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Analysis and Application of Horizontal Well Test in Low Permeability Porous Carbonate Reservoir

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Abstract: Low permeability porous carbonate rocks occupy a certain proportion in the Middle East. Horizontal injection-production well pattern development is often adopted. Due to the influence of well type and wellbore, reservoir dynamic monitoring is mainly based on conventional daily measurement data, well test and pressure monitoring. Therefore, it is particularly important to combine well test interpretation with production dynamic analysis to diagnose the main control factors and production characteristics of this type of reservoir. In this paper, the point source function is used to obtain the pressure variation function of a horizontal well in infinite formation with upper and lower closed boundary. The difference between the horizontal well test curve of A reservoir and the typical horizontal well test curve is compared and analyzed, and the abnormal well test curve of horizontal wells is characterized by a linear flow phase with a slope of 1/3 or 1/4. The abnormal well test curve accounted for 33.34%. The main influencing factors are the permeability around the well and the well trajectory. By combining well test interpretation with dynamic inversion method, the correlation between well test interpretation and dynamic characteristics of horizontal wells with different characteristics is classified and clarified. The main controlling factors that affect the difference in the water injection development effect of different horizontal wells are further clarified, and provide an important reference for the adjustment of injection-production parameters and the optimal deployment of schemes.

Keywords: low permeability; porous carbonate reservoir; well test; dynamic characteristics

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1. Introduction

The Middle East has some of the most important oil and gas resources and oil and gas production areas, and 80% of the oil and gas production in this area comes from carbonate reservoirs [1]. Generally, the recovery factor of carbonate reservoirs is low, about 10%, when exploiting them only by natural energy. Therefore, it is necessary to continuously optimize the production process and analyze the carbonate reservoir in detail from different aspects and angles, so as to obtain the production system most suitable for the study area and achieve stable production, stable oil and water control in the oilfield.

Goode, Daviau, Odeh et al. [2–5] studied the seepage mechanism and flow stage characteristics of horizontal wells, and obtained the curve characteristics of different flow stages of horizontal well test curves. In the actual horizontal well test curve, the linear flow is the easiest to observe. Cinco-Ley and Samaniego-V [6] showed that bilinear flows are usually associated with finite conductivity fractures, in which two linear flows occur simultaneously. This can be identified by the 1/4 slope in the log plot of pressure and derivative. Du and Stewart [7] showed how bilinear flows in horizontal wells can be generated in transient dual-porosity multilayer reservoirs. It is considered that bilinear flow occurs in horizontal wells in a high permeability formation overlying a low permeability formation, which is similar to a dual porosity system. Briceno et al. [8] also ascribed bilinear flow to transient dual porosity behavior caused by overlying or underlying shale barriers with different permeability and porosity of a single well. Wei Cher Feng [9] summarized the causes of bilinear flow, including the transition between radial flow and stable linear flow, the difference between horizontal and vertical permeability, the specific combinations of well length and reservoir thickness, and geological conditions, such as the presence of high permeability stripes and shale barriers. Baba et al. [10] applied the analytical solution of bilinear flow in horizontal plane to reservoirs. Cheng Shiqing and Jia Yonglu et al. [11,12] conducted research on changing well storage in well test curves, including its influencing factors and its specific performance in log-log curves.

For a low permeability carbonate reservoir, Zang Keyi et al. [13] summarized the characteristics of a horizontal well homogeneous model and horizontal well radial composite model by summarizing and classifying the field well test data of AH oilfield in Iraq, illustrating the production characteristics of different well test models. According to the parameters obtained from well test and reservoir models, combined with seismic and logging data, Li Qishen et al. [14] distinguished four types of well test curves, such as constant volume cave type curve and constant volume fracture cavity type curve, and put forward measures to improve oil recovery. Bao Jia et al. [15] analyzed pressure changes in low-permeability formations using 3D scanning and pressure pulse attenuation experiments. For pure matrix cores, the permeability determined by pulse attenuation experiments strictly follows Darcy's law, which changes proportionally with fluid viscosity. Liu Yuewu et al. [16] believed that analysis and evaluation of well test data and dynamic data is a relatively economical and applicable method at present. He Enjie et al. [17] summarized water production characteristics and water control measures of a pore carbonate reservoir. Li Yong et al. [18] summarized the different types of production of large carbonate reservoirs in the Middle East, and described the corresponding stratigraphic characteristics.

2. Geologic Reservoir Characteristic

The study area is a multilayer edge water reservoir at normal temperature and pressure, which is an unsaturated reservoir. The original formation pressure is about 4300 psi. The average reservoir pressure in formation A has been reduced to 74.5% of the original formation pressure. The saturated pressure is about 60–70% of the formation pressure, and the viscosity of underground crude oil is low at between 1 and 2 cp. The range of core porosity is 3.4–27.2%, with an average of 18.4%, and the range of core permeability is 0–254.14 mD, with an average of 4.1 mD. The reservoir thickness range is 19.1–24.3 m, the average thickness is 22.6 m. The average permeability difference between A-2 and A-3 of the two main producing layers in reservoir A is small, and the average permeability of the A-2 layer is slightly larger than that of the A-3 layer as shown in Figure 1.

The main rock types are green microalgae packstone, bioclastic packstone and plank packstone. The reservoir space is intragranular pores, followed by algal model pores and dissolved pores. There are a large number of organisms in Cretaceous reservoirs, so body cavity pores are the most common, and are common in bioclastic packstone.

The low permeability carbonate reservoir of A reservoir in Middle East is in the initial development stage. The anti-nine-spot well pattern and horizontal injection-production well pattern are used in the study area. The analysis of dynamic parameters of vertical wells and horizontal wells in A reservoir shows that compared with horizontal wells, the average daily oil output of vertical wells decreases year by year and water cut continues to rise as shown in Figures 2 and 3. The average water cut of the vertical wells is about 70% now. Meanwhile, vertical wells cannot maintain formation pressure. In general, horizontal wells are more suitable for the development of low permeability carbonate rocks. In the production process, the water cut of production wells in vertical wells is high and most of the vertical wells have been closed. The horizontal production wells have no water or are in the stage of low water cut. Analysis of horizontal well water injection effects shows that the recovery time of liquid production is for about 3 years in general. There is pressure build-up around the injection well and the surrounding formation pressure is above 4000 psi.

There are only pressure measurement data and well test data in the study area. The pressure measurement data are from 61 wells, and the well test data from 26 wells, 55 times. The acid washing of individual wells does not improve the water injection development effect, as shown by analyzing the dynamic characteristics and well test curve characteristics.

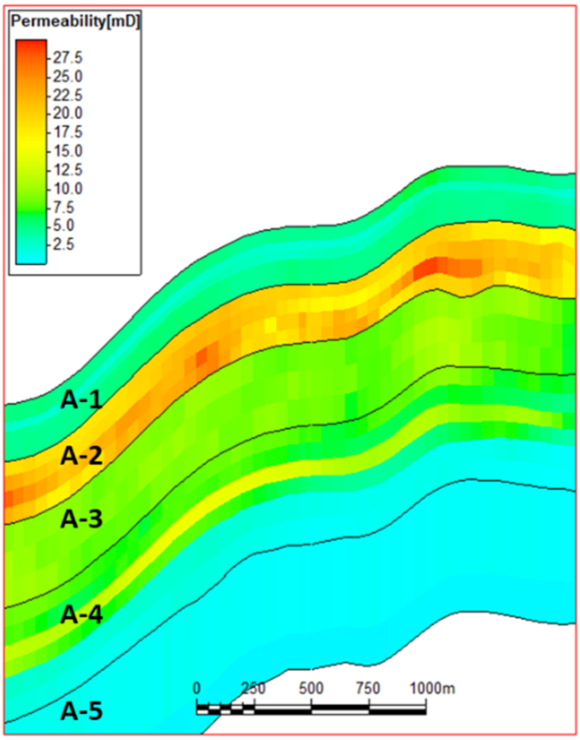

Figure 1. Permeability contrast diagram of each small layer in A reservoir.

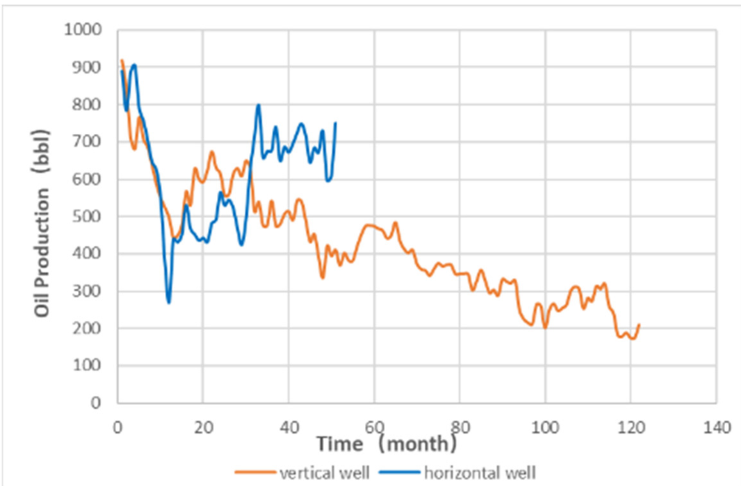

Figure 2. Comparison figure of average daily oil production between vertical wells and horizontal wells in A reservoir.

