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Characterization of Reservoir Boundaries Using Interference Tests

W. L. WANG¹⁾,^{12)*} and M. C. T. KUO¹⁾¹⁾ Dept. of Mineral and Petroleum Engineering, National Cheng Kung University, Tainan, Taiwan, R. O. C.¹²⁾ Chinese Petroleum Corporation, EDRI, 1 Ta Yuan, Wen Shan, Miaoli, Taiwan, R. O. C.

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Boundary effects in the pressure-transient tests offer an excellent opportunity to provide information about reservoir engineering parameters and to characterize reservoir boundary conditions such as, sealing fault versus nonsealing fault.

This paper investigated transient pressure for a water-drive reservoir with irregularly shaped boundaries. The paper applied the image-well method to interpret a field interference test and to characterize reservoir boundaries. This paper also interpreted a field interference test in an anisotropic aquifer to identify the recharging boundaries.

1. Introduction

Several analytical methods have been developed to interpret unsteady-state reservoir flow problems with boundary effect. For isotropic reservoirs, Matthews *et al.*¹⁾ superposed the line source solution to determine the pressure behaviors inside bounded polygon reservoirs by the method of images. Earlougher *et al.*²⁾ also provided dimensionless pressure tables at various points in several closed rectangular drainage shapes. Ramey *et al.*³⁾ presented a computer program to generate dimensionless pressures for rectangular reservoirs with mixed boundary conditions (both no-flow and constant-pressure boundaries). For anisotropic reservoirs, Yeh⁴⁾ presented the analytical solution for rectangular drainage shape reservoirs.

However, there are many practical cases where the reservoir drainage shape is too complicated to be approximated by a circular or rectangular shape. In 1990, Kuo⁵⁾ presented the image-well method to predict pressure distribution in irregularly shaped bounded reservoirs. In 1992, Kuo *et al.*⁶⁾ extended the image-well method from bounded reservoirs to water-drive reservoirs.

This paper applies the image-well method^{5), 6)} to calculate transient pressures in irregularly shaped reservoirs. The image-well method^{5), 6)} is used to analyze an interference test in an isotropic reservoir. The interpretation provides useful information about the boundary conditions of the reservoir. The image-well method is also applied to interpret a pumping test in an anisotropic

reservoir and to identify the recharging boundaries of the aquifer.

2. Methodology

Few field-case studies are presented in the literature to characterize boundaries conditions for reservoirs with irregularly shaped boundaries using interference tests. The method to interpret interference test in isotropic reservoirs and anisotropic reservoirs with irregularly shaped boundaries are discussed as follows: Reservoirs are assumed homogeneous in the following discussion.

2.1. Isotropic Reservoir

Kuo *et al.* developed the image-well method^{5), 6)} to superpose line source solutions of image wells to predict pressure-transient behavior in irregular-shape bounded reservoirs and water-drive reservoirs.

To use the image-well method^{5), 6)}, the image wells are approximately equally spaced from each other around the drainage boundary. First, the flow rates of the image wells at each time step are determined by solving a set of simultaneous linear algebraic equations. Second, the dimensionless pressures are calculated by superposing the line source solutions of image wells in time. Kuo⁵⁾ and Kuo *et al.*⁶⁾ have provided the validity of the image-well method^{5), 6)}.

2.2. Anisotropic Reservoir

To apply the image-well method^{5), 6)} in anisotropic reservoirs with irregularly shaped boundaries, it is necessary to transform anisotropic systems to isotropic systems. The approach is

* To whom correspondence should be addressed.

discussed in details as follows.

The diffusivity equation which governs fluid flow in the porous media in an anisotropic reservoir can be expressed as

$$k_{xx} \frac{\partial^2 P}{\partial X^2} + 2k_{xy} \frac{\partial^2 P}{\partial X \partial Y} + k_{yy} \frac{\partial^2 P}{\partial Y^2} = \phi \mu c \frac{\partial P}{\partial t} \quad (1)$$

To apply the image-well method for an anisotropic reservoir (**Fig. 1**), the X , Y coordinates (*i.e.*, real coordinates) are transformed in parallel to the major and minor permeability/transmissivity coordinates (X' , Y'), using Eqs. (2) and (3).

$$X' = X \cos \theta + Y \sin \theta \quad (2)$$

$$Y' = Y \cos \theta - X \sin \theta \quad (3)$$

where θ is the direction of major permeability.

This process eliminates the cross term of the permeability tensor (k_{xy}), and Eq. (1) is reduced to Eq. (4),

$$k_x \frac{\partial^2 P}{\partial X'^2} + k_y \frac{\partial^2 P}{\partial Y'^2} = \phi \mu c \frac{\partial P}{\partial t} \quad (4)$$

where k_x and k_y are the major and minor permeabilities, respectively.

