Lecture 07:
Wellbore Phenomena

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Wellbore Phenomena

● Calculation of Bottomhole Pressure
  ■ General relation (energy balance).
  ■ Static (non-flowing) bottomhole pressure (dry gas).
  ■ Flowing bottomhole pressure (dry gas).

● Near-Well Reservoir Flow Behavior
  ■ Steady-state "skin factor" concept used to represent damage or stimulation in the near-well region.
  ■ "Variable" skin effects: non-Darcy flow, well cleanup, and gas condensate banking.
Calculation of Bottomhole Pressure

- **Process**
  - General relation (energy balance).
  - Static (non-flowing) bottomhole pressure (dry gas).
  - Flowing bottomhole pressure (dry gas).

- **Issues**
  - Calculation approaches:
    - Average Pressure and Temperature method.
    - Cullender and Smith method.
    - Numerical methods.
Calculation of Bottomhole Pressure

\[ \frac{53.34 T z}{\gamma_g p} \frac{dp}{dL} + \frac{\cos \theta}{g_c} + \frac{6.67 \times 10^{-4} f}{p} \left( \frac{T z}{d^5} \right)^2 (q_g)^2 dL = 0 \]

a. Basic energy balance for flow in inclined pipes.

\[ p_{wf}^2 = p_{tf}^2 + \frac{6.67 \times 10^{-4} q_g^2 f T^2 z^2}{d^5 \cos \theta} (e^s - 1) \]

where

\[ s = 0.0375 \gamma_g L \cos \theta / z T \]

b. Solution assuming average \( T \) and \( z \)-values.

\[ \int_{p_{wf}}^{p_{tf}} \left( \frac{p}{T z} \right)^2 \cos \theta + \frac{6.67 \times 10^{-4} q_g^2}{d^5} \]

\[ = \frac{(I_{mp} + I_{tf})}{2} \left( p_{mp} - p_{tf} \right) + \frac{(I_{wf} + I_{mp})}{2} \left( p_{wf} - p_{mp} \right) \]

\[ I = \frac{p}{T z} \left( \frac{p}{T z} \right)^2 Z L + \Omega \]

\[ \Omega = \frac{6.67 \times 10^{-4} q_g^2}{d^5} \]

d. Schematic illustration of wellbore configuration.

e. Wellbore diagram — surface pressure measurement.
Calculation of Bottomhole Pressure

\[
\frac{53.34T_z}{\gamma_g} \frac{dp}{p} + \frac{g}{p} \cos \theta \frac{dL}{g_c} + \frac{6.67 \times 10^{-4} f \left( \frac{T_z}{p} \right)^2 (q_g)^2}{d^5} dL = 0.
\]

Fig. 4.2—Moody friction factor for fluid flow in pipe (after Moody\textsuperscript{12}).
"Skin Factor" Concept

- Skin Factor:
  - "Skin" is just a pressure drop due to non-ideal conditions. The "skin factor" is the "dimensionless" pressure drop.
    - Positive Skin = DAMAGE (i.e., the pressure is higher than it should be).
    - Negative Skin = STIMULATION (i.e., the pressure is lower than it should be).
  - Physical, steady-state "skin factor" concept ("Hawkins" formula) used to illustrate near-well damage.
    - Physical limitations, really only valid for damage ... or very slight stimulation.
  - Infinitesimal skin concept uses a mathematical "trick" to represent additional (positive or negative) pressure. Most practical approach for well performance (Hawkins formula does not fit in practice).
Near-Well Behavior — *Physical Skin Concept*

a. Simple skin concept — steady-state flow of a liquid in the "altered" zone.

\[ \Delta p_s = 141.2 \frac{q B \mu}{kh} \left( \frac{k}{k_s} - 1 \right) \ln \left( \frac{r_s}{r_w} \right) \]

\[ s = \Delta p_{SD} = \left( \frac{k}{k_s} - 1 \right) \ln \left( \frac{r_s}{r_w} \right) \]

b. Governing relations for steady-state flow of a liquid in the "altered" zone (\(k_s\)=permeability in the "altered" zone).

c. Schematic pressure behavior in a "steady-state" skin zone.
a. Concepts of "infinitesimal" skin as well as use of the effective wellbore radius — these schematics seek to represent the concept of "skin" as a physical phenomena, as well as a (simple) mathematical model.

b. 2-zone, radial "composite" model (condensate bank).

- **Skin Concept — Generally speaking, use of the skin concept (or skin "factor") tends to "isolate" pressure behavior that cannot be directly attributed to the reservoir. This is an oversimplification, but it is convenient, and is widely used.**
"Variable" Skin Effects: Gas Condensate Banking

Using observed performance from numerical simulation of gas condensate reservoirs, we propose the following model for gas mobility (or gas permeability) behavior:

\[
kg = k_{g,\text{min}} + (k_{g,\text{max}} - k_{g,\text{min}}) \left[1 - \exp\left(-\frac{1}{\alpha} \frac{r^2}{t}\right)\right]
\]

● Comment:
  ■ This model has been shown to consistently represent the \( k_g(r,t) \) profile.
  ■ The \( \alpha \)-parameter is presumed to represent fluid and rock-fluid properties.
  ■ Major concern/issue is that diffusivity \( (k_g/(\phi \mu_g c_g)) \) also varies, and should be considered.
Variable Skin — $k_g(r,t)$ Profile

- Drawdown performance only (buildup to be addressed later).
- Exponential model is simple and consistent (valuable for model development).
- erf($x$) model also consistent, but exp($x$) model is preferred.