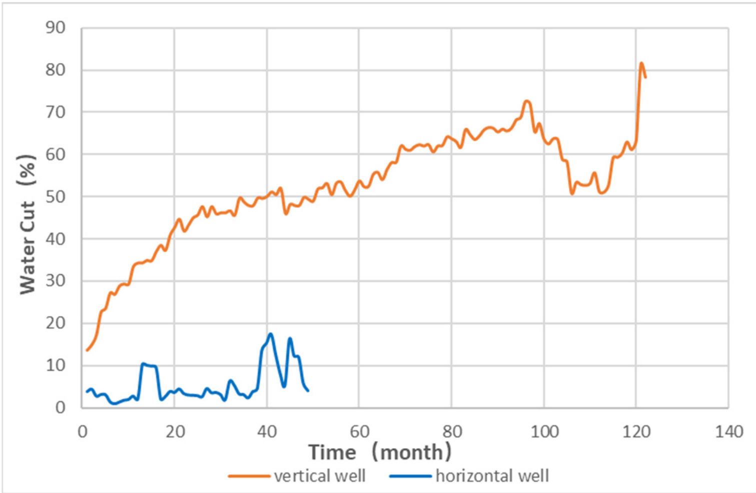

Figure 3. Comparison figure of average water cut between vertical wells and horizontal wells in A reservoir.

3. Horizontal Well Test Mathematical Model

Define dimensionless variables,

$$x_D = \frac{x}{L}, y_D = \frac{y}{L}, z_D = \frac{z^*}{h^*} = \frac{z}{h}, z_{wD} = \frac{z_W}{h}, L_{wD} = \frac{L_w}{L}, h_D^* = \frac{h^*}{L} \\ L_D = \frac{L}{h^*}, t_D = \frac{K_H t}{\phi \mu c L^2}, p_D = \frac{2\pi K_H h^* [p_i - p(x,y,z,t)]}{Q\mu} \quad (1)$$

Variable expressions to simplify formulas,

$$\overline{K} = \frac{K_V}{K_H}, z^* = z\sqrt{\frac{K_H}{K_V}}, h^* = h\sqrt{\frac{K_H}{K_V}}, \chi = \frac{K_H}{\phi \mu_c L^2}, \chi_v = \frac{K_v}{\phi \mu_c L^2} = \frac{K_V}{K_H}\chi = \overline{K}\chi \quad (2)$$

According to the basic instantaneous source function summary table proposed by Gringarten and Ramey [19], the upper and lower closed strata are set, the x direction is the strip source of infinite plane, the y direction is the linear source of infinite plane, and the z direction is the linear source in the upper and lower closed area as shown in Figure 4 [20].

$$\begin{aligned} p_i - \tilde{p}(x,y,z,t) &= \frac{dV}{\phi c}\frac{1}{2}\left[\mathrm{erf}\left(\frac{L+(x-x_w)}{\sqrt{4\chi(t-\tau)}}\right) + \mathrm{erf}\left(\frac{L-(x-x_w)}{\sqrt{4\chi(t-\tau)}}\right)\right] \\ &\cdot \frac{1}{\sqrt{4\pi\chi(t-\tau)}} \exp\left[-\frac{(y-y_w)^2}{4\chi(t-\tau)}\right] \\ &\cdot \left\{\frac{1}{h^*}\left[1 + 2\sum_{n=1}^{\infty} \exp\left(-\frac{n^2\pi^2\chi_v(t-\tau)}{(h^*)^2}\right)\cos\frac{n\pi z_w}{h}\cos\frac{n\pi z}{h}\right]\right\} \end{aligned} \quad (3)$$

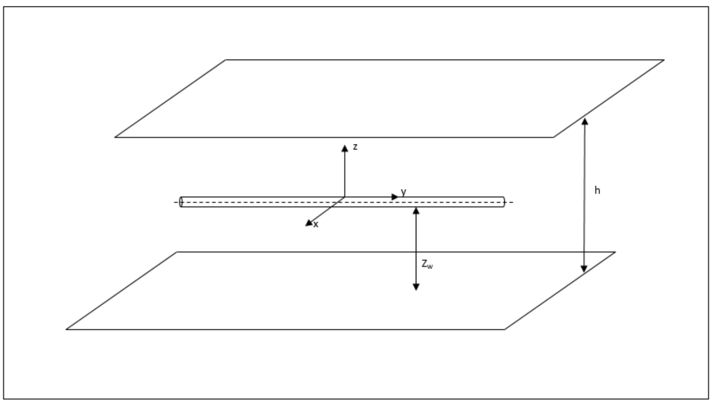

Figure 4. Horizontal well model diagram of infinite formation with upper and lower closed boundary.

The continuous source function is obtained by integrating the instantaneous source function in time 0-t. Assuming that the horizontal well is in constant production Q, the formation volume coefficient B is considered, and the wellbore flow is uniform.

$$\frac{dV}{d\tau} = q(\tau) = \frac{QB}{2L} \tag{4}$$

$$\begin{aligned} p_i - p(x,y,z,t) &= \frac{QB}{\phi c(2L)} \cdot \frac{1}{2h^*} \int_0^t \left\{ \frac{1}{\sqrt{4\pi \chi \tau}} \exp\left[-\frac{(y-y_w)^2}{4\chi\tau} \right] \right. \\ &\cdot \left[\operatorname{erf}\left(\frac{L+(x-x_{\mathrm{w}})}{\sqrt{4\chi\tau}} \right) + \operatorname{erf}\left(\frac{L-(x-x_{\mathrm{w}})}{\sqrt{4\chi\tau}} \right) \right] \\ &\cdot \left. \left[1 + 2\sum_{n=1}^{\infty} \exp\left(-\frac{n^2\pi^2\chi_{\mathrm{v}}\tau}{h^{*2}} \right) \cos\frac{n\pi z_{\mathrm{w}}}{h} \cos\frac{n\pi z}{h} \right] \right\} d\tau \end{aligned} \tag{5}$$

The above formula is dimensionless and obtained,

$$\begin{aligned} p_{\mathrm{D}}(x_{\mathrm{D}}, y_{\mathrm{D}}, z_{\mathrm{D}}, t_{\mathrm{D}}) &= \frac{\sqrt{\pi}}{4} \int_0^{t_{\mathrm{D}}} \left\{ \frac{1}{\sqrt{\tau}} \exp\left[-\frac{(y_D-y_{wD})^2}{4\tau} \right] \right. \\ &\cdot \left[\operatorname{erf}\left(\frac{1+(x_D-x_{\mathrm{wD}})}{\sqrt{4\tau}} \right) + \operatorname{erf}\left(\frac{1-(x_D-x_{\mathrm{wD}})}{\sqrt{4\tau}} \right) \right] \\ &\cdot \left. \left[1 + 2\sum_{n=1}^{\infty} \exp\left(-\frac{n^2\pi^2\overline{K}\chi\tau}{{h_D}^{*2}} \right) \cos n\pi z_{\mathrm{wD}} \cos n\pi z_{\mathrm{D}} \right] \right\} d\tau \end{aligned} \tag{6}$$

In order to simplify the expression, the coordinate system is selected to make the z axis pass through the midpoint of the horizontal wellbore. Then $x_w = y_w = 0$, and the simplified expression is the dimensionless pressure change without considering the wellbore storage effect and skin effect.

$$\begin{aligned} p_{\mathrm{D}}(x_{\mathrm{D}}, y_{\mathrm{D}}, z_{\mathrm{D}}, t_{\mathrm{D}}) &= \frac{\sqrt{\pi}}{4} \int_0^{t_{\mathrm{D}}} \left\{ \frac{1}{\sqrt{\tau}} \exp\left(-\frac{y_{\mathrm{D}}^2}{4\tau} \right) \left[\operatorname{erf}\left(\frac{1+x_{\mathrm{D}}}{\sqrt{4\tau}} \right) + \operatorname{erf}\left(\frac{1-x_{\mathrm{D}}}{\sqrt{4\tau}} \right) \right] \right. \\ &\cdot \left. \left[1 + 2\sum_{n=1}^{\infty} \exp\left(-\frac{n^2\pi^2\overline{K}\chi\tau}{h_{\mathrm{D}}^*} \right) \cos \pi z_{\mathrm{wD}} \cos n\pi z_{\mathrm{D}} \right] \right\} \mathrm{d}\tau \end{aligned} \tag{7}$$