Then Eq. (4) is further simplified by using the following coordinate transformation:

$$\bar{X} = X' \quad (5)$$

$$\bar{Y} = Y' \sqrt{(k_x/k_y)} \quad (6)$$

Equation (4) then becomes

Fig. 1 Coordinate Transformation System

$$\frac{\partial^2 P}{\partial \bar{X}^2} + \frac{\partial^2 P}{\partial \bar{Y}^2} = \frac{\phi \mu c}{k_x} \frac{\partial P}{\partial t} \quad (7)$$

Equation (7) represents the diffusivity equation in the isotropic system. The image-well method^{5),6)} can be applied to Eq. (7) to interpret interference test data transformed to the isotropic coordinates.

3. Field Cases

The image-well method is applied to interpret interference tests in both isotropic and anisotropic cases. The isotropic case demonstrates transient pressure for a water-drive reservoir with irregularly shaped boundaries to interpret a field interference test in which reservoir boundaries significantly affect the transient pressure. The anisotropic case demonstrates pressure drawdown in an anisotropic aquifer with irregularly shaped boundaries, to characterize aquifer boundary conditions and to identify the constant-head boundaries.

3.1. Isotropic Reservoir

In general, the objective of interference test is to evaluate reservoir engineering parameters such as transmissivity and storage coefficient for the reservoirs. This paper describes a field interference test with boundary effects; applies the image-well method to simulate the irregularly shaped boundary and to calculate the transient pressure for the interference test; and characterizes the reservoir boundary by matching the transient pressures calculated by the image-well method with the field interference test data.

Figure 2 represents an irregularly shaped reservoir. The throw of Fault A and Fault C is far greater than the reservoir thickness. Fault A and Fault C are sealing faults. The throw of Fault B is close to the reservoir thickness. It is difficult to judge whether Fault B is sealing or not by comparing the throw with the reservoir thickness. An interference test was designed and conducted to

Fig. 2 An Isotropic Irregularly Shaped Reservoir

characterize Fault B, *i.e.*, to tell whether Fault B was sealing or not.

In the interference test, Well A2 was the production Well and Well A1 was the observation well. The production data during the interference test and reservoir engineering parameters were as follows:

Net pay (h)=70 ft

Oil viscosity (μ)=4.2 cp

Permeability (k)=4,310 md

Transmissivity (kh/μ)=71,900 md-ft/cp

Porosity (ϕ)=0.237

Compressibility (c)= 8.32×10^{-6} psi $^{-1}$

Oil production rate ($q_o B_o$)=943 STB/D

Distance between Well A1 and Well A2 (r)=2,300 ft

Production time (t_p)=170 h

With the above production data and reservoir engineering parameters, the transient pressures at

Fig. 3 Pressure-transient Behavior at Observation Well A1, Comparison between Field Data and the Line Source Solution

Fig. 4 Pressure-transient Behavior at Observation Well A1, Comparison between Field Data and Predictions by Image-well Method

Well A1, the observation point, can be calculated by the image-well method to simulate the irregularly shaped boundaries outlined on Fig. 2. Figure 3 shows the transient pressures at Well A1 calculated by the line source solution (*i.e.*, infinite acting). Figure 4 shows the transient pressures calculated by the image-well method assuming Fault B sealing (*i.e.*, no-flow boundary) and nonsealing (*i.e.*, constant-pressure boundary) at Well A1. Field data of the transient pressures at Well A1 are also shown on Figs. 3 and 4 and compared with the calculated transient pressures.

It can be seen from Fig. 3 that the transient pressure behavior at Well A1 calculated by the line source solution is significantly different from the field data. Figure 3 also indicates that the transient pressures during the interference test is significantly affected by the reservoir boundary. Figure 4 shows that the transient pressures at Well A1 calculated by the image-well method assuming Fault B sealing are higher than those of the field data. It also shows that, when assuming Fault B is nonsealing (*i.e.*, constant-pressure boundary), the calculated transient pressures at Well A1 are in an excellent agreement with those of the field data. Fault B can be judged to be nonsealing and regarded as a constant-pressure boundary.

These results demonstrate that the image-well method for the irregularly shaped boundary can be applied for interpreting interference tests to characterize reservoir boundaries.

3. 2. Anisotropic Aquifer

Pumping tests in the aquifers are equivalent to interference tests in the reservoirs. A pumping test was conducted to an anisotropic aquifer on Lan-Yu Island with irregularly shaped boundaries. By the coordinate transformation and the image-well method, the pressure drawdown for the pumping test could be calculated. The aquifer boundaries can be characterized by matching the calculated pressure drawdowns with the field pumping test data.

Figure 5 shows the location of the wells on Lan-Yu Island (one source Well S7C and one observation Well S7A). The pumping test data and aquifer parameters were as follows.

