Research Summary

Analytical Modeling of Fractured Nanoporous Reservoirs

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Problem Statement

- US production from shale gas has increased over five-fold between 2007 and 2012 and the US is projected to export natural gas by 2040 (EIA 2014).
- Unconventional reservoirs persevere unique features:
    - Extreme low matrix permeability
    - Discrete/continuous fractures
    - Connected/isolated pores

Problem Statement

- Scale and structural heterogeneity can lead to preferential flow paths → complex flow events, variations in pressure and composition.
- Current models (DP, DPDK, DFN, etc.) were developed for reservoirs with moderate ~ low permeability ($k \approx$ D – mD).
- Are these models suitable for unconventional reservoirs?

Problem Statement

- The need for new modeling approaches in inevitable.
- Representative of the nature of the porous media and the flow behaviors.
- Fluid transport in fractured media with complex geometry is similar to diffusion in disordered media → Anomalous Diffusion.

Approach

- Several mathematical assumptions can lead to anomalous diffusion formulation.
- Displacement is related to time by:

$$\langle r^2 \rangle \sim t^\gamma \quad \text{, where} \quad \gamma \begin{cases} = 1 & \text{Normal diffusion} \\ > 1 & \text{Super diffusion} \\ < 1 & \text{Sub-diffusion} \\ \neq 1 & \text{Anomalous diffusion} \end{cases}$$

Approach

- Flux law as presented by Raghavan and Chen (2013)

– fractional flux:

$$v_x = \frac{k_\alpha}{\mu} \frac{\partial^{1-\alpha}}{\partial t^{1-\alpha}} \left(\frac{\partial p}{\partial x} \right)$$

- $\alpha < 1$
- $\alpha = 2/(2+\theta)$, θ is the anomalous diffusion index.
- Note here that: $k_\alpha = L^2 T^{1-\alpha}$

Approach

- Dual porosity idealization:
  - Cylindrical system
  - Spherical matrix (r_m)
  - Radial flow
  - Line sink
  - Matrix: anomalous diffusion
  - Natural fractures: normal diffusion

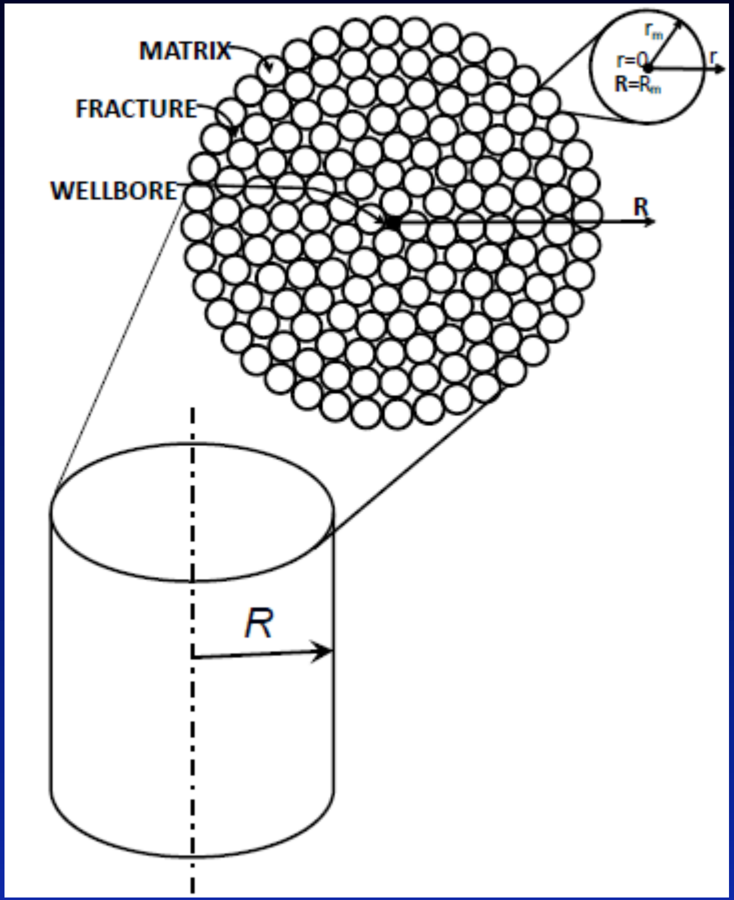

Figure 1: Dual Porosity Medium in Cylindrical System (Ozkan 2011)

