Research Report

A Spectral Solution for the Analysis of Multifractured Tight-Gas Wells with Large Viscosity-Compressibility Variation and Pressure-Dependent Permeability

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Problem Statement

Analysis of multifractured tight-gas wells

There are two approaches used in the analysis of multifractured tight-gas well performances:

- Numerical simulation
- Analytical modeling

There are known problems with both approaches

The shortcomings of the analysis approaches make the results questionable for most tight-gas well cases

Problem Statement

Numerical Simulation

Current commercial simulators are not able to capture all of the physics, and even if they did, their accuracy would be questionable.

Finite-difference methods are inherently approximate; they replace partial differential equations by local algebraic difference equations

To obtain accurate solutions, very fine grids and very small time steps need to be used

Available data usually do not justify the use of detailed numerical simulators

Problem Statement

Analytical Modeling

Continuity equation for flow of real gases in porous media is non-linear

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{p}{\mu Z}\frac{\partial p}{\partial r}\right)=\frac{\phi}{2.637\times 10^{-4}k}\frac{\partial (p/Z)}{\partial t}$$

For analytical modeling, solutions of the continuity equation must be obtained

This requires linearization of the continuity equation

Problem Statement

Analytical Modeling

A common approach to linearize the continuity equation for real-gas flow is to define a real gas pseudopressure:

$$m(\mathrm{p}) = 2\int_{p_o}^{p} \frac{p'}{\mu Z} \, dp'$$

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial m}{\partial r}\right) = \frac{\phi c_t \mu}{2.637\times 10^{-4} k}\frac{\partial m}{\partial t}$$

Still nonlinear because compressibility and viscosity are functions of pressure

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial m}{\partial r}\right) = \frac{\phi c_{ti} \mu_i}{2.637\times 10^{-4} k}\frac{\partial m}{\partial t}$$

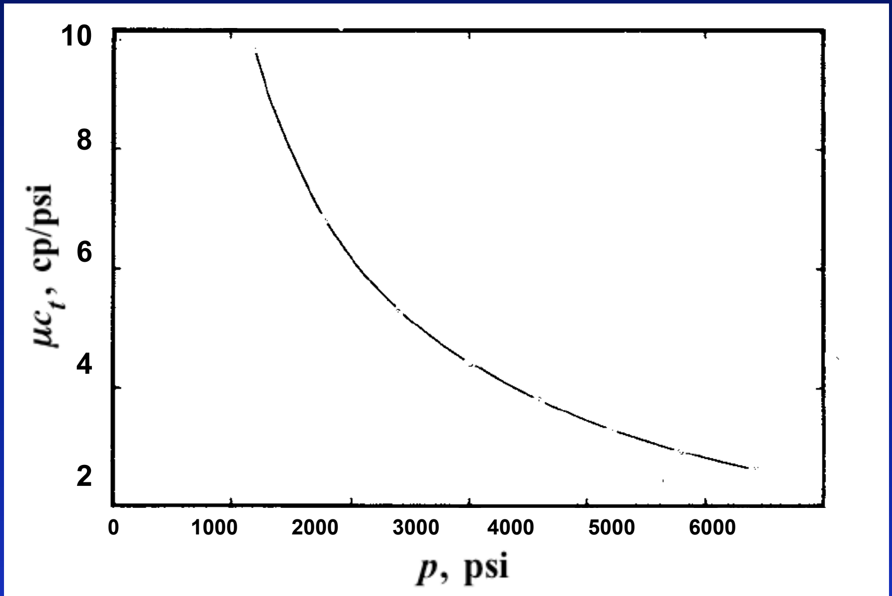
Problem Statement

Analytical Modeling

Pseudopressure linearization assumes that the change in viscosity-compressibility product is negligible

This assumption is reasonable at

- relatively high pressures
- small pressure changes
- infinite-acting behavior
- pressure-transient analysis
- …
- …



Problem Statement

Analytical Modeling

The assumptions of pseudopressure linearization may be met in the analyses of some conventional reservoirs

In tight-gas reservoirs pressure drops are very large; so we have large changes in compressibility and viscosity.

Additional complexities may exist due to

- Pressure dependent permeability
- Non-Darcy flow effects
- Multiphase flow effects
- The Klinkenberg effect

Objectives

Objectives of the Research

Document the problems encountered and errors incurred in the analysis of tight-gas well performances by pseudopressure linearization

Present an analytical and a semi-analytical spectral solution to analyze the performances of fractured wells in tight-gas reservoirs

Demonstrate the analysis with the new solution and highlight the improvement in results

Scope of the Research

Phase I – Investigation of the variable compressibility and viscosity product effects on data analysis.

$$C_1 \frac{\partial^2 m(\mathrm{p})}{\partial x^2} = \phi c_g \mu_g \frac{\partial m(\mathrm{p})}{\partial t}$$

