Proceedings Ninth Workshop Geothermal Reservoir Engineering
Stanford University, Stanford, California, December 1983
SGP-TR-74

WELL TEST ANALYSIS IN NATURALLY FISSURED, GEOTHERMAL RESERVOIRS WITH FRACTURE SKIN

A.F. Moench

U.S. Geological Survey, Menlo Park, CA

ABSTRACT

Mineral deposition or alteration is commonly found at fracture-block interfaces in fissured, geothermal reservoirs. In response to pressure reduction in the fissures such mineralization, if less permeable than the matrix rock, will retard the flow of fluid from the blocks to the fissures and is termed fracture skin in this paper. The problem of fluid flow to a production well in a double-porosity reservoir with fracture skin was analyzed theoretically. One of the findings of the analysis was that fully transient block-to-fissure flow can be approximated by pseudo-steady state flow if fracture skin permeability is sufficiently low. Type curves generated by numerical inversion of Laplace transform solutions are used to illustrate this effect. They are also used to corroborate the results of a finite-difference model of steam transport to a well in a naturally fissured, geothermal reservoir with fracture skin.

INTRODUCTION

Geothermal reservoirs are commonly composed of fractured rocks that have been subjected in varying degrees to hydrothermal alteration. Quartz, calcite, and other minerals are often found lining or filling fractures in surface outcrops and well-core samples. Interconnected, highly permeable fissures serve as primary conduits for mineral-charged water circulating naturally in geothermal reservoirs. Such fluids, when not in chemical equilibrium with the wall rock, alter or deposit minerals at fissure-block interfaces. The particular products of hydrothermal alteration or deposition depend upon physical and chemical parameters that vary from place to place. Types of products that occur in geothermal systems are described by Ellis and Mahon (1977). Such alteration products are termed "fracture skin" in this paper and are assumed to impede the free exchange of fluid between blocks and fissures.

Naturally fissured reservoirs are often treated mathematically as double-porosity systems whereby primary porosity blocks of low permeability and high storage capacity are separated by secondary porosity fissures of high permeability and low storage capacity. Two approaches have been taken to problems of well-test analysis in double-porosity reservoirs: one approach assumes that flow from blocks to fissures occurs under pseudo-steady state conditions and the other assumes fully transient conditions. In the pseudo-steady state approximation, one neglects divergence of flow within the primary porosity blocks. Therefore, this approach lacks the firm theoretical foundation of the transient-flow assumption. However, well-test data exist that support both approaches (Bourdet and Gringarten, 1980; Streltsova, 1983).

Moench (1983) has reviewed the theory of flow in double-porosity reservoirs. By introducing fracture skin to the theoretical analysis, he showed that the pseudo-steady state approximation is a special case of the theory that is based upon transient block-to-fissure flow. For large fracture skin it was shown graphically that the divergence of the flow in the blocks is small and thus the pseudo-steady state approximation is reasonable. In this paper dimensionless pressure responses obtained by numerical inversion of Laplace transform solutions are used to illustrate the effects of fracture skin. Results are compared to the response predicted by a finite-difference model described by Moench and Denlinger (1980) that was modified to incorporate fracture skin.

MATHEMATICAL MODELS

De Swaan (1976) proposed the use of either slab-shaped or sphere-shaped blocks to represent the geometry of the matrix rocks in a double-porosity reservoir and presented the equations that describe the transient flow of fluids in the fissures and blocks. In this study both these geometries are used.

Figure 1 shows a schematic diagram of a thin but finite-thickness skin of low-permeability material on the surface of a hypothetical block in a naturally fractured reservoir. It is assumed that the permeability of the skin is less than that of the block and possesses no storage capacity. Flux of fluid from the block to the fissure is assumed to be perpendicular to the interface and to obey Darcy's law. By continuity at the block-fissure interface

$$k_s \frac{(p')_{y=b'} - p}{b_s} = -k'\left(\frac{\partial p'}{\partial y}\right)_{y=b'} \quad (1)$$

where y is a generalized coordinate with its origin at the center of the block. Symbols are defined in the nomenclature and in Figure 1.