Approach

- Extending the solution to:
  - Horizontal well
  - Multi-stage fractured
  - SRV is DP region

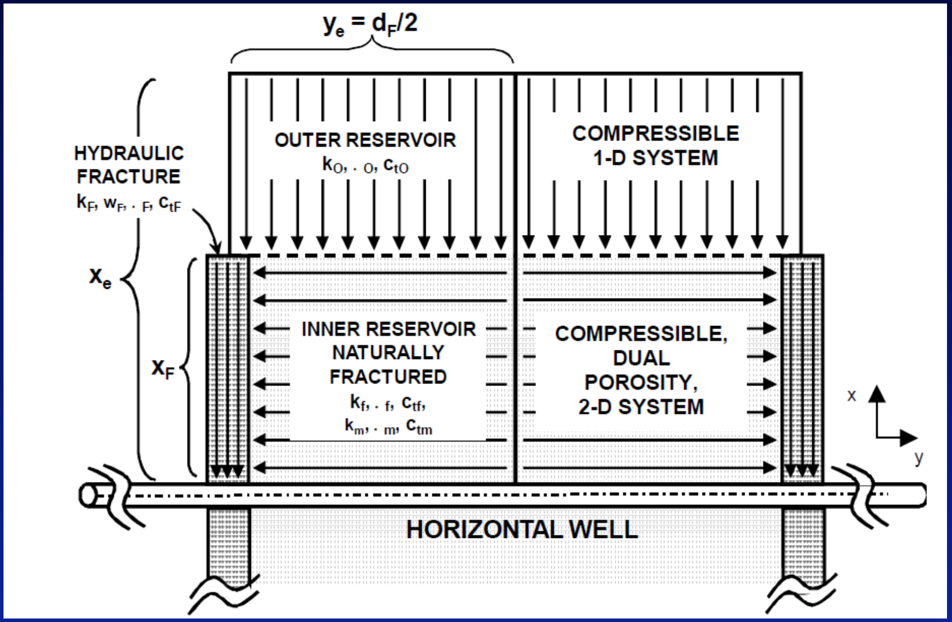

Figure 2: Tri-linear DP Model (Ozkan et al. 2009)

Approach

- Derivation:

1) $$\frac{1}{R}\frac{\partial}{\partial R}\left(R\frac{k_f}{\mu}\frac{\partial p_f}{\partial R}\right)+\hat{q}_m=(\phi c_t)_f\frac{\partial p_f}{\partial t}$$

2) $$\hat{q}_m=-(4\pi r_m^2)\left[\frac{k_\alpha}{\mu}\frac{\partial^{1-\alpha}}{\partial t^{1-\alpha}}\left(\frac{\partial p_m}{\partial r}\right)_{r=r_m}\right]/\left(\frac{4\pi r_m^2 h_f}{2}\right)$$

or,

$$\hat{q}_m=-\frac{2}{h_f}\frac{k_\alpha}{\mu}\frac{\partial^{1-\alpha}}{\partial t^{1-\alpha}}\left(\frac{\partial p_m}{\partial r}\right)_{r=r_m}$$

f = natural fractures, m = matrix

Approach

- Derivation:

3) $\frac{1}{R_D}\frac{\partial}{\partial R_D}\left(R_D\frac{\partial \bar{p}_{fD}}{\partial R_D}\right) - s\left\{\frac{2k_\alpha r_w}{h_f k_f}\left(\frac{\eta_f}{r_w^2}\right)^{1-\alpha}\frac{r_{mD}\sqrt{\beta_m}}{Tan\,h\left(\sqrt{\beta_m}\,r_{mD}\right)}s^{-\alpha}+1\right\}\bar{p}_{fD} = 0$