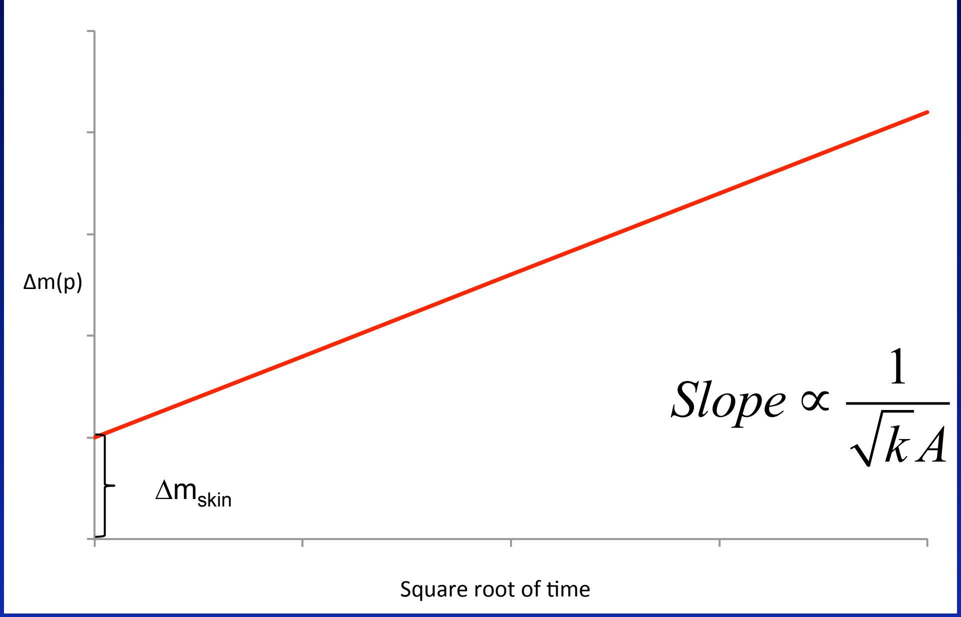
Phase II – Development of a spectral solution of the gas diffusivity equation and incorporation of the essential physics of flow in tight-gas reservoirs

Phase III – Demonstration of the data analysis with the new solution

Status

Phase I

Constant Rate Solution



- -Plot of pseudopressure drop versus square root of time is a straight line
- -Slope gives matrix properties
- -Intercept gives skin

Status

Phase I

Tight-Gas Production Data Analysis

- Tight-gas wells produce at variable rate-variable pressure
- After the initial flow period, pressure may stabilize while the rate declines

If the pseudopressure approach linearizes the real-gas continuity equation, then convolution (Duhamel's equation/ superposition) can be applied to develop solutions and analysis procedures

Status

Phase I

Tight-Gas Production Data Analysis

There are two common methods of applying the superposition solution

- Rate normalization

- Superposition time

Status

Phase I

Tight-Gas Production Data Analysis

Rate normalization

Pressure response at any time is mostly due to the most recent behavior;
If wells produce at pressures that vary slowly with time

$$\frac{\Delta m_w(\mathrm{t})}{q(\mathrm{t})} \approx \frac{\Delta m_{wc}}{q_c(\mathrm{t})}$$

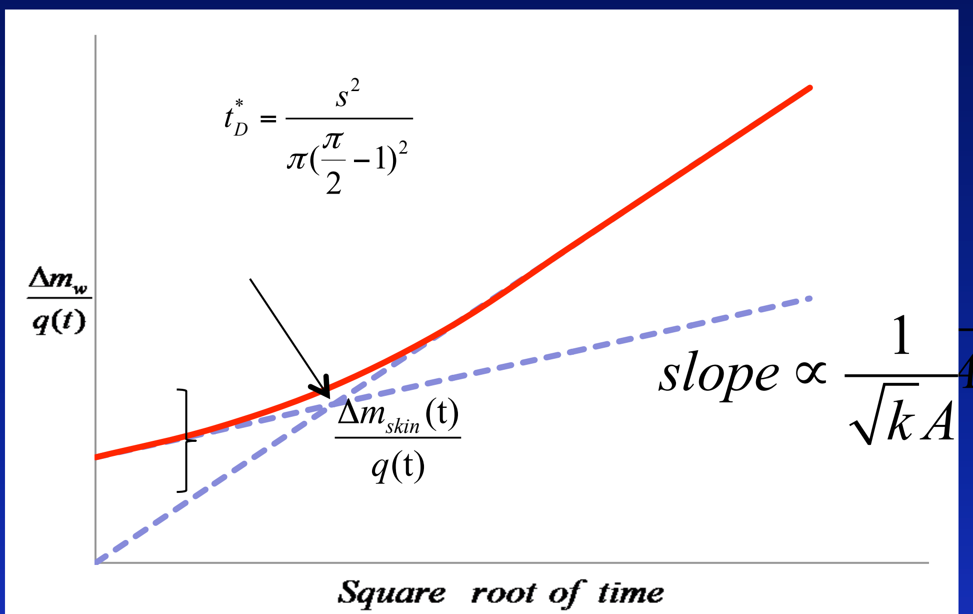
will follow the constant pressure production solution.

