Petroleum Engineering 324
Well Performance
Analysis of Pressure Tests in Dual Porosity Reservoirs

The gift of fantasy has meant more to me than my talent for absorbing positive knowledge.
—Albert Einstein

**Topic:** Analysis of Pressure Tests in Dual Porosity Reservoirs

**Objectives:** (things you should know and/or be able to do)

- Be familiar with the "fracture" and "matrix" models developed by Warren and Root and also be familiar with the Laplace and real domain results given by Warren and Root for pseudosteady-state matrix flow. These relations are:

  **Laplace domain results:**
  - Warren and Root "interporosity flow function":
    \[ f(u) = \frac{\lambda + \omega(1-\omega)u}{\lambda + (1-\omega)u} \]
  - Cylindrical source formulation: W&R Eq. 14
    \[ \bar{p}_D(u, r_D, \omega, \lambda, s) = \frac{1}{u} \frac{K_0(\sqrt{uf(u)} r_D)}{K_1(\sqrt{uf(u)})} + \frac{s}{u} \]
  - Line source formulation:
    \[ \bar{p}_D(u, r_D, \omega, \lambda, s) = \frac{1}{u} K_0(\sqrt{uf(u)} r_D) + \frac{s}{u} \]
  - "Log approximation" formulation:
    \[ \bar{p}_D(u, r_D, \omega, \lambda, s) = \frac{1}{2u} \ln \left[ \frac{4}{e^{2\gamma} r_D^2 uf(u)} \right] + \frac{s}{u} \]

  **Real domain results:**
  - Line source solution: (W&R Eq. 15—including the skin factor, \( s \))
    \[ p_D(t_D, r_D, \omega, \lambda, s) = \frac{1}{2} \ln \left[ \frac{4 \cdot t_D^2}{e^{2\gamma} r_D^2} \right] - \frac{1}{2} E_1 \left( \frac{\lambda}{\omega(1-\omega)} t_D \right) + \frac{1}{2} E_1 \left( \frac{\lambda}{(1-\omega)} t_D \right) + s \]
  - Well testing derivative of the time domain solution:
    \[ p_D'(t_D, r_D, \omega, \lambda) = \frac{1}{2} + \frac{1}{2} \exp \left[ -\frac{\lambda}{\omega(1-\omega)} t_D \right] - \frac{1}{2} \exp \left[ -\frac{\lambda}{(1-\omega)} t_D \right] \]

The real domain solutions were used by both Stewart and Ascharsoobid and Onur, et al. to develop the "type curves" for \( p_{\omega D}' \) vs. \( t_D \lambda / 4 \) (Stewart and Ascharsoobid) and for \( p_{\omega D}' \) vs. \( t_D \lambda (1-\omega) \) (Onur, et al.).

- Be able to apply the Stewart and Ascharsoobid/Onur, et al type curves for the analysis of pressure transient test data from wells in infinite-acting dual porosity (i.e., naturally fractured) reservoir systems. Note that this format of the type curve does not include wellbore storage and skin effects.
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Objectives: (Continued)

- From well test data, you should be able to distinguish between the pseudosteady-state and transient interporosity flow models (Warren and Root\textsuperscript{15}, and de Swaan\textsuperscript{25}/Najarieta\textsuperscript{35}, respectively).
- Be able to determine the following parameters using the Stewart and Ascharsobbi/Onur, \textit{et al} type curves for the analysis of pressure transient test data from wells in infinite-acting dual porosity reservoir systems: (radial flow only)
  \begin{align*}
  k & = \text{Formation permeability, md} \\
  \lambda & = \text{Dimensionless interporosity flow parameter} \\
  \omega & = \text{Dimensionless fracture storativity}
  \end{align*}

Where the following definitions are used:

\begin{align*}
  \lambda & = \alpha_w^2 \frac{k_m}{k_f} \\
  \omega & = \frac{(\phi Vc)_f}{(\phi Vc)_f + (\phi Vc)_m}
\end{align*}

The appropriate analysis relations for these type curves are:

- \textit{Formation Permeability:}
  \begin{align*}
  p_w' & \text{ vs. } t_D \lambda/4 \text{ Format:} \\
  p_w' & \text{ vs. } t_D \lambda/(1-\omega) \text{ Format:}
  \end{align*}

- \textit{Dimensionless Fracture Storativity:}
  \begin{align*}
  \omega & \text{ is taken from the type curve match}
  \end{align*}