According to Laplace transform and superposition principle, the variation formula of bottom hole pressure considering skin effect and well storage effect is obtained:

$$\overline{p}_{\mathrm{wD}}(s) = \frac{s\overline{p}_{\mathrm{D}}(s) + S}{s + C_{\mathrm{D}}s^2(s\overline{p}_{\mathrm{D}}(s) + S)} \tag{8}$$

where

K_V = Vertical permeability, mD
K_H = Horizontal permeability, mD
$\overline{K}$ = Permeability anisotropy ratio
L = Half length of horizontal wells, ft
L_D = Dimensionless half length of horizontal wells
χ = Horizontal pressure diffusivity
χ_V = Vertical pressure diffusivity
h = Reservoir thickness, ft
h^* = Normalized h, from uniform anisotropic medium to uniform isotropic medium
h_D^* = Dimensionless normalized h
p = Pressure, psi
p_i = Initial pressure, psi
p_D = Dimensionless pressure
Q = Flow rate, stb/d
r_{wD} = Dimensionless wellbore radius
r_w = Wellbore radius, ft
s = Laplace transform variable

S = Skin
t = Time, h
t_D = Dimensionless time
x = Coordinate, ft
x_w = Midpoint coordinates in horizontal segment, ft
x_D = Dimensionless coordinate
y = Coordinate, ft
y_w = Midpoint coordinates in horizontal segment, ft
y_D = Dimensionless coordinate
z = Coordinate, ft
z_D = Dimensionless coordinate
z_w = Height of horizontal section above bottom surface, ft
z_{wD} = Dimensionless height of horizontal section above bottom surface, ft
z^*= Normalize z, from uniform anisotropic medium to uniform isotropic medium
$\phi\varnothing$ = Porosity, dimensionless
μ = Fluid viscosity, cp
c = Composite compressibility, 1/psi
B = Formation volume coefficient
C_D = Dimensionless wellbore storage coefficient,
$\overline{p}_{wD}(s)$ = Image function of bottom hole pressure
erf = error function

4. Well Test Curve Characteristics of Low Permeability Carbonate Reservoir

4.1. Typical Horizontal Well Test Curve

The first flow stage of horizontal well test curve is wellbore storage stage. In the pure wellbore storage stage, the pressure and its pressure derivative curve show a slope of 1. Then, there will be initial radial flow, linear flow and later quasi-radial flow in three flow stages as shown in Figure 5 [21,22].

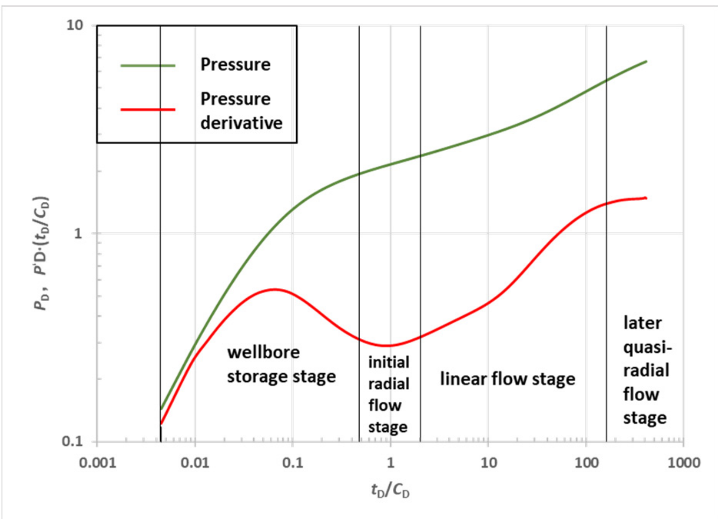

Figure 5. Double logarithmic pressure and pressure derivative diagram of horizontal well test.

- Wellbore storage stage;

The stage of the wellbore storage effect is shown in Figure 6a. When the superposition principle is used to calculate the pressure response in pressure recovery, the production is assumed to decrease from constant production to 0 at the moment of shut-in. However, in the actual situation, the bottom hole flow will not change immediately when the valve is switched, and the fluid will continue to flow into the wellbore and gradually decrease to 0. A line with a slope of 1 is shown on the pressure and derivative log-log plot.

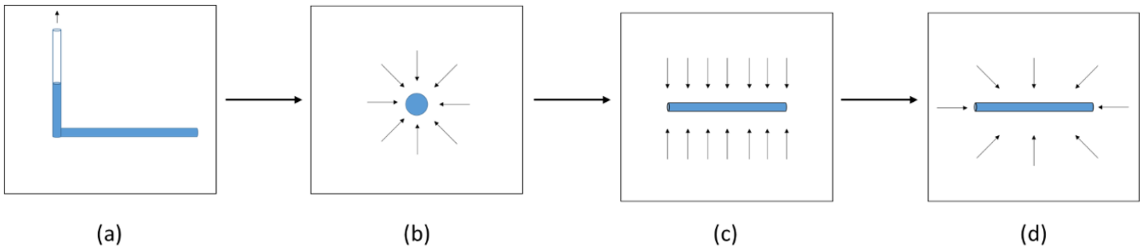

Figure 6. Schematic diagram of different flow stages in horizontal well test [21]: (**a**) Wellbore storage stage; (**b**) Initial radial flow stage; (**c**) Linear flow stage; (**d**) Later quasi-radial flow stage. The arrow represents liquid flow, the blue strip represents horizontal well, and the blue circle represents horizontal well cross section.

- Initial radial flow stage;

The initial radial flow stage is shown in Figure 6b. In this stage, the horizontal well forms a radial flow on the vertical plane. When the pressure wave propagates to the upper and lower boundaries, the stage ends. It is shown as a horizontal line in the pressure and derivative double logarithmic diagram.

- Linear flow stage;

The linear flow stage is shown in Figure 6c. When the vertical flow reaches the quasi-steady state, the flow on the horizontal plane begins to play a major role. If the centripetal flow at both ends of the horizontal well is ignored, there will be linear flow. In the pressure and derivative plot, this is shown as a straight line with a slope of 1/2.

- Later quasi-radial flow stage;

The quasi-radial flow stage is shown in Figure 6d. When the horizontal and vertical directions reach the boundary, the same radial flow will occur as for the vertical well. It is shown as a horizontal line in the pressure and derivative double logarithmic diagram.

A reservoir in the Middle East is in the initial development stage. The area well pattern and horizontal injection-production well pattern are used in the study area. By comprehensive comparison, horizontal wells are more suitable for extraction from low permeability carbonate rocks. In the production process, the water cut of production wells in vertical wells is high and most of the vertical wells have been closed. The horizontal production wells have no water or are in the stage of low water cut. Analysis of the effects of horizontal well water injection shows that the liquid volume of the production well is restored for about 3 years in general. There is pressure build-up around the injection well and the surrounding formation pressure is above 4000 psi.

4.2. Influencing Factors of Well Test Curve Characteristics

There are many characteristics that affect the well test curve. In performing the well test, equipment and other factors may affect the results, resulting in poor quality of well test results and inability to truly reflect the formation characteristics. At the same time, formation characteristics and well characteristics will also affect the shape of the well test curve [23–25].

Test time: Due to the large wellbore volume and long wellbore storage effect of horizontal wells, it is difficult to identify the initial radial flow stage. Linear flow and its transition may take a long time, resulting in the inability to measure the later quasi-radial flow stage.

Interlayer permeability: When the interlayer permeability is low, there will be deviation in the early or medium term. If the wellbore storage effect does not exist, this deviation will soon disappear or cannot be identified. When the vertical permeability of the interlayer is low, the linear flow will only reflect the characteristics of the wellbore sublayer.

Permeability difference: The difference of permeability between layers will have a significant impact on well test results.

Well trajectory: Keeping the well trajectory horizontal can make fluid flow close to horizontal, so that the real results are more consistent with the theoretical well test results.

4.3. Well Test Curve Characteristics of Low Permeability Carbonate Reservoir

Through the analysis and summary of the well test curves in the study area, the horizontal well test curves have been divided into three categories, namely, the 1/2 linear flow slope curve, the 1/3 linear flow slope curve and the 1/4 linear flow slope curve, as shown in Figures 7–9.

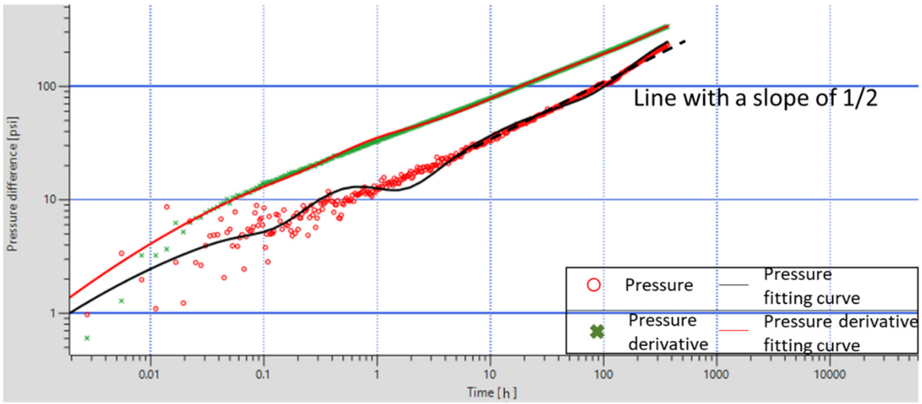

Figure 7. Horizontal well test curve with linear flow slope of 1/2.