Status

Phase I

Tight-Gas Production Data Analysis

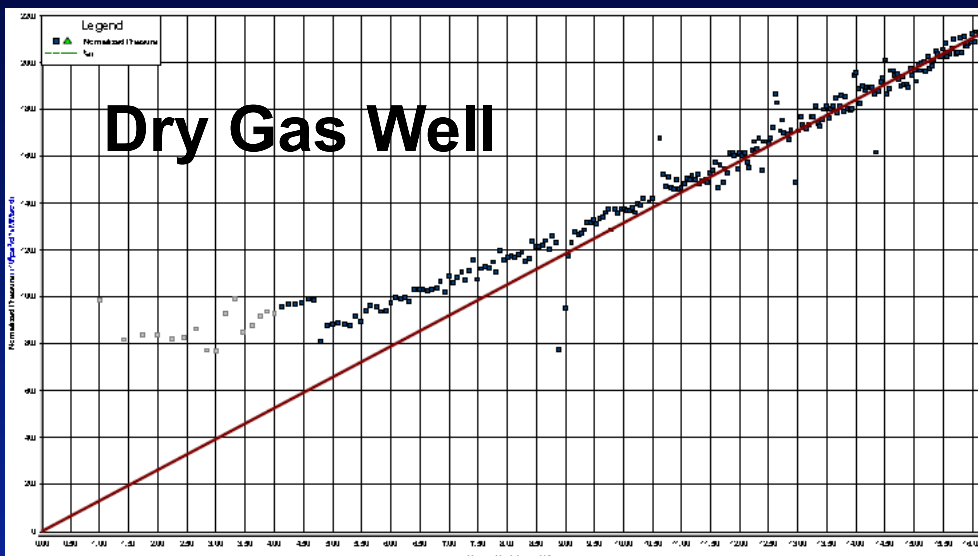
Rate-Normalization & Constant Pressure Solution (Wattenbarger)



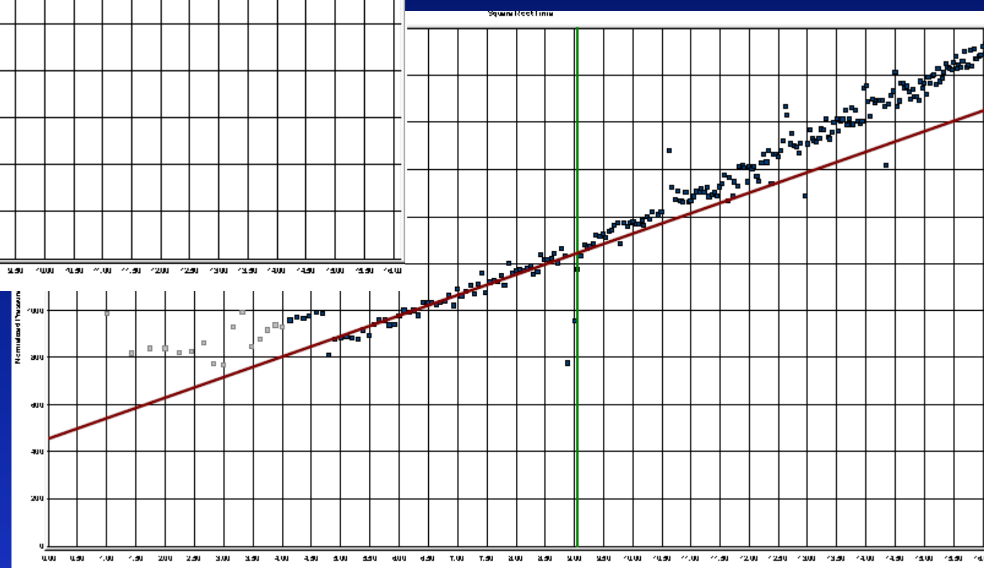
- Solution is not a straight line, but asymptotic to straight lines at "early(<90 days)" and "late" times
  - Early time $\dfrac{1}{[q_{Dc}]_{ET}} \approx \sqrt{\pi t_D} + s$
  - Late time $[q_{Dc}]_{LT} \approx \dfrac{2}{\pi\sqrt{\pi t_D}}$

Phase I

Tight-Gas Production Data Analysis



Rate-Normalization & Constant Pressure Solution (Wattenbarger)



Ratio of late to early time slopes is 1.57

Status

Phase I

Tight-Gas Production Data Analysis

Superposition time & Constant rate solution:

$$m_{Dc}(\mathrm{t_D}) = \sqrt{\pi t_D} + s$$

Apply to the superposition solution:

$$m_{Dc}(\mathrm{t_D}) = \int_0^{t_D} q_D(\tau) m'_{Dc}(\mathrm{t}_D - \tau)\,\mathrm{d}\tau$$

Superposition time:

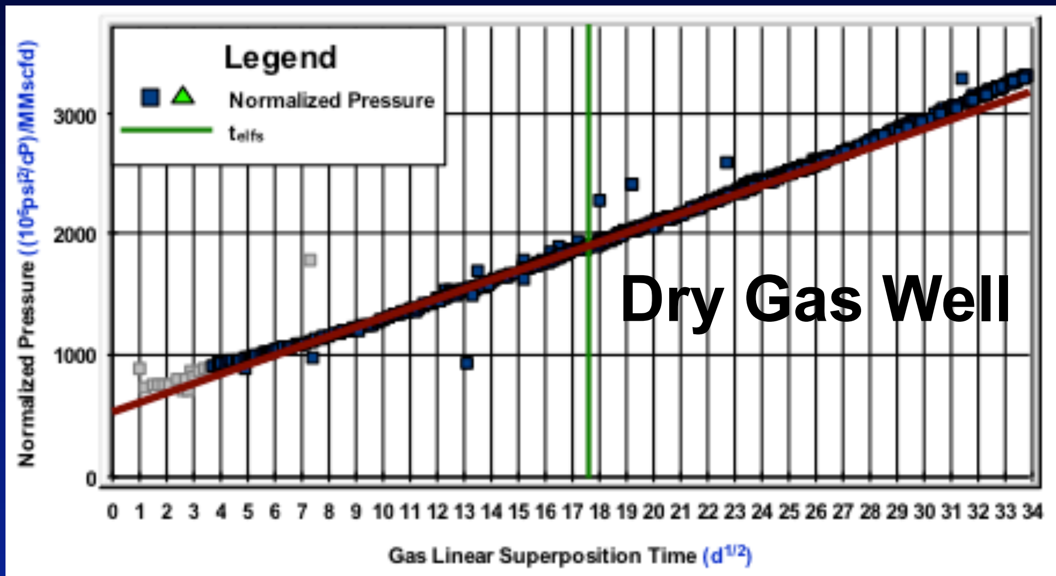
$$t_s = \frac{q(\mathrm{t}_1)\sqrt{t_n}}{q(\mathrm{t}_n)} + \sum_{k=2}^{n} \frac{q(\mathrm{t}_k) - \mathrm{q}(\mathrm{t}_k - 1)}{q(\mathrm{t}_n)} \sqrt{t_n - t_{k-1}}$$

Normalized pseudopressure vs. superposition time should follow the constant rate solution