$\underbrace{\left\{\cdots\right\}}_{f(s)}$

Verification & Results

- Verification vs. Tri-linear model

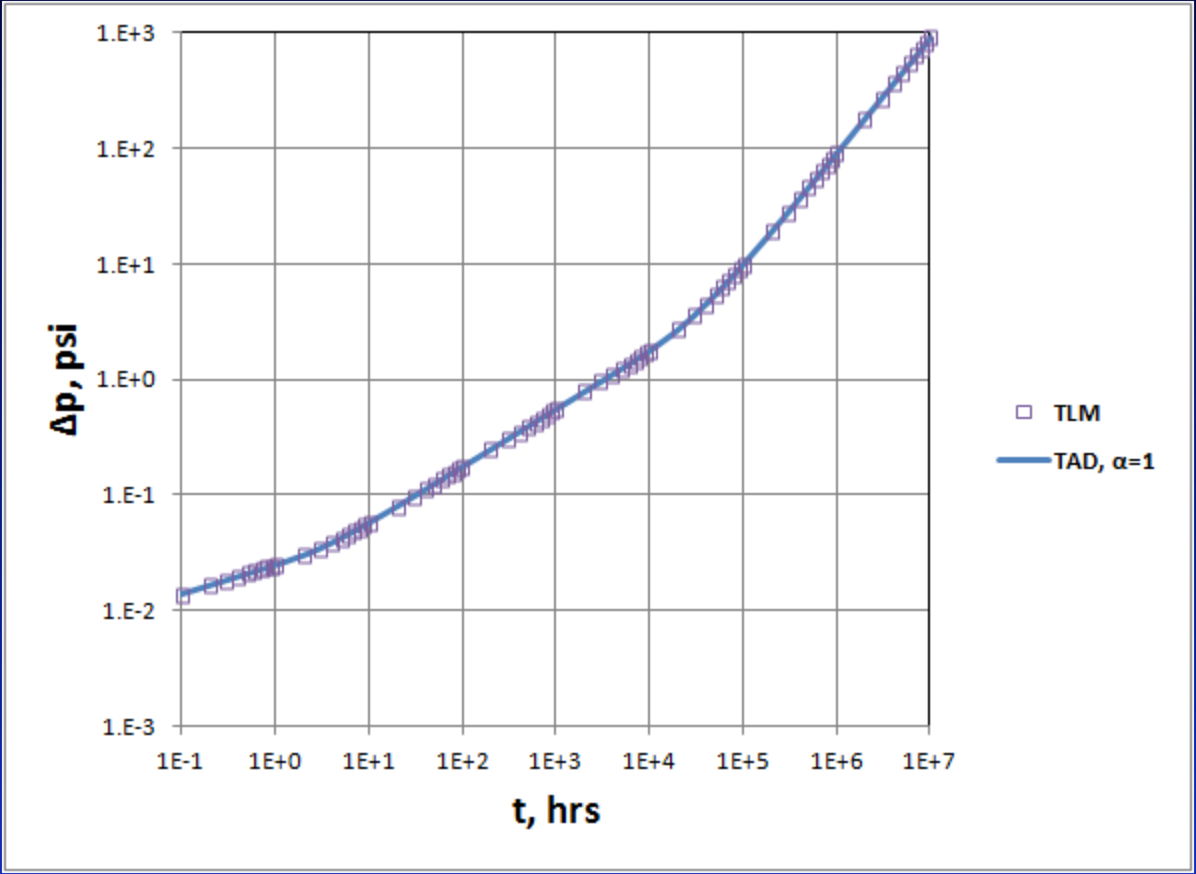

Figure 3: Verification with Tri-linear Model

Verification & Results

- Results:
- Sensitivity α

$\alpha = \{1, 0.7, 0.3, 0.1\}$

$\rho_f = \{0.9 \text{ and } 0.3\}$

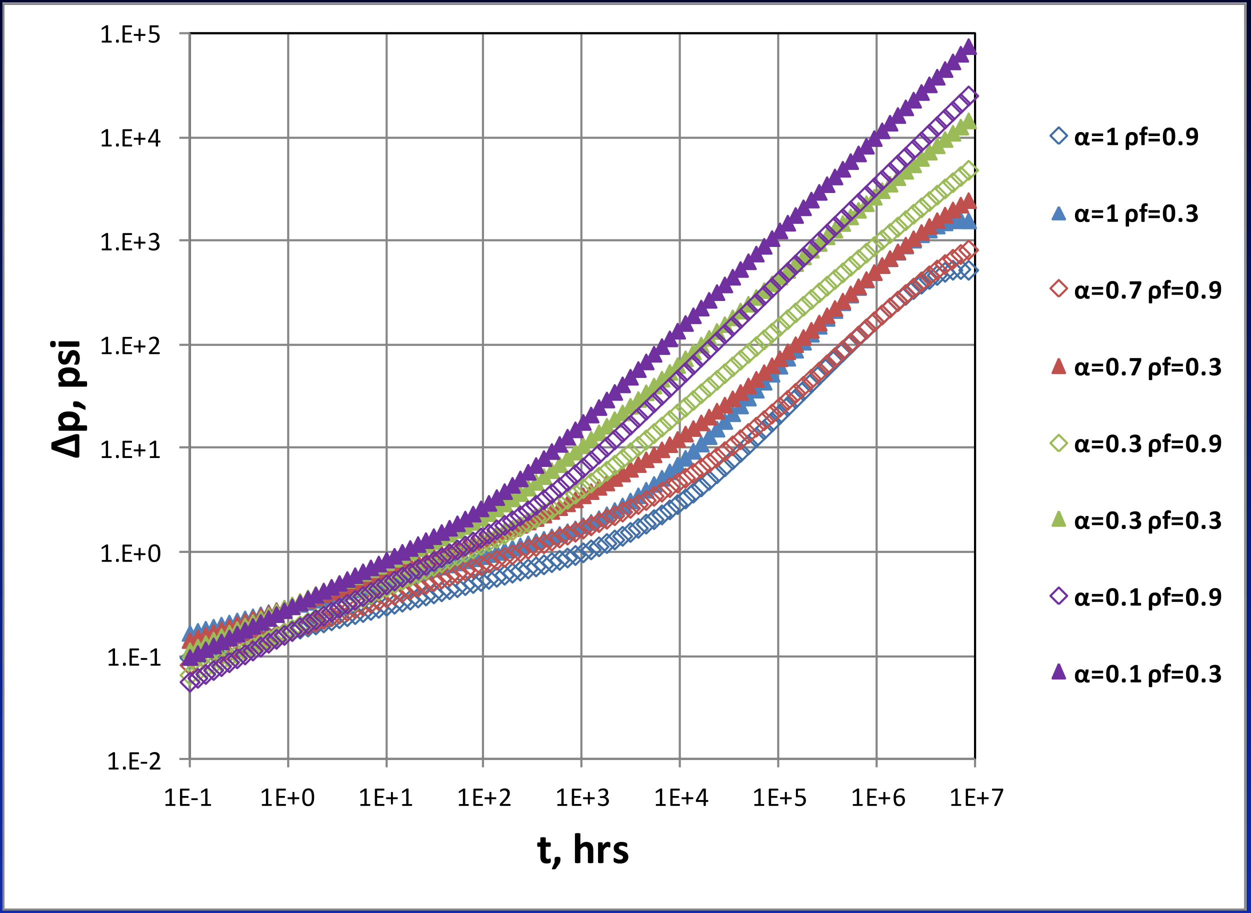