- \textit{Dim-less Interporosity Flow Parameter:}
  \begin{align*}
  \frac{1}{\lambda/4} & = 0.0002637 \frac{k}{\phi \mu C_f \rho_w^2} \\
  \frac{1}{\lambda/(1-\omega)} & = 0.0002637 \frac{k}{\phi \mu C_f \rho_w^2}
  \end{align*}

Lecture Outline:

- Illustration of dual porosity/naturally fractured reservoir models.
- Discussion of the various patterns of flow behavior for an unfractured well in an infinite-acting dual porosity reservoir system.
  - \textit{p}_w\textsubscript{D} and \textit{p}_w\textsubscript{D} vs. \textit{t} \textsubscript{D} (various \lambda and \omega values—Warren and Root Solution)
  - \textit{p}_w\textsubscript{D} vs. \textit{t} \textsubscript{D} \lambda/4 (the Stewart and Ascharsobbi type curve)
  - \textit{p}_w\textsubscript{D} vs. \textit{t} \textsubscript{D} \lambda/(1-\omega) (the Onur, \textit{et al} type curve)
- Example data analysis:
  - Solve the pressure match point relation for formation permeability, \textit{k}.
  - Read the family parameter (\omega, the dimensionless fracture storativity ratio).
  - Solve the time match point relation for dimensionless interporosity flow coef., \lambda.
  - The skin factor, \textit{s}, is obtained from semilog analysis or history-matching.
  - The dimensionless wellbore storage coefficient, \textit{C}_D, is obtained from history-matching (i.e., computer-aided analysis).
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Analysis of Pressure Tests in Dual Porosity Reservoirs

References:

Solutions:

Data Analysis Methods:

Reading Assignment:

Text Reading:

Various Attachments on Dual Porosity Reservoirs:
- Review attachments.

Reference Articles:
Example Plots:

Dual Porosity Reservoirs: Semilog Plot (Fig. 5—Warren and Root paper)
Dual Porosity Reservoirs: Log-Log Plot—$p_D$ cases (Warren and Root Model)

Model Legend: Solution for an Unfractured Well Produced at a Constant Flowrate in a Naturally-Fractured Reservoir, Pseudosteady-State Interporosity Flow ($\lambda=0, Q_p=0$).

Both numerical inversion and semi-analytical solutions are plotted.

Slight difference in numerical inversion (cylindrical source) and semi-analytical (line source) solutions.

Legend ($\omega$ cases)
- $\omega=10^{-3}$
- $\omega=10^{-2}$
- $\omega=10^{-1}$

Dual Porosity Reservoirs: Log-Log Plot—$p'_D$ cases (Warren and Root Model)

Model Legend: Solution for an Unfractured Well Produced at a Constant Flowrate in a Naturally-Fractured Reservoir, Pseudosteady-State Interporosity Flow ($\lambda=0, Q_p=0$).

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Legend ($\omega$ cases)
- $\omega=10^{-3}$
- $\omega=10^{-2}$
- $\omega=10^{-1}$
"Stewart and Ascharsooji" Type Curve: $p_{wd}$ vs. $t_D \lambda/4$—Various $\lambda$ and $\omega$ Values

"Onur, Satman, and Reynolds" Type Curve: $p_{wd}$ vs. $t_D \lambda(1-\omega)$—Various $\lambda$ and $\omega$ Values
"Stewart and Ascharchsibbi" Type Curve: $P_w/D$ vs. $t_D\lambda/4$—Various $\lambda$ and $\omega$ Values

"Onur, Satman, and Reynolds" Type Curve: $P_w/D$ vs. $t_D\lambda/(1-\omega)$—Various $\lambda$ and $\omega$ Values
Field Case: Well Mach-3X (SPE 13054)
These data were obtained from a field in Western Venezuela and in this case the analysts claim that the well performance indicates pseudosteady-state interporosity flow character. You are to verify (or disprove) this conjecture using the attached drawdown test data.

Reservoir properties:
$\phi=0.048 \quad r_w=0.2917 \text{ ft} \quad h=65 \text{ ft}$

Oil properties: (initial reservoir pressure unknown)
$B_o=1.8235 \text{ RB/STB} \quad \mu_o=0.362 \text{ cp} \quad c_i=24.5 \times 10^{-6} \text{ psia}^{-1}$

Production parameters:
\begin{align*}
\text{Drawdown Test Sequence} & \quad \text{Buildup Test Sequence} \\
q_o=2700 \text{ STB/D (constant)} & \quad q_o=3224 \text{ STB/D (constant)} \\
p_{wf}(t=0) =11,348.0 \text{ psia} & \quad p_{wf}(\Delta t=0) = 9911.0 \text{ psia} \\
& \quad t_p=56 \text{ hr}
\end{align*}

Required:
Using the attached plots, you are to perform "type curve" analysis on these data and provide estimates of the following parameters:
\begin{itemize}
  \item a. The formation permeability, $k$
  \item c. The dimensionless wellbore storage coefficient, $C_D$
  \item e. The near-well skin factor, $s$.(compare to semilog analysis)
  \item f. The dimensionless fracture storativity ratio, $\alpha^*$
  \item g. The dimensionless interporosity flow coefficient, $\lambda^*$
\end{itemize}
* Assuming that naturally fractured reservoir behavior is exhibited.