In accordance with commonly used definitions, dimensionless pressure is defined as

$$p_D = \frac{2\pi kH}{q\mu}(p_i - p) \quad (2)$$

dimensionless time is defined as

$$t_D = \frac{kt}{\mu\phi c_t r_w^2} \quad (3)$$

and dimensionless distance is defined as

$$r_D = r/r_w \quad (4)$$

Because of the low permeability of the matrix rock, the problem of flow to a production well is usually solved by assuming fluid enters the wellbore only through fissures and not through matrix rock. The mathematical development requires that gravitational effects are negligible and that pressure in the reservoir is initially uniform throughout. Further details and complete boundary value problems are given by Moench (1983). Assuming radial flow to a fully penetrating well discharging at a constant rate from an infinitely extensive double-porosity reservoir confined above and below by impermeable formations, the Laplace transform, line-source solution for dimensionless pressure drawdown in the fissure system is

$$\bar{p}_D = \frac{1}{s} K_o(r_D\sqrt{s + \bar{q}_D}) \quad (5)$$

where, for slab-shaped blocks,

$$\bar{q}_D = \frac{\gamma^2 m \tanh(m)}{1+S_F m \tanh(m)} \quad (6)$$

and, for sphere-shaped blocks,

$$\bar{q}_D = \frac{3\gamma^2[m \coth(m)-1]}{1+S_F[m \coth(m)-1]} \quad (7)$$

where $$S_F = \frac{k' b_s}{k_s b'} \quad (8)$$

The parameter m is defined as

$$m = \frac{\sqrt{\sigma s}}{\gamma} \quad (9)$$

where

$$\sigma = \frac{\phi' c_t'}{\phi c_t} \quad (10)$$

$$\gamma^2 = \left(\frac{r_w}{b'}\right)^2 \frac{k'}{k} \quad (11)$$

If the dimensionless fracture skin, S_F, is zero these solutions reduce to previously published solutions (see, for example, Deruyck and others, 1982; Gringarten, 1982).

The pressure response predicted by models that assume sphere-shaped blocks is very similar to that obtained by assuming slab-shaped blocks. Examination of (6) and (7) reveals that for S_F=0 and at early time, $\bar{q}_D=\gamma\sqrt{\sigma s}$ for slab-shaped blocks, and $\bar{q}_D= 3\gamma\sqrt{\sigma s}$ for sphere-shaped blocks. Hence at early time, the response due to sphere-shaped blocks will be the same as that due to slab-shaped blocks if the permeability of the sphere-shaped blocks is reduced by a factor of nine (see Figure 2). At late time the responses will be the same by virtue of the fact that $\bar{q}_D=\sigma s$ in (6) and (7).

For the special case in which dimensionless fracture skin is large and m is small (6) becomes

$$\bar{q}_D = \frac{\gamma^2 m^2}{1+S_F m^2} \quad (12)$$

and (7) becomes

$$\bar{q}_D = \frac{3\gamma^2 m^2}{3+S_F m^2} \quad (13)$$

The expressions (12) and (13) when combined with (5) can be shown to be identical to the commonly used pseudo-steady state, block-to-fissure flow models for double-porosity systems. It is necessary, however, to substitute fracture-skin permeability for block permeability in the pseudo-steady state flow model (Moench, 1983). The dimensionless parameter, λ, defined by Warren and Root (1963) to relate block and fissure system permeability, becomes

$$\lambda = \frac{k_s r_w^2}{k\, b' b_s} = \frac{\gamma^2}{S_F} \qquad (14)$$

for slap-shaped blocks, and

$$\lambda = \frac{3k_s r_w^2}{k\, b' b_s} = \frac{3\gamma^2}{S_F} \qquad (15)$$

for sphere-shaped blocks. Substitution of these expressions into (12) and (13) yields

$$\bar{q}_D = \frac{s}{1/\sigma + s/\lambda} \qquad (16)$$

Although expressed in different notation, (16) and (5) combine to form the same solution as given by Kazemi and others (1969) which is an extension for interference tests of the Warren and Root model.

