi C_t}\frac{1}{2}&\left\{\operatorname{erf}\left[\frac{L+(x-x_{\mathrm{w}})}{\sqrt{4\eta(t-\tau)}}\right]+\operatorname{erf}\left[\frac{L-(x-x_{\mathrm{w}})}{\sqrt{4\eta(t-\tau)}}\right]\right\}\\ &\frac{1}{\sqrt{4\eta(t-\tau)}}\exp\left[-\frac{(y-y_w)^2}{4\eta(t-\tau)}\right]\\ &\frac{1}{h^*}\left\{1+2\sum_{n=1}^{\infty}\exp\left[-\frac{\mathrm{n}^2\pi^2\eta_V(t-\tau)}{h^{*2}}\right]\cos\frac{\mathrm{m}\pi z_{\mathrm{w}}}{h}\cos\frac{\mathrm{m}\pi z}{h}\right\}\end{aligned} \tag{4}$$

where $h^* = h\sqrt{K_h/K_v}$

The following dimensionless quantities are defined:

$$h_D^* = h^*/L \; \eta_V = \frac{K_v}{K_h}\eta = \beta^2\eta \; t_D = \eta\frac{t}{L^2} \; p_D = \frac{2\pi K_h h^*[p_i - p(x,y,z,t)]}{q\mu B} \; L_D = \frac{L}{h^*}$$

So the dimensionless horizontal well pressure distribution can be written:

$$\begin{aligned}p_D(x_D,y_D,z_D,t_D) = \frac{\sqrt{\pi}}{4}\int_0^{t_D}&\frac{1}{\sqrt{t}}\exp[-\frac{(y_D-y_{wD})^2}{4t}]\\ &\{\operatorname{erf}[\frac{1+(x_D-x_{\mathrm{wD}})}{\sqrt{4t}}]+\operatorname{erf}[\frac{1-(x_D-x_{\mathrm{wD}})}{\sqrt{4t}}]\}\\ &[1+2\sum_{n=1}^{\infty}\exp(-\frac{n^2\pi^2\beta^2 t}{h_D^{*2}})\cos n\pi z_{\mathrm{wD}}\cos n\pi z_{\mathrm{D}}]dt\end{aligned} \tag{5}$$

The above formula is a dimensionless bottom hole pressure solution for horizontal wells without considering wellbore storage effect and skin effect.

when considering well storage The dimensionless pressure drop at the bottom of well is considered as follows:

$$p_{\mathrm{wDC}} = \int_0^{t_D}[1 - C_D\frac{dp_{\mathrm{wDC}}}{dt_D}]\frac{dp_D(t-\tau)}{d\tau}d\tau \tag{6}$$

where

$$C_D = \frac{C}{2\pi h^*\phi C_{\mathrm{f}}L^2} \tag{7}$$

when considering skin effect, The dimensionless pressure drop at the bottom of well is considered as follows:

$$p_{\mathrm{wDS}} = \frac{1}{L_D}(1 - C_D \frac{dp_{\mathrm{wDS}}}{dt_D})S \tag{8}$$

When evaluating the initial productivity of horizontal oil wells, we should analyze the influence of different testing time and different types of boundary. Therefore, the following dimensionless productivity index is defined as follows:

$$J_D = \frac{q}{\left(p_i - p_{wf}\right)} \cdot \frac{1.842 \times 10^{-3} \mu B}{K_h h \sqrt{\frac{K_h}{K_v}}} = \frac{1}{p_{\mathrm{wDs}}} \tag{9}$$

Because of the length of the horizontal well, the location of the horizontal well in the reservoir, and the heterogeneity of the reservoir, the flow pattern of the horizontal well is different from the vicinity of the wellbore to the middle of the reservoir. In the shorter test time, the horizontal well can not reach stable flow or quasi-stable flow, so when using the horizontal well test data to evaluate productivity, the test time correction coefficient and boundary correction coefficient should also be defined.