Note:
As in your previous work, you are also to verify/calculate properties using the appropriate specialized plots (pressure versus shut-in time and pressure versus logarithm of shut-in time, effective shut-in time, and Horner time).
Field Case: Well Mach-3X (SPE 13054)—Pressure Drawdown Test Sequence

Well Test Data Functions:

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Field Case: Well Mach-3X (SPE 13054)—Pressure Drawdown Test Sequence

Well Test Data Functions:

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Field Case: Well Mach-3X (SPE 13054)—Pressure Drawdown Test Sequence

Early Time Cartesian Analysis:

Results from the Early Time Cartesian Plot:

\[ m_{wbs} = 1436 \text{ psi/hr} \]
\[ p_{wf}(t=0) = 11,348 \text{ psia} \]

The analysis relation for \( C_s \) is

\[ C_s = \frac{q_{sw}B}{24 \ m_{wbs}} \]

Solving for \( C_s \) from our data we obtain

\[ C_s = \frac{(2700 \ STB/D) (1.8235 \ RB/STB)}{24 \ (1436 \ psi/hr)} = 1.429 \times 10^{-2} \ RB/psi \]

The identity for \( C_D \) is

\[ C_D = 0.894 \ \frac{C_s}{\phi h c r_w^2} \]

Solving for \( C_D \) from our previous result (\( C_s \)), we have

\[ C_D = 0.894 \ \frac{(1.429 \times 10^{-1} \ RB/psi)}{(0.048) \ (65 \ ft) (24.5 \times 10^{-6} \ psia^{-1}) \ (0.2917 \ ft)^2} = 19,636 \]

Semilog Analysis: Semilog Plot

Results from the Semilog Plot:

"Fracture System" (1st Line)  "Total System" (2nd Line)
\[ m = 1140 \text{ psi/cycle} \]  \[ m = 1140 \text{ psi/cycle} \]
\[ p_{wf,1hr} = 11,280 \text{ psia} \]  \[ p_{wf,1hr} = 11,592 \text{ psia} \]

Permeability:

The analysis relation for the permeability, \( k \), is

\[ k = 162.6 \ \frac{qB\mu}{mh} \]

Solving for the permeability, \( k \), from our data, we obtain

\[ k = 162.6 \ \frac{(2700 \ STB/D) (1.8235 \ RB/STB) (0.362 \ cp)}{(1140 \ psia/cycle) \ (65 \ ft)} = 3.91 \text{ md} \]
Field Case: Well Mach-3X (SPE 13054)—Pressure Drawdown Test Sequence
Semilog Analysis: (continued)

Skin Factor:
The analysis relation for the skin factor, \( s \), is given by
\[
s = 1.1513 \left( \frac{(p_{wf}(t=0) - p_{wf,1 hr(tot)})}{m} - \log \left( \frac{k}{\phi \mu_c \tau_w^2} \right) + 3.2275 \right)
\]
Solving for the skin factor, \( s \), from our data we obtain
\[
s = 1.1513 \left( \frac{(11,348 \text{ psia}) - (11,592 \text{ psia})}{(1140 \text{ psia/cycle})} \right) + 1.1513 \left( - \log \left( \frac{(3.91 \text{ md})}{(0.048) (0.362 \text{ cp}) (24.5 \times 10^{-6} \text{ psia}^{-1}) (0.2917 \text{ ft})^2} \right) + 3.2275 \right)
\]
Or finally, we have
\[s = -5.78\]

Type Curve Analysis:

Type Curve Match: Onur, et al Type Curve
Matching Parameter, \( \omega = 5 \times 10^{-2} \)
\[
[t_D / \lambda (1-\omega)]_{MP} = 1 \quad [t]_{MP} = 45 \text{ hr} \quad [\Delta p]_{MP} = 1025 \text{ psi}
\]