For the purpose of analyzing production-well data it is often necessary to include effects of wellbore storage and skin. In this paper, for the purpose of simplicity, wellbore skin is neglected. The Laplace transform solution that included effects of wellbore storage but neglects wellbore skin is

$$\bar{p}_D = \frac{K_o(r_D x)}{s[sC_D K_o(x) + xK_1(x)]} \qquad (17)$$

where $x = \sqrt{s+\bar{q}_D}$

The wellbore storage parameter is defined in the usual manner as

$$C_D = \frac{C}{2\pi r_w^2 \phi c_t H} \qquad (18)$$

TYPE CURVES

The Laplace transform solutions given by (5) and (17) are easily inverted with the Stehfest (1970) algorithm. Figure 2 shows a comparison of line-source type curves for slab-shaped blocks and sphere-shaped blocks, using (5)-(7), in the absence of fracture skin. Only for large values of $(r_D\gamma)^2$ do the type curves for the two geometries deviate from one another significantly. Also shown in Figure 2 and in the figures that follow are two dashed curves that are the Theis curve (σ=0) and the Theis curve shifted to the right by a factor of 1+σ. These can be obtained from (5) by letting $\bar{q}_D=\sigma s$.

Figure 3a shows line-source type curves for different values of S_F for slab-shaped blocks. The same curves plotted on semi-logarithmic paper are shown in Figure 3b. In the absence of fracture skin Figure 3b shows the expected semi-logarithmic half slope during the intermediate-time transition period. As S_F increases the response approaches that expected for pseudo-steady state, block-to-fissure flow.

Figure 4 shows a comparison of the type curves in Figure 3a with the corresponding curves for the pseudo-steady state approximation. The latter were obtained using (5) and (16) where $r_D^2\lambda=(r_D\gamma)^2/S_F$, as required by (14) for slab-shaped blocks. As S_F increases the two type curves approach one another. A similar correspondence can be shown for sphere-shaped blocks.

Similar type curves were used by Moench (1983) to analyse groundwater pumping-well and observation-well data from the fractured, hydrothermally altered, volcanic rock terrane of the Nevada Test Site. The data compare favorably with the theory for double-porosity reservoirs with fracture skin.

COMPARISON WITH FINITE-DIFFERENCE MODEL

The finite-difference model for steam transport in a naturally fissured, vapor-dominated, reservoir described by Moench and Denlinger (1980) was modified to incorporate fracture skin at the surface of the slab-shaped blocks. It was assumed that pore water and adsorbed water were absent so that the steam behaved as a noncondensable gas. In the absence of vaporization or adsorption the finite-difference model becomes isothermal. The well discharge rate was made sufficiently small so that the pressure changes that occur in the fissures and blocks do not introduce nonlinear effects. Since the finite-difference model was designed for slab-shaped blocks and includes wellbore storage the comparison with the analytical model is made using (6) and (17).

For steam transport, assuming rock compressibility is negligible compared with steam compressibility, the dimensionless parameters, are the following:

$$p_D = \frac{2\pi k_f b M_w}{q_f \mu Z R T} (p_i^2 - p^2)$$

$$t_D = \frac{k_f t}{\mu \phi_f \beta r_w^2}$$

$$\gamma^2 = \left(\frac{r_w}{b'}\right)^2 \frac{k' b'}{k_f b}$$

$$\sigma = \frac{\phi' b'}{\phi_f b}$$

$$C_D = \frac{\pi r_w^2 L}{2\pi r_w^2 \phi_f \frac{b}{b'} \beta H}$$

$$= \frac{L}{4\phi_f bn}$$

where $n = \frac{H}{2b'}$

Figures 5 and 6 show the results obtained with the finite-difference model using the reservoir parameters listed in Table 1. Results obtained by numerical inversion of the Laplace transform solution, also shown in Figures 5 and 6, appear to corroborate the results obtained with the finite-difference model.