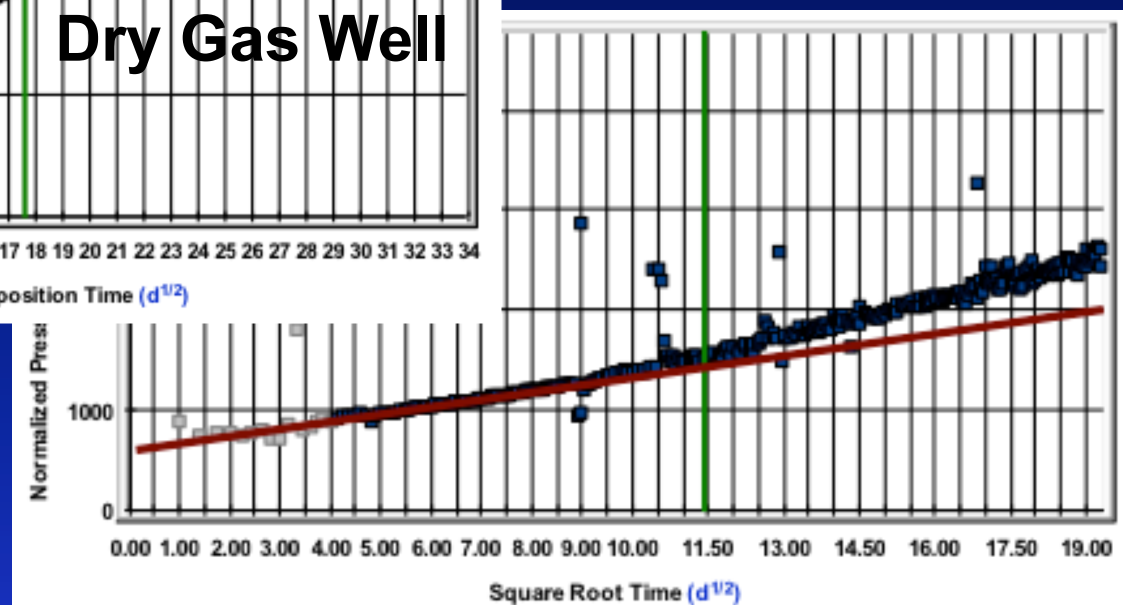
Status

Phase I

Tight-Gas Production Data Analysis



Superposition time &
Constant rate solution

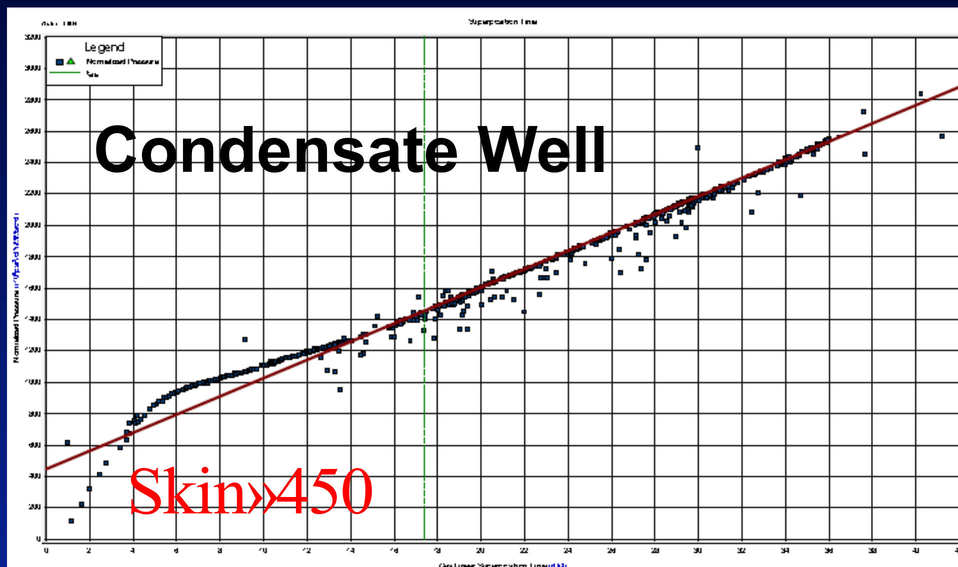


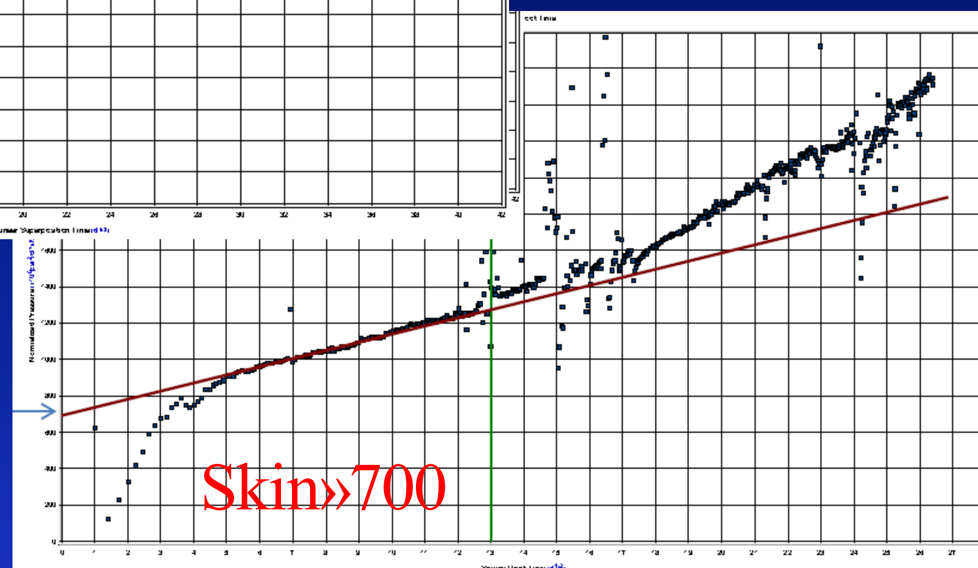
Early square root of time and superposition time and slopes should be the same

Status

Phase I

Tight-Gas Production Data Analysis





Ratio of superposition time to early time slopes is 0.9

Status

Phase II

Spectral Methods

Assumption: The solution of nonlinear diffusion equations is given in the form of an infinite series

Solution: Substitute the infinite series into the diffusion equation and solve for the coefficients

Approach: Approximate the infinite series solution by a truncated Chebyshev series and solve for the (time dependent) coefficients