$k_g(r,t)$ Profile:

- $\lambda_g(r,t) = \lambda_g,_{min} + \left(\lambda_g,_{max} - \lambda_g,_{min}\right) \left[1 - \exp\left(-t^{2/\lambda_g,_{f}}\right)\right]$ (Standard Form: (exp($x$) model))
- $\lambda_g(r,t) = 1 - \beta \exp\left[-\left(1/\lambda_g\right)\left(r_g/\lambda_g\right)^2\right]$ (Dimensionless Form: (exp($x$) model))
- $\lambda_g(r,t) = \lambda_g,_{min} + \left(\lambda_g,_{max} - \lambda_g,_{min}\right) \text{erf}\left(r_g^2 / \lambda_g,_{f}\right)$ (Alternate Mobility Model: (exp($x$) model))

Schematic Behavior of Gas Mobility as a Function of Radial Distance
Gas Condensate Reservoir (Modified from Roussennac (Fig. 2.7))
Variable Skin — $S_o(r,t)$ Profile

*$S_o(r,t)$ Profile: (from Roussennac Thesis — Fig. 2.6)*
- Region 1: Near well region affected by condensate "bank" (liquid dropout).
- Region 2: "Transition" of condensate "bank" to "dry gas" region.
- Region 3: "Dry gas" region.
Variable Skin — \( p_D(\varepsilon_D) \) "Type Curve"

\[ p_D(\varepsilon_D) \text{ Type Curve:} \]

- Drawdown performance only.
- \( \alpha_D \)-parameter is a "scaling parameter" — note behavior for large \((r_D^2/\alpha_D t_D)\).
- Near-well behavior is controlled by \( k_{\text{min}}/k_{\text{max}} \) ratio (as would be expected).
Variable Skin — $p_{Dd}(\varepsilon_D)$ "Type Curve"

- $p_{Dd}(\varepsilon_D)$ Type Curve:
  - Drawdown performance only.
  - $\alpha_D$-parameter is a "scaling parameter" — only influences large ($r_D^2/\alpha_D t_D$).
  - $k_{\text{min}}/k_{\text{max}}$ controls $|\varepsilon_D dp_D/d\varepsilon_D|$ in "near-well" region (note horizontal trends).
Variable Skin — $p_{Dd}(t_D)$ "Type Curve"

**$p_{Dd}(t_D)$ Type Curve:**

- **Drawdown performance only.**
- $\alpha_D$-parameter only influences early time behavior (i.e., small values of $(\alpha_D t_D)/r_D^2$).
- $|t_D dp_D/dt_D|$ reflects $k_{min}/k_{max}$ influence as mobility profile moves.
"Roussennac Fig. 2.7" (log(\(\Delta p_p(r,t)\)) versus log(\(r^2/t\)) (s=0))

- Good agreement in data and model trends (with the noted exception of the non-line source" portion of the \(\Delta p_p\) data — recall that the new model is based on the line source assumption \(r_w\approx0\), the simulated data have no such constraint).
"Roussennac Fig. 2.9" (log($\Delta p_p(r,t)$) versus log($r^2/t$) ($s\neq0$ case))

- Excellent agreement in data and model trends for $r^2>1\times10^0$ (note that the \textit{finite} skin zone is $0.53\text{ ft}<r<1.5\text{ ft}$ (or $0.28\text{ ft}^2<r<2.25\text{ ft}^2$)).
- Excellent match validates model for this particular case.

\begin{itemize}
  \item Excellent agreement in data and model trends for $r^2>1\times10^0$ (note that the \textit{finite} skin zone is $0.53\text{ ft}<r<1.5\text{ ft}$ (or $0.28\text{ ft}^2<r<2.25\text{ ft}^2$)).
  \item Excellent match validates model for this particular case.
\end{itemize}
"Vo Fig. 3.1" (log(Δp(t,r)) versus log(r²/Δt) (s=0 case))
- Very good agreement in data and model trends (entire range of data).
- Excellent match validates model for this particular case.
Validation: Other Reservoir Models

**Combination Plot: Radial Composite, Sealing Faults, New Model**

- Sealing fault responses (blue) appear similar to new model for various cases.
- 2-zone radial composite model (diffusivity ratio \((\phi_1 c_{t,1})/(\phi_2 c_{t,2})\) of unity) is a limiting case of our new model (i.e., the interface is fixed at a radius for all time).
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(End of Lecture)

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