CONCLUSIONS

The graphical results presented in Figures 2-4 show that fracture skin can have a profound influence on the pressure response in a naturally fractured reservoir. They also show that the prevailing theories of flow that assume either transient or pseudo-steady state, block-to-fissure flow can be unified by incorporating fracture skin in the mathematical development.

Because of fracture skin, data plotted on semi-logarithmic paper may appear to have an intermediate-time slope of between zero and one-half that of the late-time slope. Hence caution is urged in the use of the standard semi-logarithmic, straight-line method for evaluating the permeability-thickness product. This is especially true if the test is too short for the late-time portion of the pressure response to manifest itself.

NOMENCLATURE

2b	average aperture of fissure
2b'	average fracture spacing
b_s	average thickness of fracture skin
C	wellbore storage coefficient
C_D	dimensionless wellbore storage
c_t	fissure system compressibility
c_t'	block system compressibility
H	reservoir thickness
k	$[=k_f b/b']$ fissure system permeability
k_f	$[=(2b)^2/12]$ average fissure permeability
k'	block system permeability
k_s	average fracture skin permeability
K_o	modified Bessel function of the first, second and order zero
K_1	modified Bessel function of the first, second and order unity
L	length of wellbore
m	defined by (9)
M_w	molecular weight of water
n	number of producing fissures
p	pressure in fissure
p'	pressure in block
p_D	dimensionless pressure in fissure
$\bar{p}_D$	Laplace transform of p_D
p_i	initial pressure
q	total well discharge rate
q_f	discharge rate to well from an average fissure
q_D	source term for flow from blocks to fissures
$\bar{q}_D$	Laplace transform of q_D
r	radial distance
r_w	effective radius of pumped well
R	gas constant
s	Laplace transform variable
S_F	dimensionless fracture skin defined by (8)
t	time
T	temperature
y	generalized block coordinate
Z	steam compressibility factor (deviation from ideal gas)
λ	parameter defined by Warren and Root (1963) and by (14) and (15)
μ	viscosity of the fluid
ϕ	$[\phi_f b/b']$ fissure system porosity
ϕ_f	average fissure porosity
ϕ'	block system porosity
σ	defined by (10)
γ	defined by (11)
β	steam compressibility

REFERENCES

Bourdet, D., and A.C. Gringarten, Determination of fissure volume and block size in fractured reservoirs by type-curve analysis, Unpublished preprint, SPE-9293, presented at 55th Annual Fall Technical Conference and Exhibition of the Society of Petroleum Engineers of AIME, Dallas, TX, Sept. 21-24, 1980.

Deruyck, B.G., D.P. Bourdet, G. DaPrat, and H.J. Ramey, Jr., Interpretation of interference tests in reservoirs with double porosity behavior - theory and field examples, Unpublished preprint, SPE-11025, presented at 57th Annual Fall Technical Conference and Exhibition of Society of Petroleum Engineers of AIME, New Orleans, LA, Sept. 26-29, 1982.

Ellis, A.J., and W.A.J. Mahon, Chemistry and Geothermal Systems, Academic Press, Inc., New York, 392 pp., 1977.

Gringarten, A.C., Flow-test evaluation of fractured reservoirs, in Recent Trends in Hydrogeology, Geol. Soc. Amer., Special Paper 189, 237-263, 1982.

Kazemi, H., M.S. Seth, and G.W. Thomas, The interpretation of interference tests in naturally fractured reservoirs with uniform fracture distribution, Trans., AIME, 246: Soc. Petr. Eng. J.. 463-472, Dec. 1969.

Moench, A.F., Double-porosity models for a fissured groundwater reservoir with fracture skin, Water Resour. Res., in review, 1983.