Figure 4: Sensitivity Cases - α

Verification & Results

- Results:
- Sensitivity ρ_f

$\rho_f = \{0.9, 0.6, 0.3, 0.03\}$

$\alpha = \{1 \text{ and } 0.1\}$

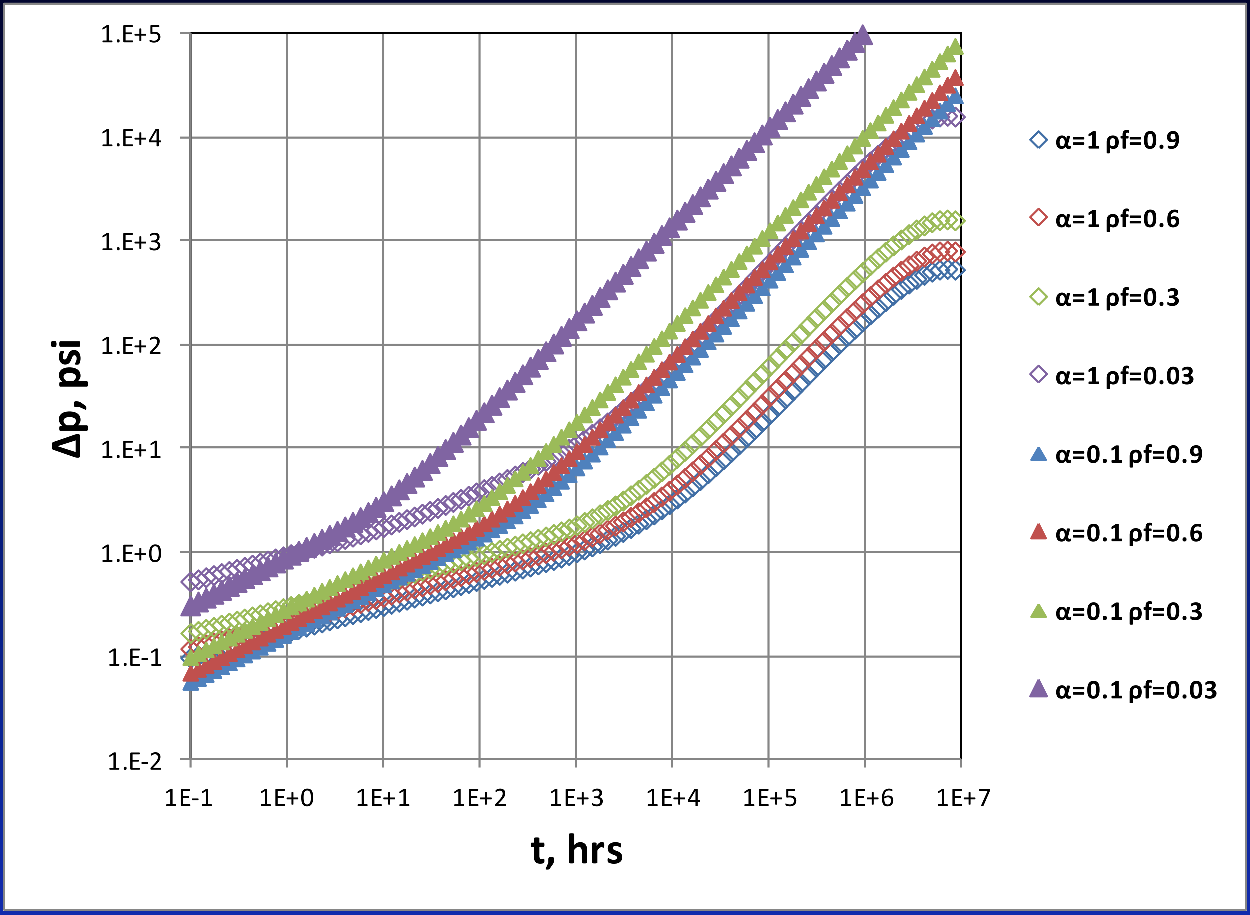

Figure 5: Sensitivity Cases - ρ_f

Conclusion

- Modeling fluid flow using anomalous diffusion has not been fully explored.
- Providing alternatives to dual-porosity models for unconventional reservoirs.
- Applying fractals and anomalous diffusion models to unconventional reservoirs (d_f).

Conclusion

- Impact on petrophysical interpretations, pressure transient analysis, description of natural and hydraulic fractures, numerical simulation models and phase behavior studies.

Thank you

References

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