Formation Permeability:
The analysis relation for the effective permeability, \( k \), is given by
\[
k = 141.2 \frac{q B \mu}{h} \frac{[p_{wD}]_{MP}}{[\Delta p]_{MP}}
\]
Solving for the effective permeability, \( k \), we obtain
\[
k = 141.2 \frac{(2700 \text{ STB/D}) (1.8235 \text{ RB/STB}) (0.362 \text{ cp}) (1.0)}{(65 \text{ ft}) (1025 \text{ psi})} = 3.78 \text{ md}
\]

Dimensionless Interporosity Flow Parameter:
The analysis relation for the interporosity flow parameter, \( \lambda \), is given by
\[
\frac{1}{\lambda (1-\omega)} = 0.0002637 \frac{k}{\phi \mu_c \tau_w^2} \frac{[t]_{MP}}{[t_D / \lambda (1-\omega)]_{MP}}
\]
Solving for the parameter group, we have
\[
\frac{1}{\lambda (1-\omega)} = 0.0002637 \frac{k}{\phi \mu_c \tau_w^2} \frac{[t]_{MP}}{[t_D / \lambda (1-\omega)]_{MP}}
\]
Field Case: Well Mach-3X (SPE 13054)—Pressure Drawdown Test Sequence

Type Curve Analysis: (continued)

Which, for our case, gives

\[
\frac{1}{\lambda/(1-\omega)} = 0.0002637 \frac{(3.78 \text{ md})}{(0.048) (0.362 \text{ cp}) (24.5 \times 10^{-6} \text{ psia}^{-1}) (0.2917 \text{ ft}^2)} \frac{(45 \text{ hr})}{(1.0)}
\]

Reducing, we have

\[
\frac{1}{\lambda/(1-\omega)} = 1.238 \times 10^6
\]

Solving for \( \lambda \) we obtain

\[
\lambda = \frac{(1.5 \times 10^{-2})}{(1.238 \times 10^6)} = 7.672 \times 10^{-7}
\]

Summary:

<table>
<thead>
<tr>
<th>Analysis</th>
<th>( CD )</th>
<th>( k ) (md)</th>
<th>( s )</th>
<th>( \omega )</th>
<th>( \lambda )</th>
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</thead>
<tbody>
<tr>
<td>Cartesian</td>
<td>19,636</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Semilog</td>
<td>—</td>
<td>3.91</td>
<td>-5.78</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Log-Log</td>
<td>—</td>
<td>3.78</td>
<td>—</td>
<td>5 \times 10^{-2}</td>
<td>7.67 \times 10^{-7}</td>
</tr>
</tbody>
</table>
Field Case: Well Mach-3X (SPE 13054)—Pressure Drawdown Test Sequence
Cartesian Plot: "Wellbore Storage" Plot (with analysis)

Semilog Plot: Pressure Versus Time Data (with analysis)
Field Case: Well Mach-3X (SPE 13054)—Pressure Drawdown Test Sequence (with analysis)

Log-log Plot: Pressure Drop and Pressure Drop Derivative Versus Time Data (1 inch x 1 inch)
Field Case: Well Mach-3X (SPE 13054)—Pressure Drawdown Test Sequence (with simulation match)

Log-log Plot: Pressure Drop and Pressure Drop Derivative Versus Time Data (1 inch x 1 inch)
Well Test Analysis (Paper SPE 13054)
An Infinite-Acting Dual Porosity
(Naturally Fractured) Reservoir

- History Matching (Simulation) Solutions
  - Based on Type Curve Analysis
Well A-17 (Paper SPE 13054) – Drawdown Analysis (Transient Interporosity Flow)
Well A-17 (Paper SPE 13054) – Drawdown Analysis (Pseudosteady-State Interporosity Flow)
Well A-17 (Paper SPE 13054) – Buildup Analysis (Transient Interporosity Flow)

Log-Log Plot (Full Test History--No Rate History)

Legend: Well A-17 Buildup (SPE 13054)
- Δp data
- Δp' data
- Simulation (Optimized Match)

Well Model:
Unfractured Well in an Infinite-Acting Dual Porosity Reservoir, Transient Interporosity Flow

Results for A-17 Well:
- $k=27.5$ md
- $s=-5.4$
- $C_p=16,100$
- $\lambda=2.02 \times 10^{-5}$
- $\alpha=1.001 \times 10^{-3}$