Moench, A.F., and R. Denlinger, Fissure-block model for transient pressure analysis in geothermal steam reservoirs, Proc. sixth workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, p. 178-187, 1980.

Streltsova, T.D., Well pressure behavior of a naturally fractured reservoir, Soc. Petr. Eng. J., 769-780, 1983.

Stehfest, H., Numerical inversion of Laplace transforms, Commun. ACM, 13(1), 47-49, 1970.

deSwaan-O.,A., Analytic solutions for determining naturally fractured reservoir properties by well testing, Trans., AIME, 261; Soc. Petr. Engr. J. 117-122, 1976.

Warren, J.E., and P.J. Root, The behavior of naturally fractured reservoirs, Trans., AIME, 228; Soc. Petr. Engr. J., 3(3), 245-255, Sept. 1963.

Table 1. Parameters Used in Simulations*

$2b$	0.02 cm
b'	1640 cm
b_s	0.1 cm
L	10^5 cm
H	0.492×10^5 cm
r_w	16 cm
n	15
ϕ_f	0.5
ϕ'	0.0005
k_f	3.3×10^{-5} cm^2
k'	10^{-12} cm^2 (0.1 millidarcys)
k_s	10^{-17} and 10^{-16} cm^2 (1 and 10 nanodarcys)
kH	9.84×10^{-6} cm^3 (9.84 darcy-meters)
q_f	2.77 g/s
T	234°C
p_i	30 bars

*parameters not listed are known properties of water at prevailing temperature and pressure.

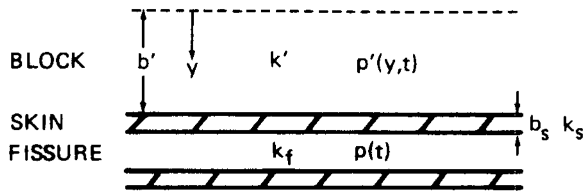

Figure 1. Schematic diagram of block and fissure with fracture skin.

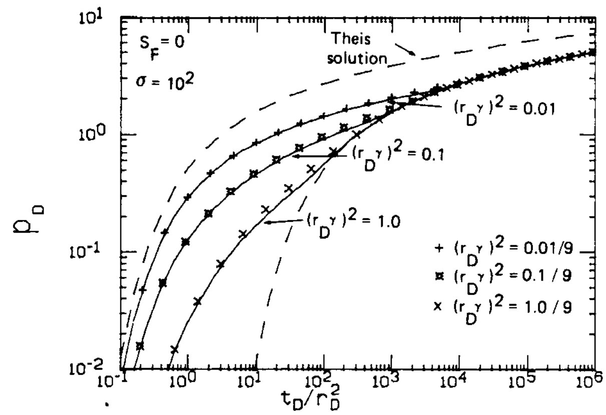

Figure 2. Line-source, type curve comparisons for slab-shaped blocks (solid lines) and sphere-shaped blocks (symbols) without fracture skin.

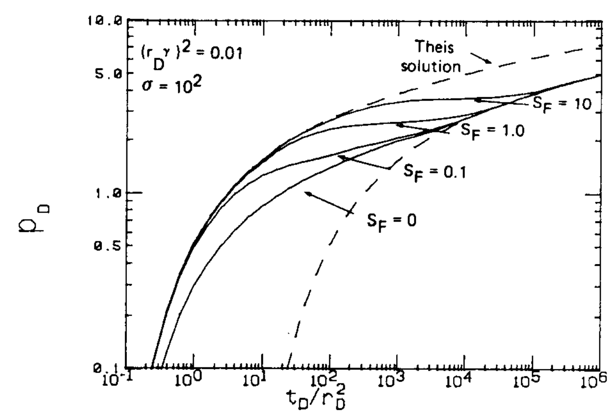

Figure 3a. Line-source type curves for transient flow from slab-shaped blocks with fracture skin