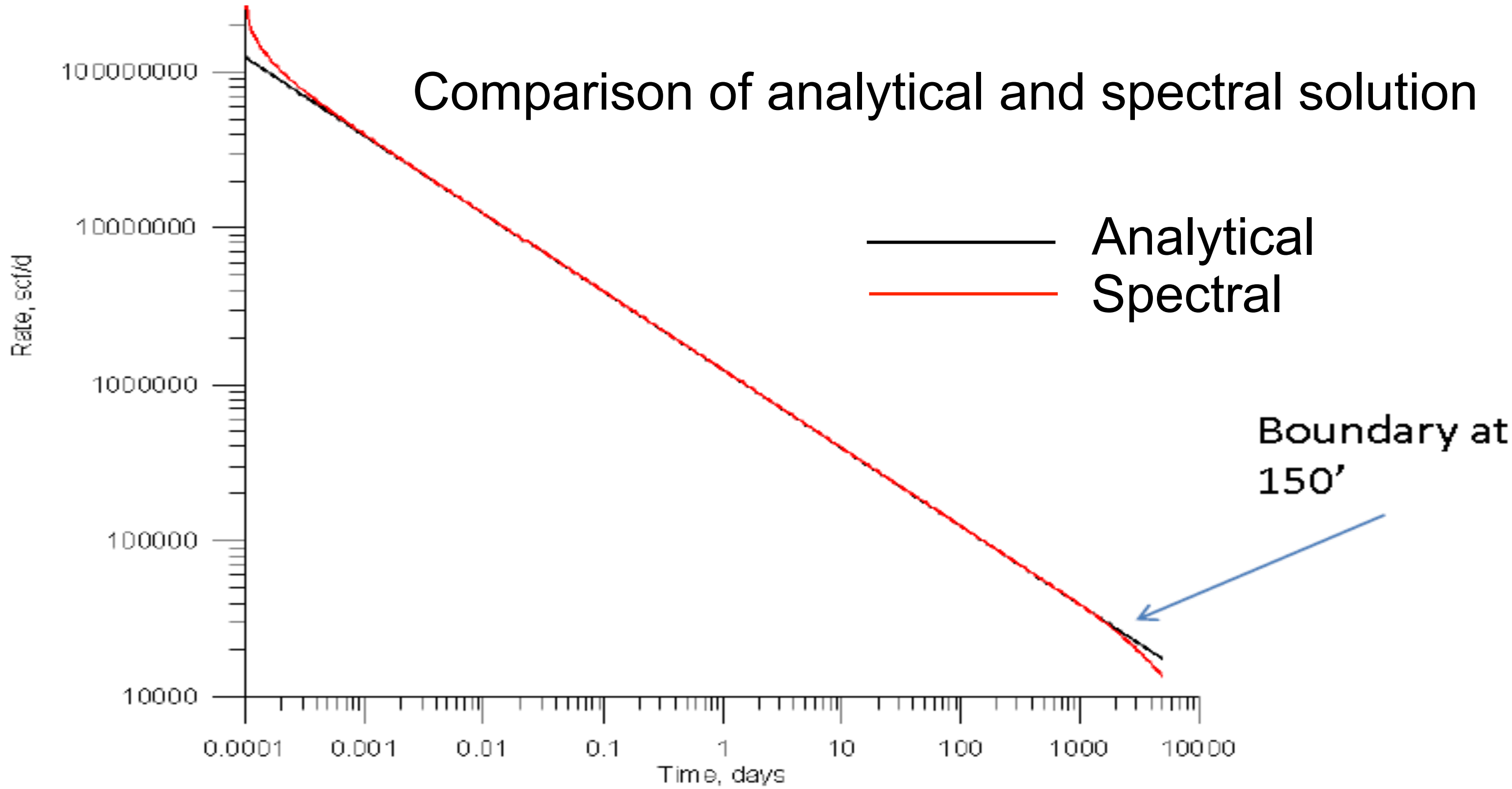
$$p_M(\mathrm{x},\mathrm{t}) \approx \sum_{k=0}^{N} c_k p(\mathrm{t}) \cos(\mathrm{k} \arccos \mathrm{x})$$

Status

Phase II

Variable compressibility effect on constant pressure results

We have an analytical solution and a spectral solution for constant pressure production incorporating variable compressibility effect