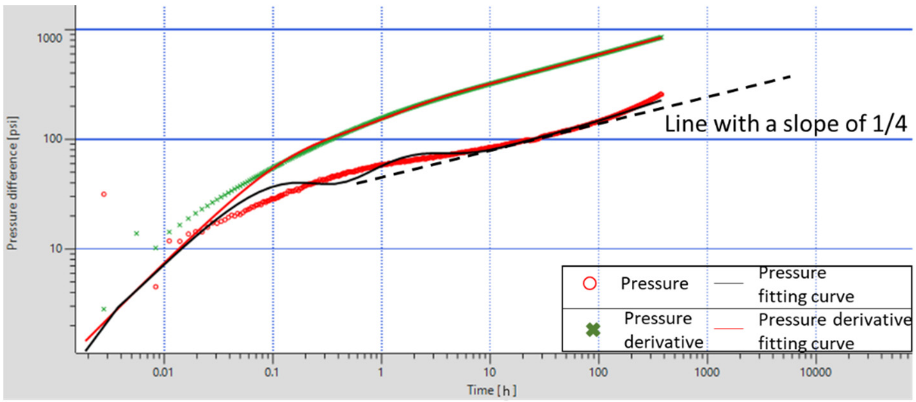

Figure 8. Horizontal well test curve with linear flow slope of 1/4.

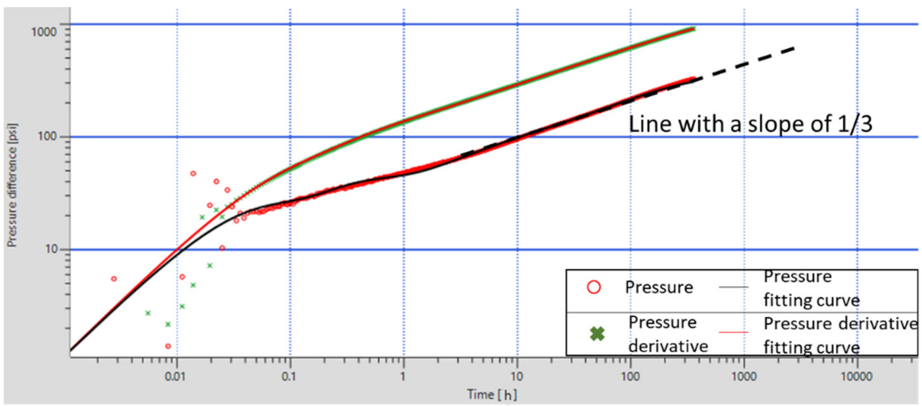

Figure 9. Horizontal well test curve with linear flow slope of 1/3.

Most horizontal wells show linear flow with a slope of 1/2, which is consistent with the theoretical understanding. There are also a few linear flow stages with a slope of 1/3 and a slope of 1/4 which are called bilinear flows. The linear flow slope of all production wells is 1/2, and the proportion of 1/2 slope of linear flow in water wells is 66.67%, as shown in Table 1.

Table 1. Proportion table of well test curves with different characteristics of water injection wells.

Liner Flow Stage Slope	1/2	1/3	1/4
Total	8	2	2
Proportion	66.67%	16.67%	16.67%

Well test curves in the study area have three characteristics, as below.

- There is no radial flow stage in the well test curves: The permeability of the main reservoir in the study area is low, and the permeability is 10 mD. At the same time, the development of the white spot section in the reservoir hinders the migration of the fluid, resulting in low pressure conductivity of the reservoir, slow water injection efficiency, and inability to achieve radial flow during the test time.
- Characteristics of variable well storage: The characteristics of changing wellbore storage mainly appear in the well test curve of production wells. Low permeability reservoirs generally have the characteristics of variable well storage. In the water injection development area, there is a multiphase flow in the wellbore. Shutdown for a period of time will redistribute the phase in the wellbore, resulting in a decrease in the fluid compression coefficient and a decrease in the wellbore storage coefficient.
- Double logarithmic curve opening is small: Reservoir A has good formation conditions and no pollution blockage exists. Reflected in the well test curve, the explanatory skin coefficient parameter is negative, and the opening of the double logarithmic curve is small.

The study area is a low permeability pore carbonate reservoir. There is no interlayer. The reasons for the formation of bilinear flow are summarized as follows:

- Well trajectory: Well trajectory is mainly A-3; the average permeability of this layer is slightly lower. At the same time, the well trajectory slants through the formation as shown in Figure 10 or shows bending shape in the formation. The fluid flow direction in the formation intersects with the fluid flow direction in the production well or the injection well, which is inconsistent with the theoretical model, leading to the abnormality of the field well test curve.

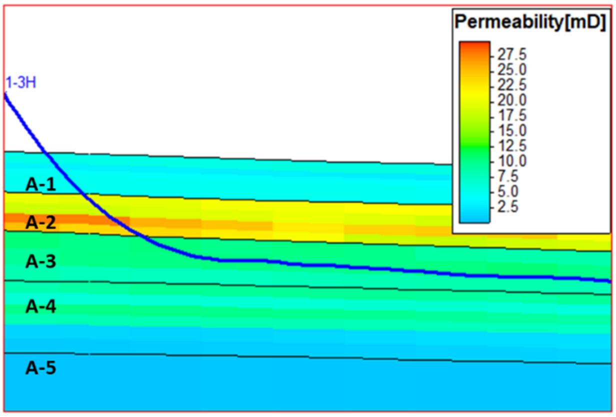

Figure 10. Well trajectory of abnormal linear flow slope well.

- Reservoir properties: Combined with geological understanding, reservoir properties around the well with bilinear flow are poor. Combined with a series of well test curves under different formation permeability conditions established by PTA in KAPPA, we can see that when the formation permeability is low, the slope of the linear flow section becomes lower, the linear flow occurs late, and does not reach the radial flow stage, as shown in Figure 11.

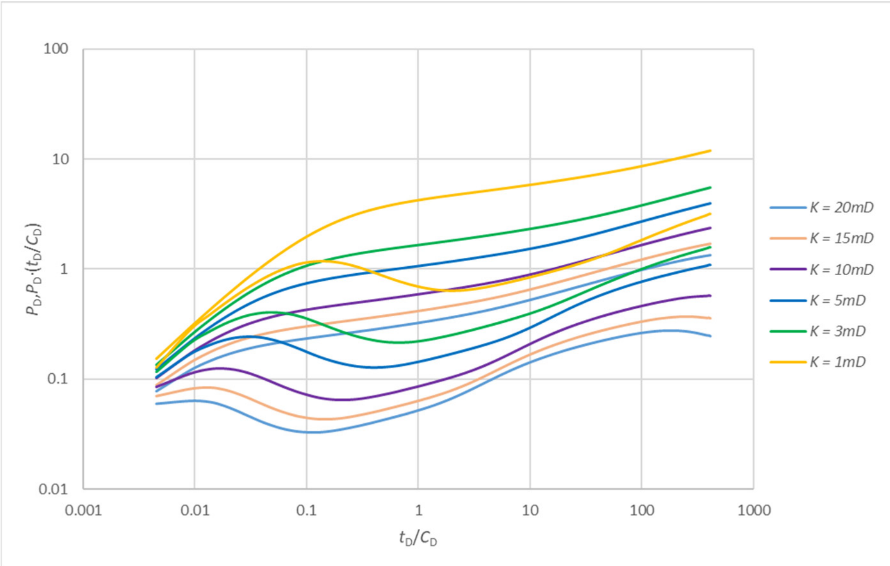

Figure 11. Well test curves of different formation permeability.

The lower the formation permeability, the greater the differential pressure required to overcome formation resistance under the same other parameters, so the pressure and pressure derivative are at the top of the figure when the reservoir permeability is low. Low formation permeability results in slow pressure conduction and the occurrence of each flow stage is delayed. In the linear flow stage, the pressure wave propagates to the distant formation, and the small formation permeability leads to the slow conduction of the pressure wave, which cannot bring enough pressure recovery, and the slope of the pressure derivative becomes smaller.

- Other factors: The possible influencing factors also include the transition between radial flow and stable linear flow and the existence of white spots. Due to well test time constraints, the transition between initial radial flow and 1/2 slope linear flow may not be observed. The main production layers of reservoir A developed discontinuous white spots, which hindered the fluid flow to a certain extent. However, due to its horizontal discontinuous distribution, its influence is limited.

In summary, the influencing factors of the abnormal well test curve of the low permeability carbonate reservoir in the study area are the well trajectory and the physical properties of the formation. Possible influencing factors include the transition between radial flow and stable linear flow and the existence of white spots.