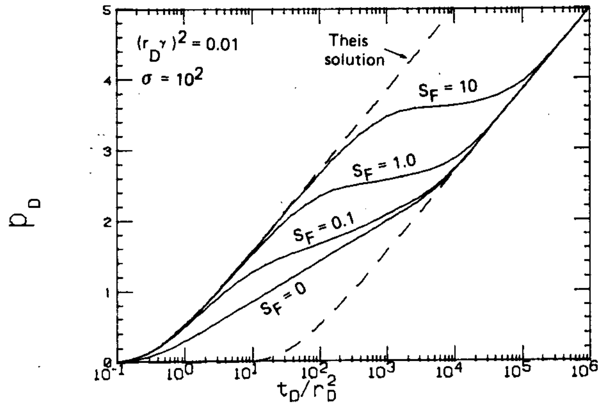

Figure 3b. Semi-logarimthmic plot of Figure 3a.

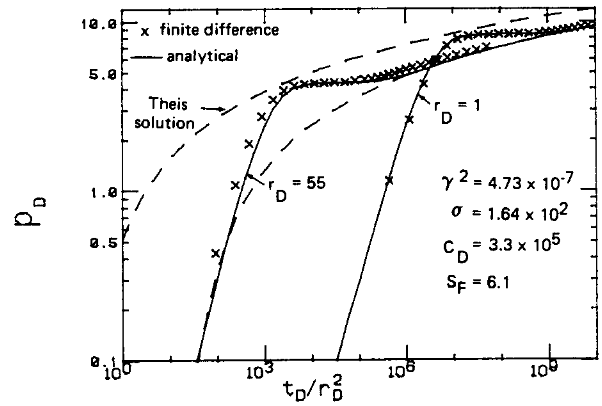

Figure 5. Comparison of the finite-difference model for simulated pressure drawdown in a dry-steam, double-porosity reservoir with the analytical model for the indicated parameters.

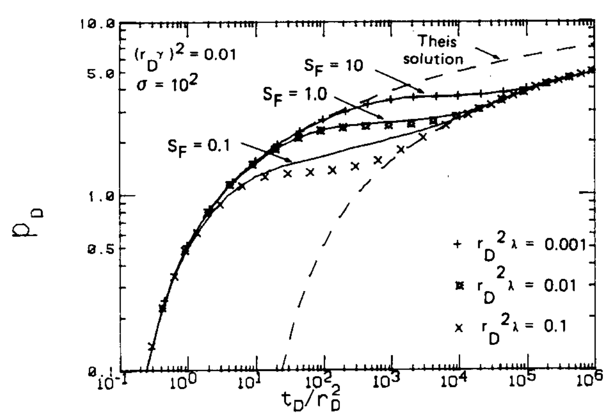

Figure 4. Comparison of type curves for transient flow from slab-shaped blocks with fracture skin (solid lines) with corresponding type curves for the pseudo-steady state flow model (symbols).

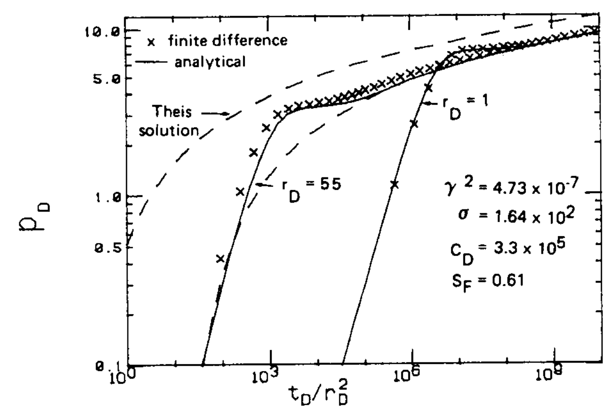

Figure 6. Comparison of the finite-difference model for simulated pressure drawdown in a dry-steam, double-porosity reservoir with the analytical model for the indicated parameters.