Major transmissivity (T_x)=Major transmissibility ($k_x h/\mu$)

= 2.378×10^5 md-ft/cp

Minor transmissivity (T_y)=Minor transmissibility ($k_y h/\mu$)

= 2.880×10^4 md-ft/cp

Direction of major transmissivity (θ)=10.2°

Storage coefficient (S)=Storage ($\phi c h$)

=0.173 ft/psi

Pumping rate (Q)=1,028 STB/D

Fig. 5 Location of Wells and Aquifer Boundary on Lan-Yu Island (real coordinates)

Fig. 6 Location of Wells and Aquifer Boundary on Lan-Yu Island (after transformation)

With the above pumping test data and aquifer parameters, the pressure drawdowns are calculated at observation Well S7A by considering the irregularly shaped boundaries outlined on **Fig. 5**. In order to apply the image-well method, the procedure described in the methodology for anisotropic aquifers is used. First the real coordinates

Fig. 7 Drawdown at Observation Well S7A, Comparison between Field Data and Predictions by Image-well Method

(X , Y) (**Fig. 5**) are transformed to major transmissivity coordinates (X' , Y') by Eqs. (2) and (3) and then to isotropic coordinates ($\bar{X}$, $\bar{Y}$) by Eqs. (5) and (6) (**Table 1** and **Fig. 6**).

To characterize the aquifer boundaries, pressure drawdown behaviors are calculated under the three different boundary conditions at the observation Well S7A. The first calculation is based on the line source solution (*i.e.*, infinite acting). The second is the pressure drawdown calculated by assuming constant-head boundary on shoreline. The third is the one assuming constant-head boundary on both the shoreline and west of Well S7C.

Figure 7 shows the field data and the calculated pressure drawdowns at observation Well S7A. It can be seen that the calculated pressure drawdown by the line source solution is significantly different from the field data after 2,500 minutes. The pressure drawdowns during the pumping test are significantly affected by aquifer boundaries. **Figure 7** indicates that the calculated pressure drawdown assuming constant-head boundaries on both the shoreline and west of Well S7C is in better agreement with the field data than the one assuming constant-head boundary on the shoreline only.

These results demonstrate that the approach developed in this study can be applied for interpreting pumping tests to characterize the con-

Table 1 Field Example Coordinate Transformation (ft)

Well No.	Real coord.		Major trans. coord.		Isotropic coord.	
	X	Y	X'	Y'	$\bar{X}$	$\bar{Y}$
S7C	1,056	961	0	0	0	0
S7A	1,132	951	72.5	-23.0	72.5	-66.3

ditions of irregularly shaped boundaries in anisotropic aquifers.

4. Conclusions

- 1) This paper successfully demonstrates that the image-well method can be applied to interpret field interference tests in both isotropic and anisotropic reservoirs.
- 2) The image-well method is applicable for interpreting a field interference test to characterize fault conditions whether they are sealing or not in an isotropic reservoir. The method is also useful for interpreting a field pumping test in an anisotropic aquifer to identify the constant-head boundaries.

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Nomenclatures

A	: area of drainage region	[ft ²]
c	: compressibility	[psi ⁻¹]
h	: formation thickness	[ft]
k	: permeability	[md]
k_{xx}, k_{xy}, k_{yy}	: permeability tensor	[md]
P	: pressure	[psi]

$q_o B_o$	: oil production rate	[STB/D]
Q	: constant-well discharge	[STB/D]
r	: radial distance from source well	[ft]
s	: drawdown	[ft]
S	: storage coefficient	[ft/psi]
t	: time	[h]
t_p	: production time	[h]
T	: transmissivity	[md-ft/cp]
T_{xx}, T_{xy}, T_{yy}	: transmissivity tensor	[md-ft/cp]
X	: x coordinate	[ft]
Y	: y coordinate	[ft]
$\bar{X}, \bar{Y}$	: permeability/transmissivity coordinates	[ft]
$\bar{X}, \bar{Y}$	: isotropic coordinates	[ft]
ϕ	: porosity	[—]
μ	: viscosity	[cp]
θ	: direction of major permeability/transmissivity	[°]

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要 旨

圧力干渉試験による油層の境界評価

W. L. WANG^{†1)}, M. C. T. KUO^{†2)}

^{†1)} Dept. of Mineral and Petroleum Engineering, National Cheng Kung University, Tainan, Taiwan, R.O.C.

^{†2)} Chinese Petroleum Corp., EDRI, 1 Ta Yuan, Wen Shan, Miaoli, Taiwan, R.O.C.

坑井圧力遷移試験において油層境界の影響は、断層の連続性評価に有用である。本報は、不定形の境界を持つ水押し油層に対する坑井圧力遷移試験を行い、イメージ坑井（仮想坑井）を

油層境界に設定する圧力干渉試験方法で、等方性油層境界および異方性の水層境界をケーススタディの形式で評価している。

Keywords

Well test, Interference test, Irregularly shaped reservoir, Boundary effect, Anisotropic reservoir