5. Dynamic Analysis of Typical Horizontal Well Pattern

The well pattern of A reservoir is mainly divided into two parts. In the middle part, the vertical well pattern is adopted. Due to the limited injection capacity of vertical wells in low permeability reservoirs and the high water cut of vertical well production wells, most wells in the vertical well pattern are in the shut-in state. The edge mainly has a horizontal well pattern, as shown in Figure 12. The permeability of the formation around the horizontal injection-production pattern is about 10 mD as shown in Figure 13. Horizontal wells have obvious advantages in the development of low permeability carbonate reservoirs. Horizontal production wells in the study area are basically in the stage of no water or low water cut. The well pattern in the study area has clear correspondence as shown in Table 2, which plays an important role in determining the development strategy in the future. The well test characteristics and dynamic characteristics of horizontal well injection-production area are clarified through the study of 8–10 row group in reservoir A. The relationship between the two characteristics was established, and the injection-production technology policy adjustment and optimization were implemented on the basis of relationship.

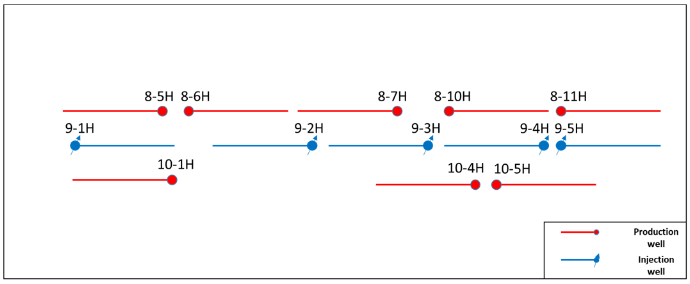

Figure 12. Horizontal well pattern in the study area. The circles represent wellhead positions.

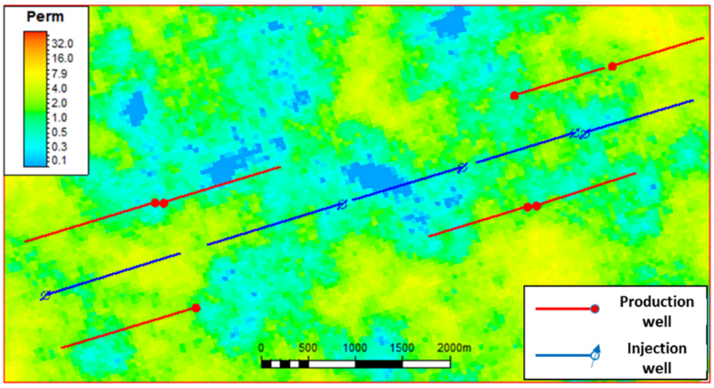

Figure 13. Permeability distribution map of injection-production area in a horizontal well. The circles represent wellhead positions.

Table 2. Table of injection-production relationship of horizontal well pattern.

Production Well	Corresponding Injection Well
8-5H	9-1H
8-6H	9-2H
8-7H	9-2H, 9-3H
8-10H	9-4H, 9-5H
8-11H	9-5H
10-1H	9-1H
10-4H	9-3H, 9-4H
10-5H	9-4H, 9-5H

The dynamic performances of the horizontal injection-production well pattern are that the injection water advances uniformly, the pressure build-up during the water injection, and the effective time of water injection is long. Water injection is one of the most effective development methods for low permeability carbonate reservoirs. One of the main factors restricting its development is injection capacity. Large-scale development of bioclastic limestone still does not have a perfect development model. In view of the problems existing in the study area, it is necessary to further analyze the dynamic characteristics and determine the appropriate production strategy.

5.1. Well Test Result

The homogeneous model is that the pressure is within the range of test pressure, and the reservoir parameters are close to uniformity. The radial composite model refers to the formation properties near and far from the well change.

From the latest well test curve, there is an abnormal linear flow stage in 9-3H well, which is related to the low permeability of the surrounding strata and the tortuous well trajectory. According to the latest well test interpretation results, there is no pollution in the formation as shown in Table 3. The permeability around 9-3H, 9-4H and 9-5H wells is low, which is basically consistent with the reservoir property parameters, and is basically the same as the position where there is pressure build-up in dynamic characteristics.

Table 3. Comparison table of well test parameters of injection wells.

Well	Time	Skin	Permeability (mD)	Effective Length (m)	Injectivity Index (bbl/d/psia)	Interpretation Model
9-1H	August 2019	−0.12	2.58	575	−1.65	Horizontal and Homogeneous
	June 2020	0.00	4.06	518	−1.97	Horizontal and Homogeneous
9-2H	January 2019	−0.08	4.66	616	−3.06	Horizontal and Radial Composite
	May 2020	−0.13	3.43	591	−1.92	Horizontal and Radial Composite
9-3H	June 2019	−0.14	4.65	628	−2.29	Horizontal and Homogeneous
	January 2020	−0.12	3.41	656	−1.90	Horizontal and Homogeneous
9-4H	April 2019	−0.16	4.32	520	−2.22	Horizontal and Homogeneous
	February 2020	−0.11	2.47	811	−1.84	Horizontal and Homogeneous
9-5H	April 2020	−0.17	2.80	610	−1.63	Horizontal and Homogeneous

Except 9-2H well, the two well test interpretation results of other injection wells did not change significantly, as shown in Figures 14–17. In the early stage of well test, the pressure of 9-2H well changed dramatically, as shown in Figure 18. Combined with the dynamic parameters of surrounding water injection wells and production wells, the sudden change of pressure is related to the sudden increase of water injection in 9-4H well, and is not related to the change of reservoir physical properties or fluid.

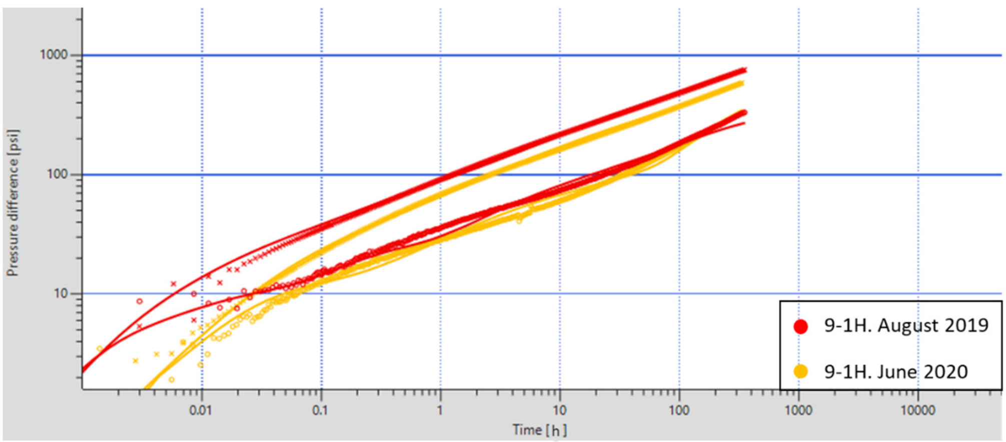

Figure 14. 9-1H well test curve.

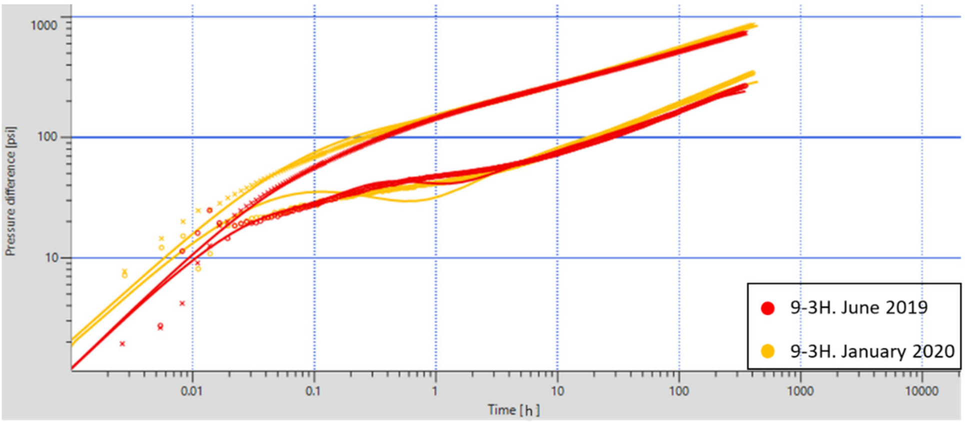

Figure 15. 9-3H well test curve.

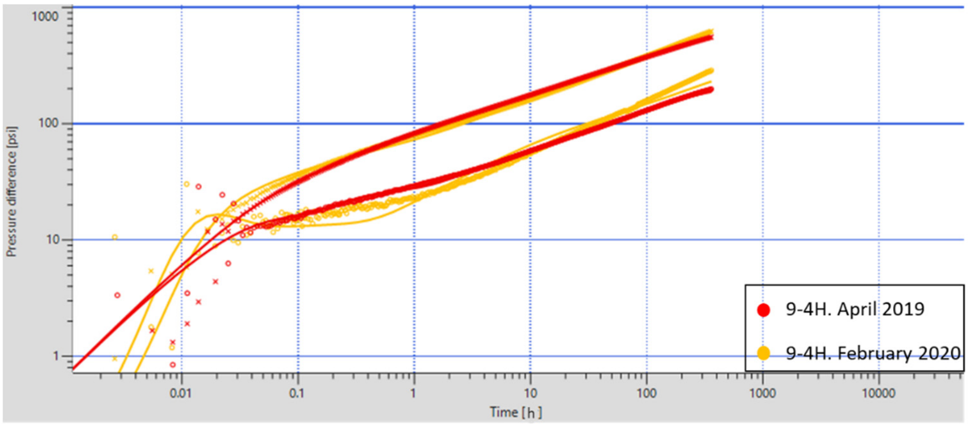

Figure 16. 9-4H well test curve.