The determination principle of test time correction factor: Taking upper and lower layers closed and infinite plane reservoirs as an example, dimensionless recovery index of horizontal wells gradually decreases and finally achievs stability with the extension of production time. The stable production index and the ratio of production index to different test time are defined as test time correction coefficient, as shown in formula 10.

$$\Delta J_t = \frac{\mathrm{J}_{DTest}}{J_{Dstable}} \tag{10}$$

The determining principle of boundary correction factor:

Because the horizontal well has a certain length, the stable productivity varies with the distribution of oil wells and faults. The stable recovery index of infinite reservoir is taken as the base, and the ratio of stable recovery index with different fault distances is defined as the boundary correction coefficient, as shown in formula 11.

$$\Delta J_b = \frac{\mathrm{J}_{Dbstable}}{J_{DIstable}} \tag{11}$$

2.1 Test Time Correction Coefficient Plates

The actual offshore oilfield DST test time is very short, generally in about 5–15 h. During the horizontal well testing, the vertical radial flow occurs earlier and lasts less than an hour. Therefore, in the DST test time range, the duration of linear flow and quasi-radial flow is long, and sometimes only the linear flow section may not appear quasi-radial flow section. According to the productivity equation of horizontal wells in different testing stages, the productivity curves of horizontal wells under different reservoir and well parameters are established, as shown in Figs. 2 and 3.

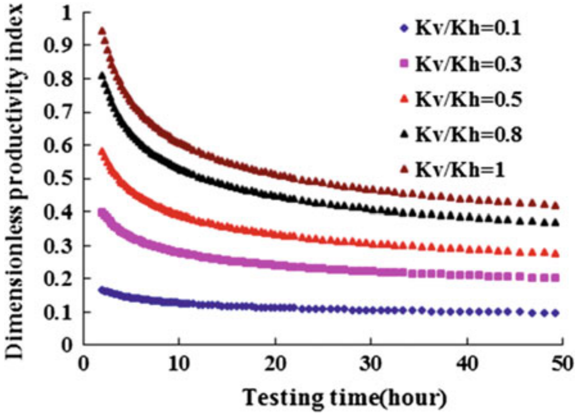

Fig. 2 Horizontal well dimensionless PI versus time curves in different Kv/Kh

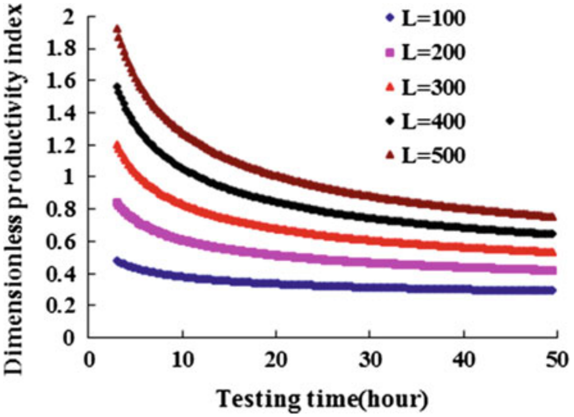

Fig. 3 Horizontal well dimensionless PI versus time curves in different well length

In the process of horizontal well testing, the pressure and flow sections are affected by the length of horizontal well and the anisotropy of oil field, so the length and anisotropy of different horizontal sections are determined separately when evaluating the correction of testing time for productivity. Figure 4 gives the time productivity correction factor for homogeneous and anisotropic horizontal wells.

The time productivity correction coefficients are different under different anisotropic conditions. When the length of horizontal wells is the same, the productivity is greatly affected by anisotropy, that is, the greater the ratio of vertical permeability to horizontal permeability, the smaller the correction coefficient of test time; under the same reservoir physical conditions, the longer the horizontal section, the greater the influence of time on productivity, the smaller the correction coefficient. The average test time is about 5–15 h, and the correction time is about 0.5–0.7.