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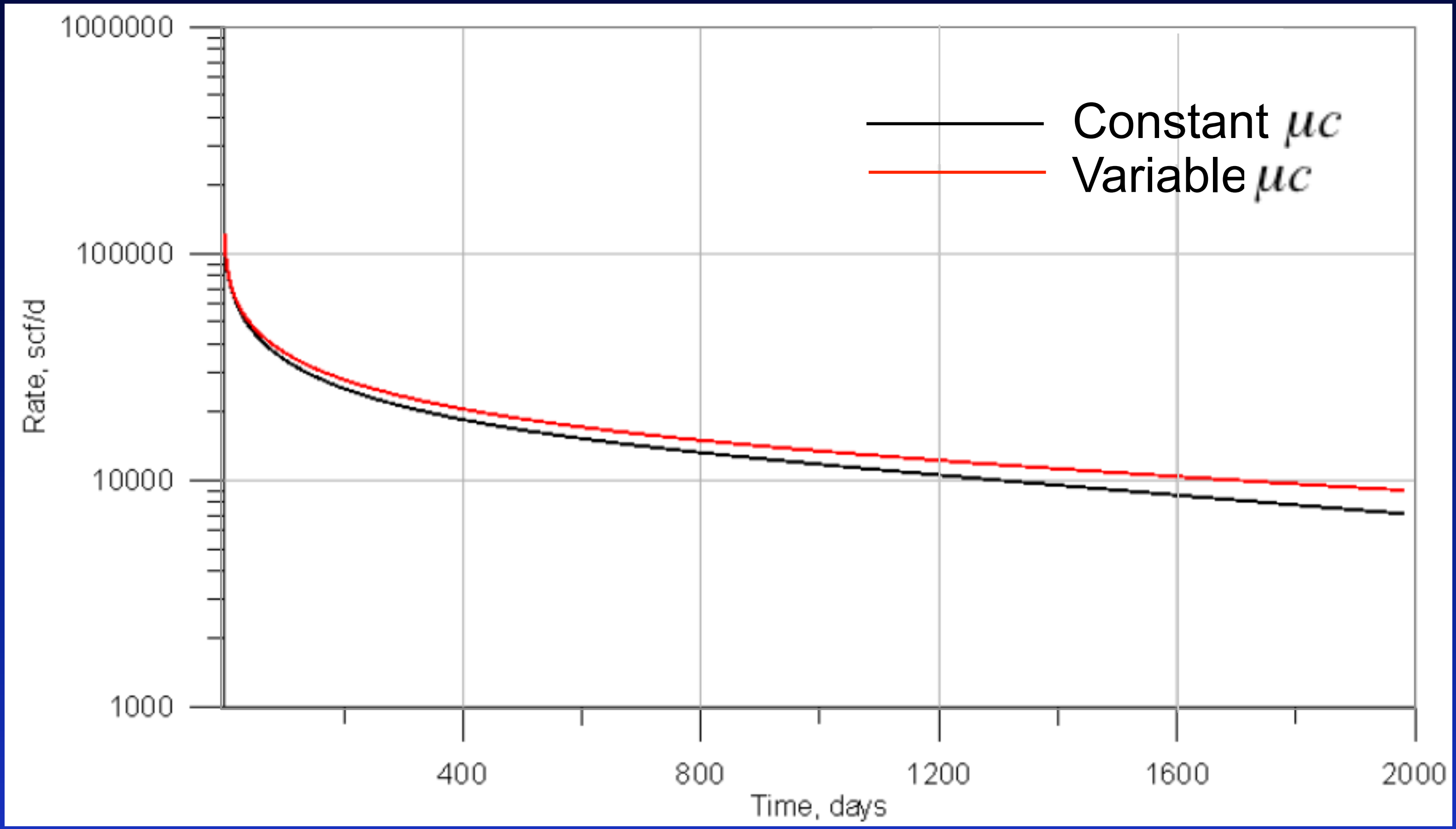
Phase II

Effect of Variable Compressibility



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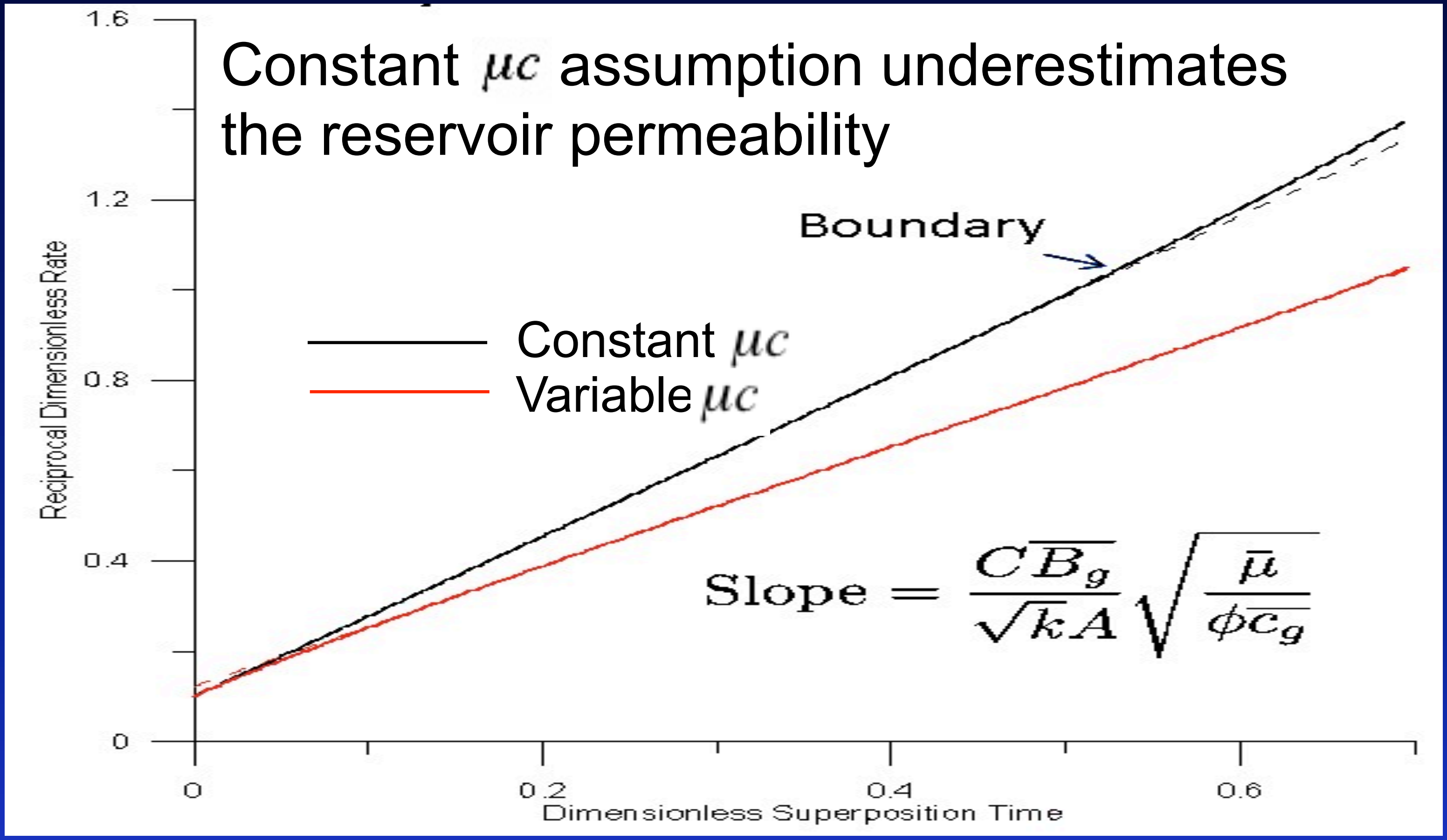
Phase II