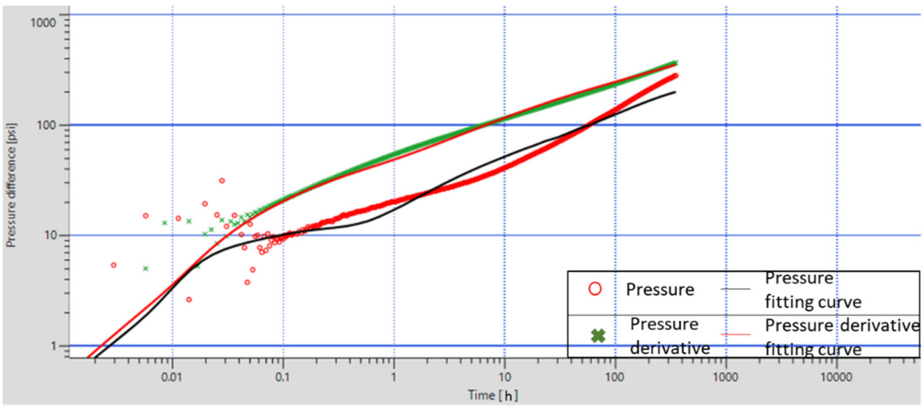

Figure 17. 9-5H well test curve.

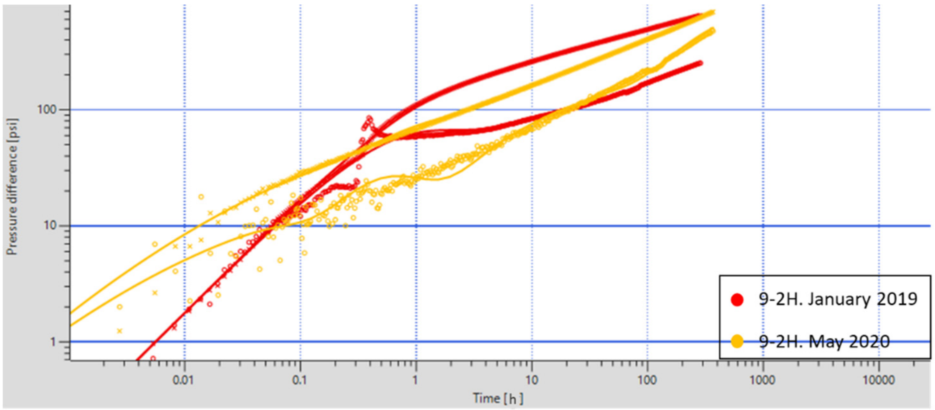

Figure 18. 9-2H well test curve.

According to the well test interpretation results, there is no pollution in the for-mation as shown in Table 4. The permeability around 10-1H well is better than 8-5H well.

Table 4. Comparison table of well test parameters for production wells.

Well	Time	Skin	Permeability (mD)	Effective Length (m)	Production Index (bbl/d/psia)	Interpretation Model
8-5H	December 2020	−6.96	2.31	317	0.80	Horizontal and Homogeneous
10-1H	December 2022	−7.30	7.29	513	1.22	Horizontal and Homogeneous

The well test curves of two production wells in the injection-production area of horizontal wells show the characteristics of changing well storage, as shown in Figures 19 and 20. The changes of well storage coefficients in 8-5H and 10-1H well are exponential changes. The well storage coefficient of exponential change shows S shape in the derivative curve of a double logarithmic curve. At the beginning of the derivative curve, a small hump appears; it then becomes concave upward, moves straight upward, and finally forms a hump in the transition period.

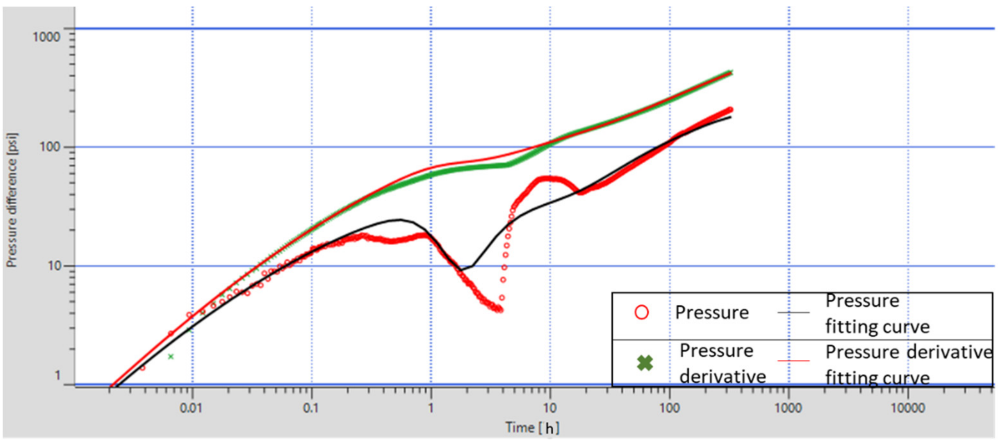

Figure 19. 8-5H well test curve.

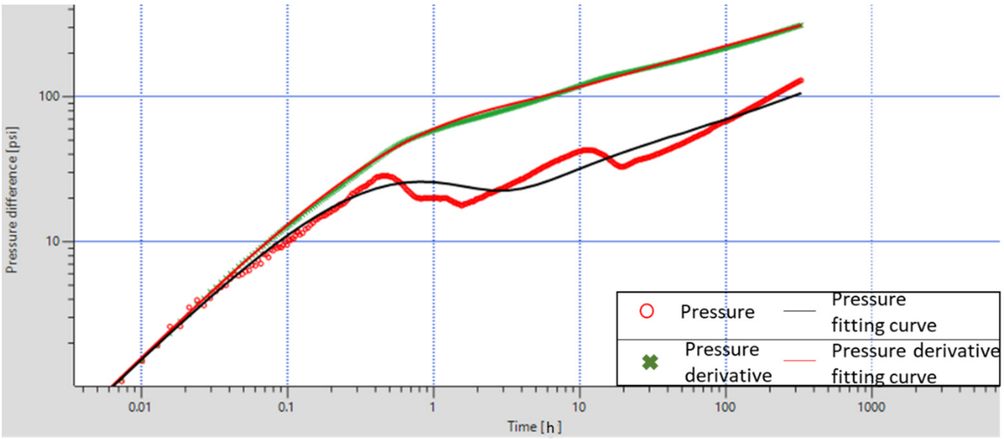

Figure 20. 10-1H well test curve.

By using the numerical well test method, considering the influence of the surrounding 9-1H well on 8-5H as shown in Figure 21, the fitting effect of the well test theoretical curve is perfect as shown in Figure 22. This also indirectly reflects the better connectivity between the two wells [26].

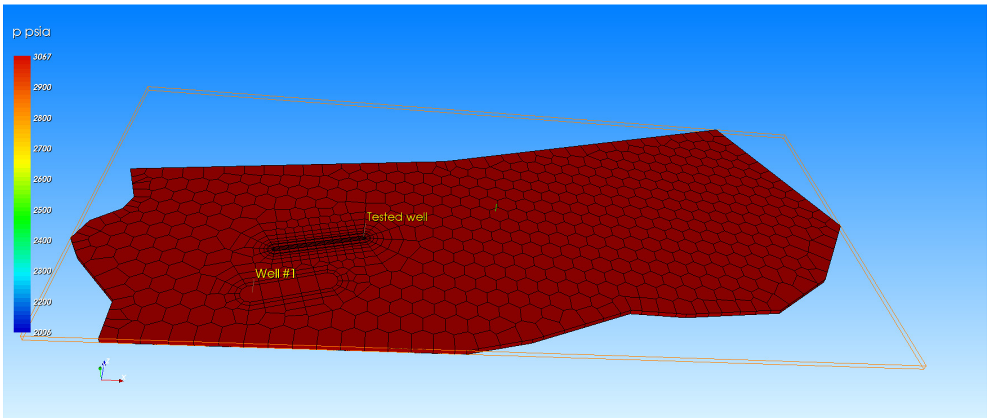

Figure 21. Numerical well test grid of 8-5H well. Tested well represents 9-1H well and Well #1 represents 8-5H well. Lines and arrows. The lines form a grid, and the arrows represent directions.