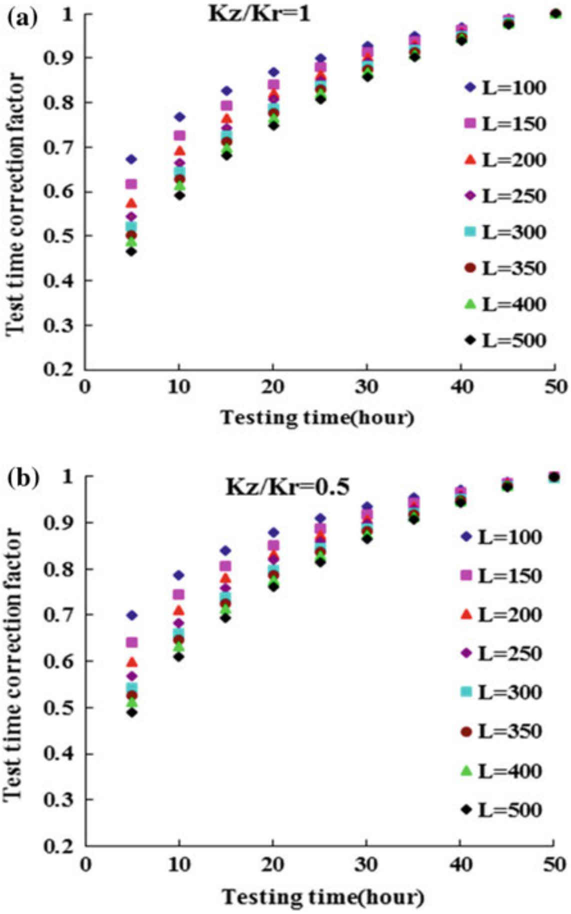

Fig. 4 **a** Test time correction coefficient in different well length (Kv/Kh = 1.0). **b** Test time correction coefficient in different well length (Kv/Kh = 0.5)

2.2 Boundary Correction Coefficient Plates

Taking a fault as an example, as shown in Fig. 5, a single fault has the following distribution relationship with a horizontal well, parallel to and perpendicular vertical to the fault. The productivity of horizontal well under these two conditions is analyzed.

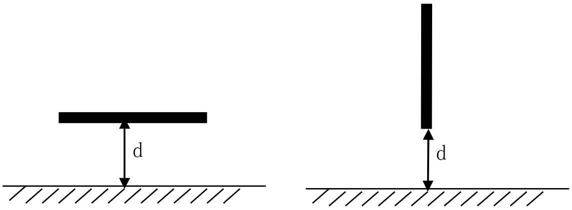

Fig. 5 Horizontal well models near faults schematic diagram

When the horizontal well is parallel to the fault, the fault response occurs earlier in well testing curves than the horizontal well is vertical to the fault. Sometimes the linear flow sections are covered when the horizontal well is perpendicular to the fault, the fault response time is later, and the pesudo radial flow occur when the linear flow ends. In both cases, the pressure derivatives eventually converge, but the pressure drop parallel to the fault is greater than that perpendicular to the fault, as shown in Fig. 6.

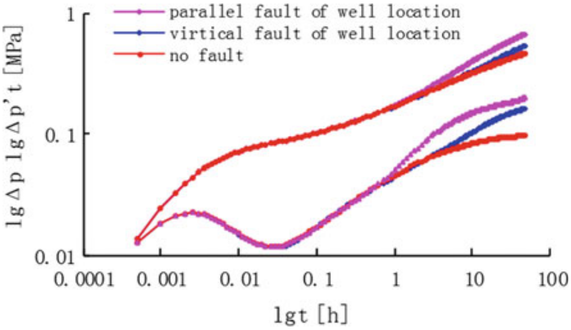

Fig. 6 Horizontal well testing type curves under different fault conditions

The curves of dimensionless PI versus time under two conditions are shown in Fig. 7. The vertical radial flow lasted for a short time, and the dimensionless production index changed the same. The dimensionless production index of horizontal wells parallel to faults decreases rapidly and early than the well perpendicular to faults. The dimensionless PI of horizontal wells is ultimately stable due to the influence of faults, but the pseudo stable flow productivity index of well parallel to the fault is smaller than that perpendicular to the fault.