Shut-in Time, $\Delta t$, hrs
Well A-17 (Paper SPE 13054) – Buildup Analysis (Pseudosteady-State Interporosity Flow)
Well Mach-3X (Paper SPE 13054) – Drawdown Analysis (Pseudosteady-State Interporosity Flow)
Well Mach-3X (Paper SPE 13054) – Buildup Analysis (Pseudosteady-State Interporosity Flow)
Well 14RN-2X (Paper SPE 13054) – Drawdown Analysis (Pseudosteady-State Interporosity Flow)
Well 14RN-2X (Paper SPE 13054) – Buildup Analysis (Pseudosteady-State Interporosity Flow)
Pressure Behavior of a Well in an Infinite-Acting Dual Porosity (Naturally Fractured) Reservoir

- Models for Regional Fracturing (Reservoir Schematics)
- Conceptual Models for Dual Porosity (Naturally Fractured) Reservoir Systems
- Performance of Naturally Fractured Reservoir Systems—Transient Flow (No Wellbore Storage or Skin Effects)
  - Pseudosteady-State Interporosity Flow
  - Transient Interporosity Flow (Various)
- Performance Models for Dual Porosity (or "Naturally Fractured") Reservoirs
Models for Regional Fracturing
(Reservoir Schematics)

Major Reference(s):
Fracture Pattern 1: $\sigma_1$, $\sigma_3$ acting in the bedding plane and $\sigma_2$ acting normal to the bedding plane ($\sigma_3$ - dip direction; $\sigma_1$ - strike direction). (Stearns$^3$, Courtesy AAPG).

Fracture pattern 2: $\sigma_1$, $\sigma_3$ acting in the bedding plan and $\sigma_2$ acting normal to the bedding plane ($\sigma_3$-dip direction, $\sigma_1$-strike direction). (Stearns$^3$, Courtesy AAPG.)

Various types of fractures generated by folding (courtesy of Leroy²).

2.11 – Composite core of a fractured reservoir

Conceptual Models for Dual Porosity (Naturally Fractured) Reservoir Systems

- Warren and Root Reservoir Model
  - Pseudosteady-State Interporosity Flow
- de Swaan/Najurieta Reservoir Model
  - Transient Interporosity Flow (Slabs/Cubes)
- Moench Reservoir Models
  - Transient Interporosity Flow ("sticks" and spheres, as well as "fracture" skin)

Major Reference(s):
FIG. 1 — IDEALIZATION OF THE HETEROGENEOUS POROUS MEDIUM.

Fig. 1—Schematic of reservoir with rectangular matrix elements.

MODEL 1

REPEATED ELEMENT

Idealized reservoir: model 1 - stratified matrix; model 2 - blocks matrix.

Fig. 1. Schematic diagram of a double-porosity reservoir of thickness $H$ showing a typical representative elementary volume (REV) for the fissure system.

Fig. 2. Geometrical configuration for (a) slab-shaped blocks and sphere-shaped blocks.

Fig. 5. Schematic diagram of a block and fissure with fracture skin.


Performance of Naturally Fractured Reservoir Systems—Transient Flow (No Wellbore Storage or Skin Effects)

- Stewart and Ascharsoobbi Type Curve:
  - $p_w' D$ vs. $t_D \lambda/4$—Various $\lambda$ and $\omega$ Values

- Onur, et. al. Type Curve:
  - $p_w' D$ vs. $t_D \lambda/(1-\omega)$—Various $\lambda$ and $\omega$ Values

Major Reference(s):

"Stewart and Ascharsobbi" Type Curve: \( p_{\omega D} \) vs. \( t_{D \lambda/4} \)—Various \( \lambda \) and \( \omega \) Values

"Onur, Satman, and Reynolds" Type Curve: \( p_{\omega D} \) vs. \( t_{D \lambda/(1-\omega)} \)—Various \( \lambda \) and \( \omega \) Values

Type Curve for an Unfractured Well in an Infinite-Acting Naturally-Fractured Reservoir with NO Wellbore Storage or Skin Effects — Plotting Format From: paper SPE 18173, Stewart, G. and Ascharsobbi: "Well Test Interpretation for Naturally-Fractured Reservoirs"

Type Curve for an Unfractured Well in an Infinite-Acting Naturally-Fractured Reservoir with NO Wellbore Storage or Skin Effects — Plotting Format From: paper SPE 23830, Onur, M., and Satman, A. "New Type Curves to Determine Naturally Fractured Reservoir Parameters"
"Stewart and Ascharchsibi" Type Curve: \( p_{WD}' \) vs. \( t_D \alpha \lambda /4 \) — Various \( \lambda \) and \( \omega \) Values

"Onur, Satman, and Reynolds" Type Curve: \( p_{WD}' \) vs. \( t_D \alpha \lambda / (1-\omega) \) — Various \( \lambda \) and \( \omega \) Values