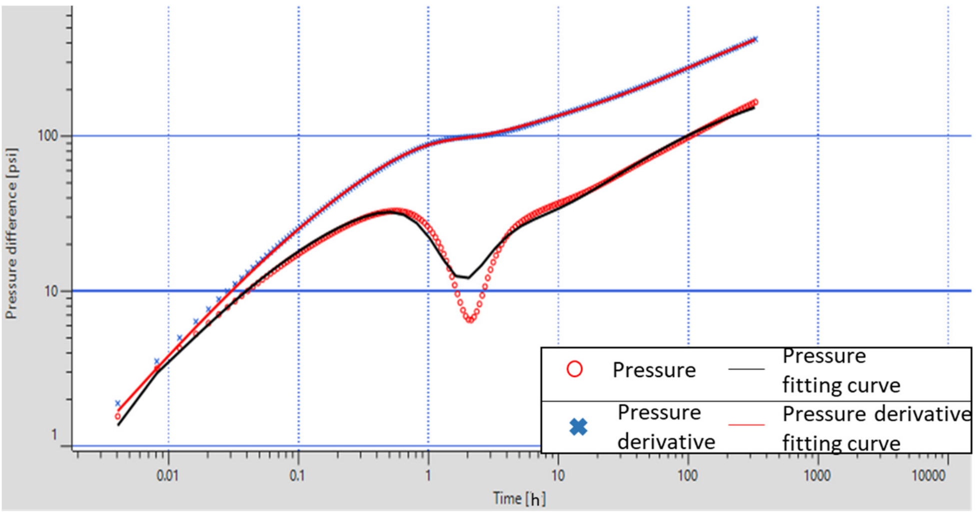

Figure 22. Numerical well test curve of 8-5H well.

5.2. Reservoir Pressure

By using the interpolation method and combining with the field measured pressure data, the pressure distribution map of the injection-production area of horizontal wells can be plotted as shown in Figure 23. From the pressure distribution diagram, there is pressure holding around the root of 9-2H, 9-3H and 9-4H of the injection well. At the same time, the pressure holding between rows 9 and 10 is more obvious, which is related to the horizontal heterogeneity of the reservoir.

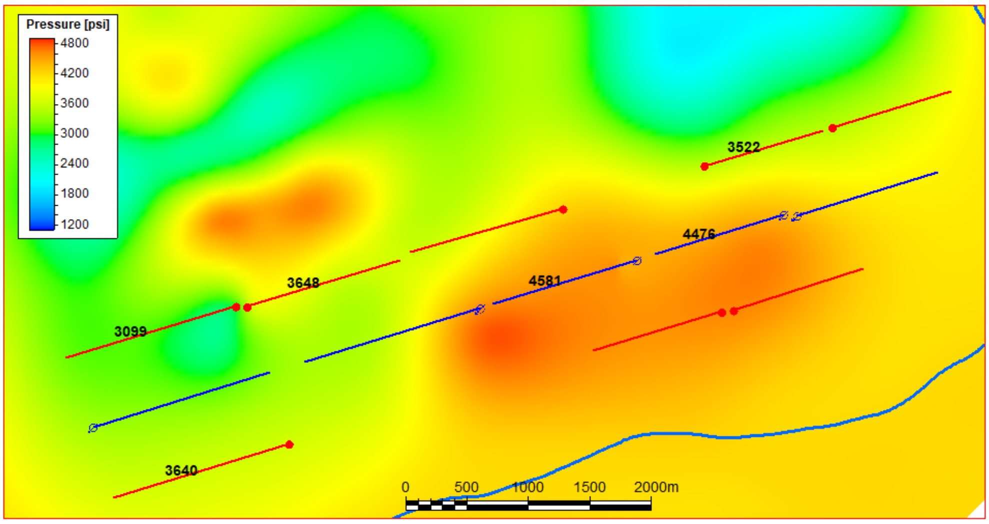

Figure 23. Pressure distribution map of injection-production horizontal well pattern.

5.3. Well Water Cut

Through streamline simulation, the water injection area of horizontal well pattern has been clarified. The injected water migrates evenly to the production wells on both sides mainly along A-2, and the leading edge advances uniformly as a whole, as shown in Figure 24. Partially injected water advances along the A-2 band with better properties. The advancing speed of the injection water is 0.9 m/day, and the current position of the water flooding front is 380 m away from the water injection well.

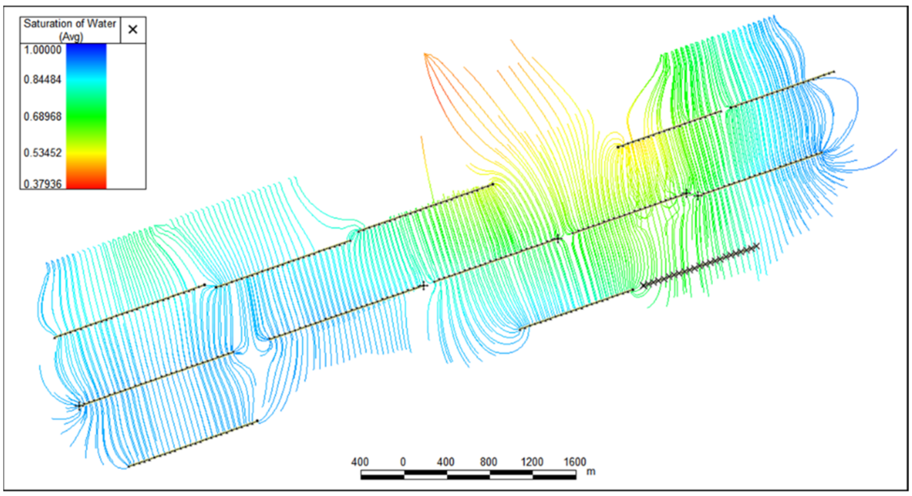

Figure 24. Streamline diagram of injection-production horizontal well pattern.

From the production well water cut curve, 8-5H, 8-6H, 8-10H, 8-11H and 10-1H wells have water breakthrough. The rising pattern of water cut in the well pattern rises slowly, and the water cut of the 8-10H well suddenly rises after shut-in, resulting in flooding. It can be seen from Figure 25 that except for 8-10H, the other wells are still in low water cut stage. The water breakthrough wells are concentrated in the 8-well row, and the water cut content of the 8-well row production wells is high.

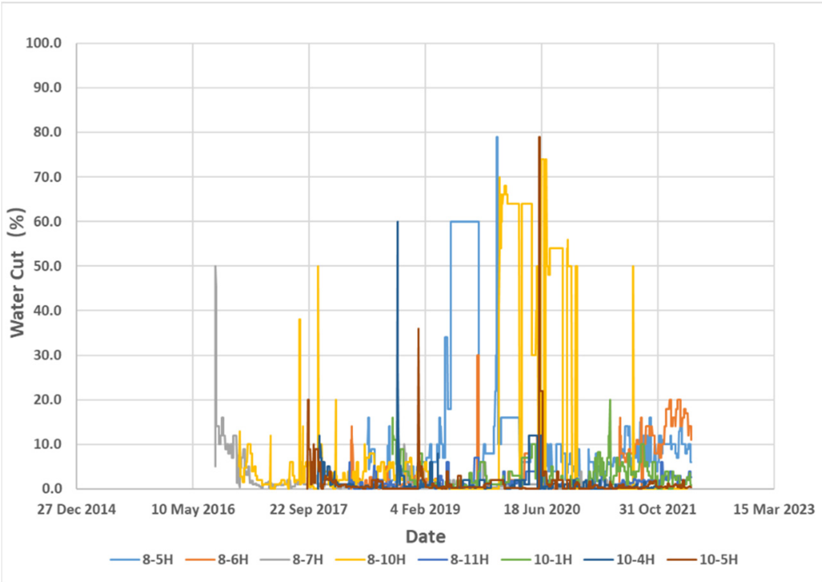

Figure 25. Water cut variation curve of injection-production horizontal well pattern.

5.4. Well Production

The monthly average production level of each production well in the injection-production area of horizontal wells is equivalent, as shown in Figure 26. From the well test analysis of production wells, the formation around the production well is not polluted, and the production capacity is good. Further development measures focus on the changes of water cut and pressure.

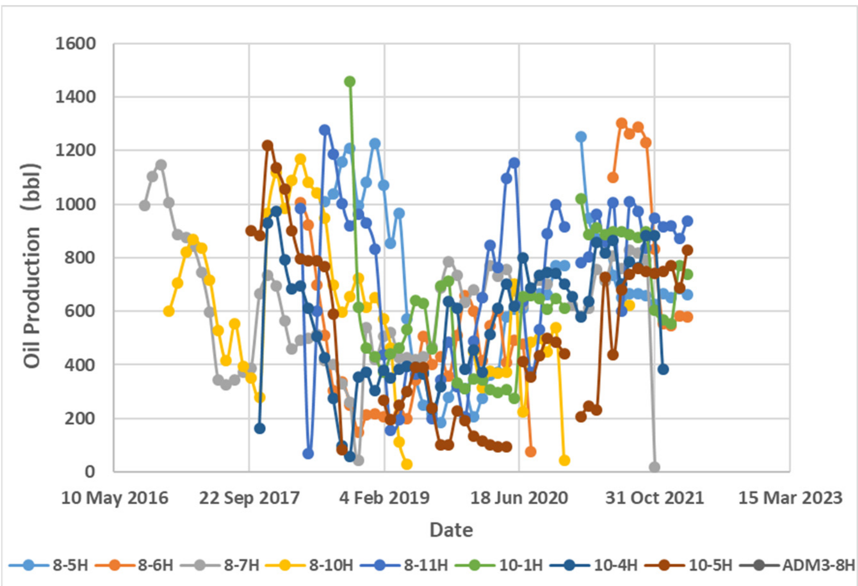

Figure 26. Oil production variation curve of injection-production horizontal well pattern.