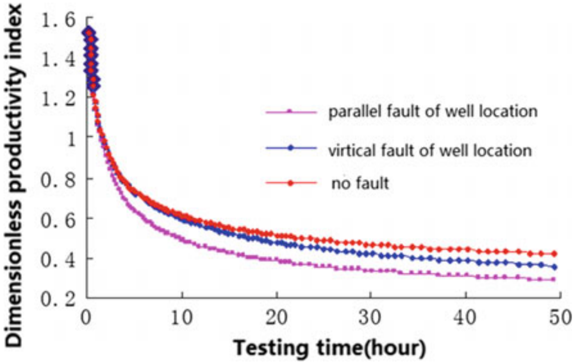

Fig. 7 Horizontal well dimensionless PI versus time curves under different fault distances

The smaller of distance horizontal well to fault, and the smaller the ratio of vertical permeability to horizontal permeability, the boundary correction coefficient is larger. The ratio of actual well spacing fault distance to horizontal well length is generally between 0.2 and 1.0, and the boundary correction coefficient is between 0.68 and 0.85. The horizontal well boundary correction coefficient plates are shown in Fig. 8.

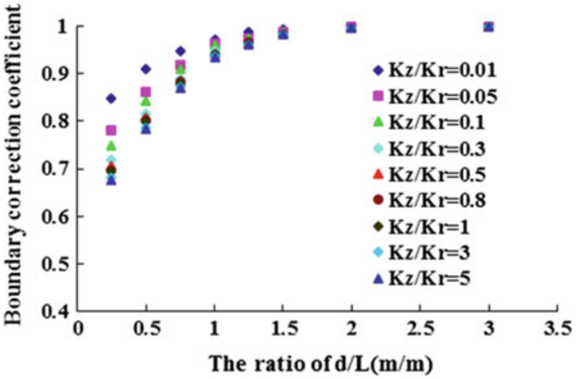

Fig. 8 Boundary correction coefficient plates in different Kv/Kh

2.3 Case Studies

A reservoir is a deep-water submarine fan channel deposit. The porosity is medium and the permeability is high in this reservoir. There are some faults in the sand layer. Well A9 is a horizontal well in this reservoir. The effective length of the horizontal well drilled into the reservoir is 260 m. The effective thickness of the reservoir is 8.5 m. Horizontal wells pass through faults. The distance between the two ends of the horizontal well is about 100–200 m. The horizontal well is completed with high quality screen pipe, Well A9 location map is shown in Fig. 9.

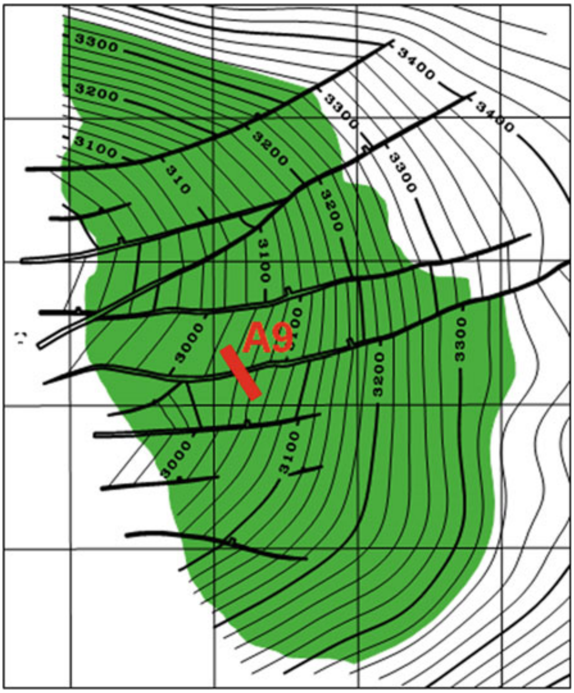

Fig. 9 Well A9 location map

The well test time is about 50 h, and the nozzle is replaced every four hours during well testing. Because the duration of each flow section is short, the flow is not completely stable or quasi-stable, so the test time and faults have a great influence on the productivity. The curve of productivity index with time in the test phase is shown in Fig. 10, the productivity index decreases with time.

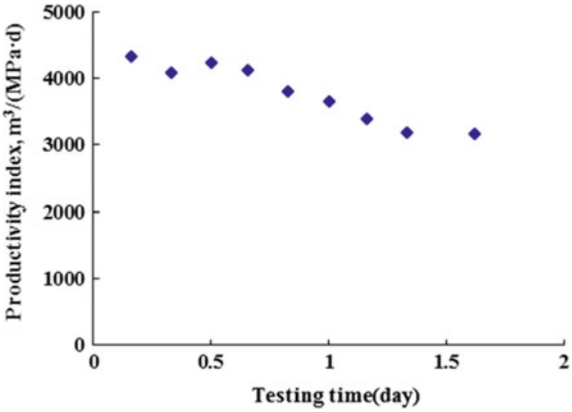

Fig. 10 A9 well blow off testing PI versus time curves

The vertical radial flow, linear flow and quasi-radial flow all occur in the log-log curve of horizontal well test, but the response of fault on the well test curve may coincide with the linear flow and can not be distinguished. The well test fitting curve is shown in Fig. 11.

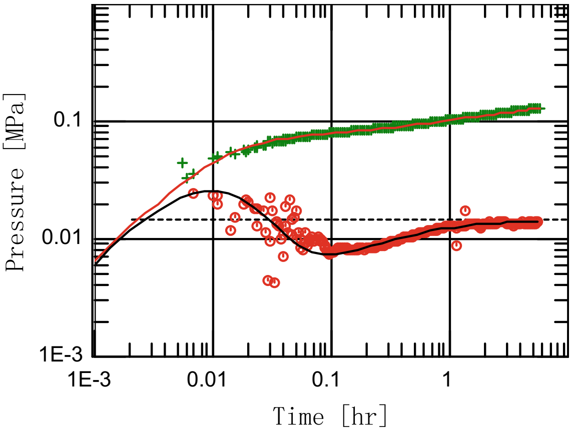

Fig. 11 A9 well testing fitting curves

Because of unstable flow in the well test stage, the testing time is about 1.5 days and the length of horizontal well is 260 m. According to previous theoretical analysis, the time correction coefficient is about 0.7–0.8, the ratio of horizontal well spacing fault distance to horizontal well length is about 0.3, so the boundary correction coefficient is 0.7. The composite correction coefficient is equal to the product of the time correction coefficient and the boundary correction coefficient, which is about 0.52.

We use the production data to verify the composite correction coefficient. The test productivity and production productivity are converted to the ideal production index. The ideal productivity index of the well test is 5150 m^3/(MPa·d), the well initial stable ideal productivity index is 2450 m^3/(MPa·d), so the actual composite correction coefficient is close to 0.47, which is close to the theoretical analysis results (Fig. 12).

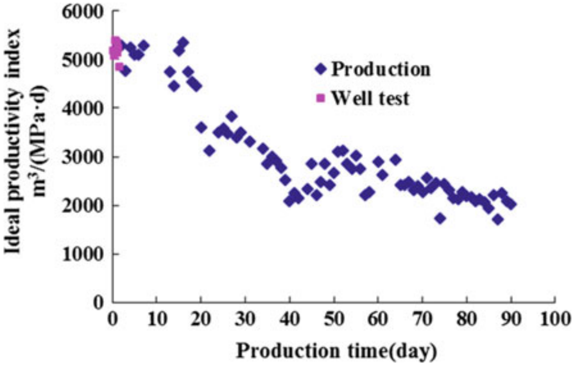

Fig. 12 A9 well early period production curves

3 Conclusion

Aiming at the problems of short test time and unstable production capacity of DST in offshore block oilfield evaluation well. The productivity equations of different flow sections of horizontal wells are established, and the time-dependent variation of dimensionless recovery index of horizontal wells under different conditions is analyzed.

(1) Horizontal well productivity test time correction coefficient chart and boundary correction coefficient chart are established.
(2) when the test time is 5–15 h, Test time correction coefficient is about 0.8.
(3) The ratio of actual well spacing fault distance to horizontal well length is generally between 0.2 and 1.0, and its productivity correction coefficient is between 0.68 and 0.85.
(4) Combining with the actual horizontal well test and the production performance data, the reliability of the theoretical chart is verified.

The establishment of the two kinds of chart has guiding significance for the future productivity evaluation of horizontal wells in fault-block oilfields.

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