6. Discussion

It is found that the difference of permeability between layers is the main factor of bilinear flow in the previous studies. However, the reservoir in the study area that is relatively homogeneous also produces the characteristics of bilinear flow. The permeability difference between layers in the study area is small, and their influence can be ignored. Through analysis, the main factors of bilinear flow are found to be the well trajectory and the reservoir properties.

The results of well test and dynamic inversion show that there is no pollution blockage in the study area, and the horizontal heterogeneity and the corresponding injection-production relationship lead to the production problems such as pressure build-up in injection wells and waterflooding in production wells. The influence of the injection well corresponding to the production well on the pressure change is considered by the numerical well test method, and the well test curve considering the influence of the injection well can better fit the interpretation model. It can be seen that there is a good connectivity between the production well and the injection well.

In the next study, the injection-production optimization measures can be discussed by combining well test interpretation parameters and dynamic inversion results, and the suitable production parameters such as production rate, injection-production ratio and infilling well location can be studied by means of numerical simulation and optimization algorithm. At the same time, we need to take measures to stabilize production, water cut and pressure.

7. Conclusions

1. The well test curves of low permeability carbonate reservoirs in the study area are generally characterized by no radial flow stage, changing wellbore storage effect and small openings of the double logarithmic curve.
2. Most horizontal wells show a linear flow with a slope of 1/2, and there are also a few linear flow stages with a slope of 1/3 and a slope of 1/4. This anomalous feature is less affected by the difference in inter-layer permeability, and the influencing factors are well trajectory and reservoir properties. The transition between radial flow and stable linear flow and the existence of white spots also have certain effects on the characteristics of well test curves.
3. Based on the above dynamic and static data and the analysis of well test interpretation results, it can be obtained that there is no pollution in the formation of the study area, and the development effect is overall good. However, there are still differences among various injection wells and production wells, and the main control factors are reservoir properties.
4. Further injection-production optimization measures include:
    - The injection parameters of 9-3H and 9-4H need to be adjusted to improve the pressure build-up condition.
    - It is necessary to detect production parameters such as yield, water cut and pressure in time to prevent rapid increase of water cut and ensure stable production.
    - The water injection volume of injection wells around reopened production wells should be adjusted according too a time frame designed to prevent flooding.

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References

1. Roberts, D.G. Sedimentary Basins and Petroleum Geology of the Middle East. *Mar. Pet. Geol.* **1997**, *16*, 379. [CrossRef]
2. Daviau, F.; Mouronval, G.; Bourdarot, G.; Curutchet, P. Pressure Analysis for Horizontal Wells. *SPE Form. Eval.* **1988**, *3*, 716–724. [CrossRef]
3. Goode, P.A.; Thambynayagam, R. Pressure Drawdown and Buildup Analysis of Horizontal Wells in Anisotropic Media. *SPE* **1987**, *2*, 683–697. [CrossRef]
4. Odeh, A.S.; Babu, D.K. Transient Flow Behavior of Horizontal Wells, Pressure Drawdown, and Buildup Analysis. *SPE Form. Eval.* **1990**, *5*, 7–15. [CrossRef]
5. Spivey, J.P.; Lee, W.J. Estimating the Pressure-Transient Response for a Horizontal or a Hydraulically Fractured Well at an Arbitrary Orientation in an Anisotropic Reservoir. *SPE Res. Eval. Eng.* **1999**, *2*, 462–469. [CrossRef]
6. Cinco-Ley, H.; Samaniego, V.F. Transient Pressure Analysis for Fractured Wells. *J. Pet. Technol.* **1981**, *33*, 1749–1766. [CrossRef]
7. Du, K.; Stewart, G. Transient Pressure Response of Horizontal Wells in Layered and Naturally Fractured Reservoirs with Dual-Porosity. In Proceedings of the SPE Annual Technical Conference and Exhibition, Washington, DC, USA, 4–7 October 1992. [CrossRef]
8. Briceno, M.; Summers, L.E.; Quijada, O.J. Horizontal Wells Pressure Build Up Analysis in Orinoco Heavy Oil Belt. In Proceedings of the SPE International Thermal Operations and Heavy Oil Symposium and International Horizontal Well Technology Conference, Calgary, AB, Canada, 4–7 November 2002. [CrossRef]
9. Feng, W.C.; Nurafza, P.; Al-Shamma, B.; Gringarten, A. Bilinear Flow in Horizontal Wells in a Homogeneous Reservoir: Huntington Case Study. In Proceedings of the European Conference 2015, Madrid, Spain, 1–4 June 2015. [CrossRef]
10. Baba, A.; Azzouguen, A.; Mazouzi, A.; Tiab, D.; Aissaoui, K. Determination of the Controlling Factors and Origins of the Bilinear Flow from Horizontal Well Transient Responses. In Proceedings of the Canadian International Petroleum Conference, Calgary, AB, Canada, 11–13 June 2002. [CrossRef]
11. Yonglv, J.; Xuewen, Y.; Jianguo, G. Study on Variable Well Storage in Well Test Analysis. *Xinjiang Pet. Geol.* **1998**, *19*, 4.
12. Shiqing, C.; Weirong, X.; Kangliang, G.; Jianlin, L. Typical Curve Characteristics and Case Analysis of Variable Wellbore Storage Effect. *Well Test.* **1992**, *4*, 9.
13. Keyi, Z.; Lize, L.; Liping, J.; Kangliang, G.; Fei, L.; Haiping, H.; Xin, L. Pressure buildup curve behavior of pore type carbonate reservoir in AH Oilfield of Iraq. *Fault-Block Oil Gas Field* **2014**, *21*, 762–766. [CrossRef]
14. Qishen, L.; Cheng, H.; Wei, D. A new well test model solution for fractured—Pore reservoir. *J. Southwest Pet. Inst.* **2002**, *24*, 71–73. [CrossRef]
15. Jia, B.; Xian, C.-G. Permeability measurement of the fracture-matrix system with 3D embedded discrete fracture model. *Pet. Sci.* **2020**. [CrossRef]
16. Liu, Y.; Wu, X.; Wang, Y.; He, F.; Yuan, Y. Build a bridge between well testing theory and application. *Well Test.* **2006**, *15*, 5. [CrossRef]
17. Enjie, H.; Lize, L.; Keyi, Z.; Xinmin, W.; Liping, J.; Zhaolei, S.; Kai, H. Water Production Characteristics and Control Measures of Porous Carbonate Reservoir in Iraq. *J. Yangtze Univ.* **2015**, *12*, 1–6. [CrossRef]
18. Yong, L.; Qi, Z.; Chenji, W.; Benbiao, S. Dynamic Characterization of Different Reservoir Stacked Patterns for a Giant Carbonate Reservoir in Middle East. In Proceedings of the SPE Reservoir Characterisation and Simulation Conference and Exhibition, Abu Dhabi, United Arab Emirates, 5 May 2017. [CrossRef]
19. Gringarten, A.C.; Ramey, H.J.J. The Use of Source and Green's Functions in Solving Unsteady-Flow Problems in Reservoirs. *Soc. Pet. Eng. J.* **1973**, *13*, 285–296. [CrossRef]
20. Xiangyan, K. *Advanced Seepage Mechanics*, 2nd ed.; University of Science and Technology of China Press: Hefei, China, 2010; pp. 203–233.
21. Nengqiang, L. *Practical Modern Well Test. Interpretation Method*, 4th ed.; Petroleum Industry Press: Beijing, China, 2009; pp. 149–153.
22. Xiaoping, L.; Liehui, Z.; Qiguo, L. *Well Test. Analysis Method*, 1st ed.; Petroleum Industry Press: Beijing, China, 2008; pp. 50–53.
23. Suzuki, K.; Nanba, T. Horizontal Well Pressure Transient Behavior in Stratified Reservoirs. In Proceedings of the SPE Annual Technical Conference and Exhibition, Dallas, TX, USA, 6–9 October 1991. [CrossRef]
24. Xiaoyun, L.; Yongqiang, W.; Chong, C.; Lianchao, J.; Lu, L. Theory and Application of Unstable Well Test Analysis for Horizontal Wells. *Well Test.* **2012**, *21*, 5–10.
25. Liang, W.; Ruiting, B. Well Test Analysis and Application of Horizontal Well In Low Permeability Reservoir. *West.-China Explor. Eng.* **2010**, *22*, 44–47. [CrossRef]
26. Xin, L.; Baozhen, J.; Zheng, C.; Yang, W.; Ting, Z. Application of Combination of Dynamic Analysis and Numerical Well Test In Solving Multi-solution Problem of Well Test. *Neijiang Technol.* **2014**, *35*, 3. [CrossRef]