Superposition Time Plot



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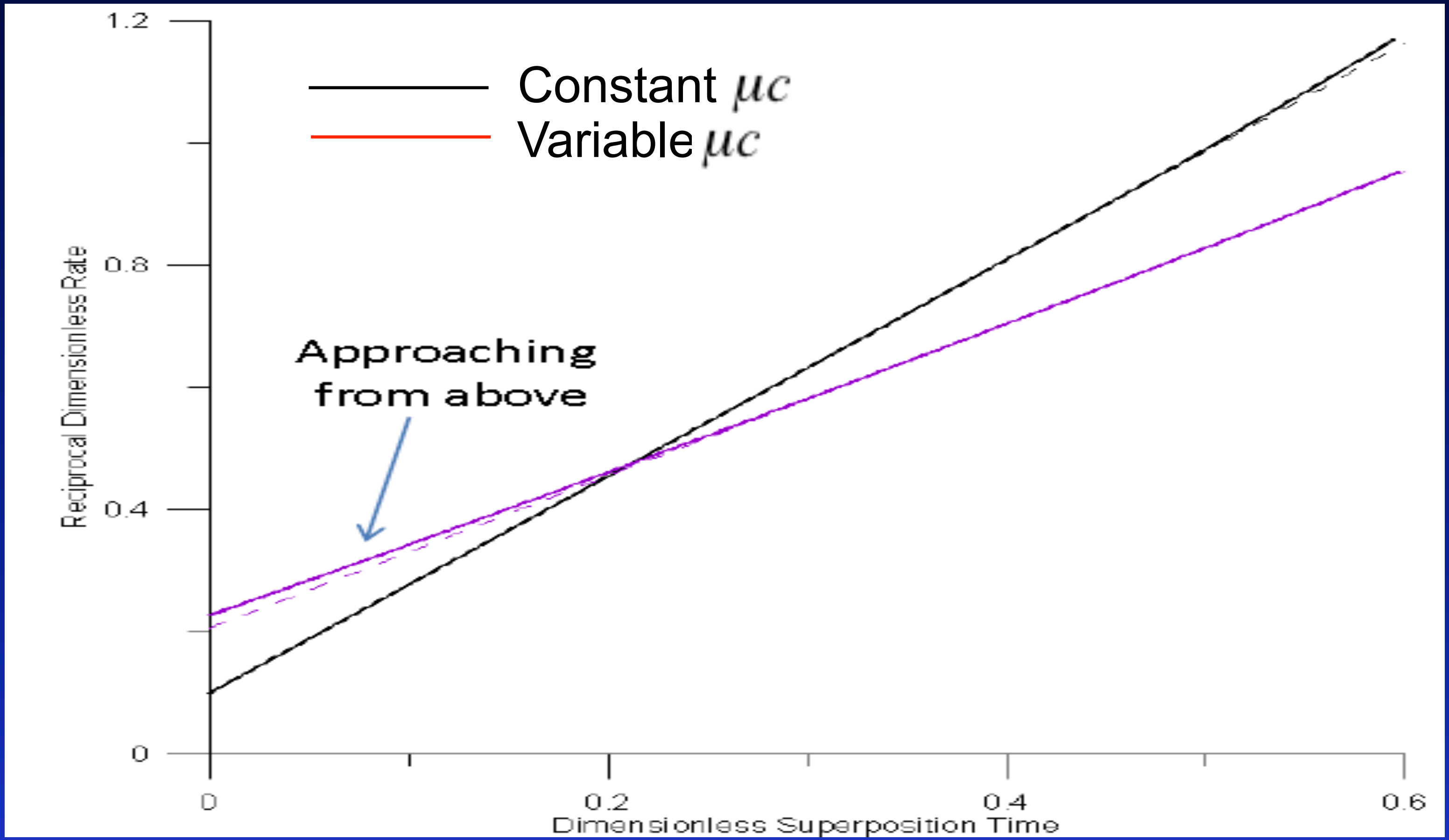
Phase II

Variable $c_g \mu_g$ + Non-Darcy effects



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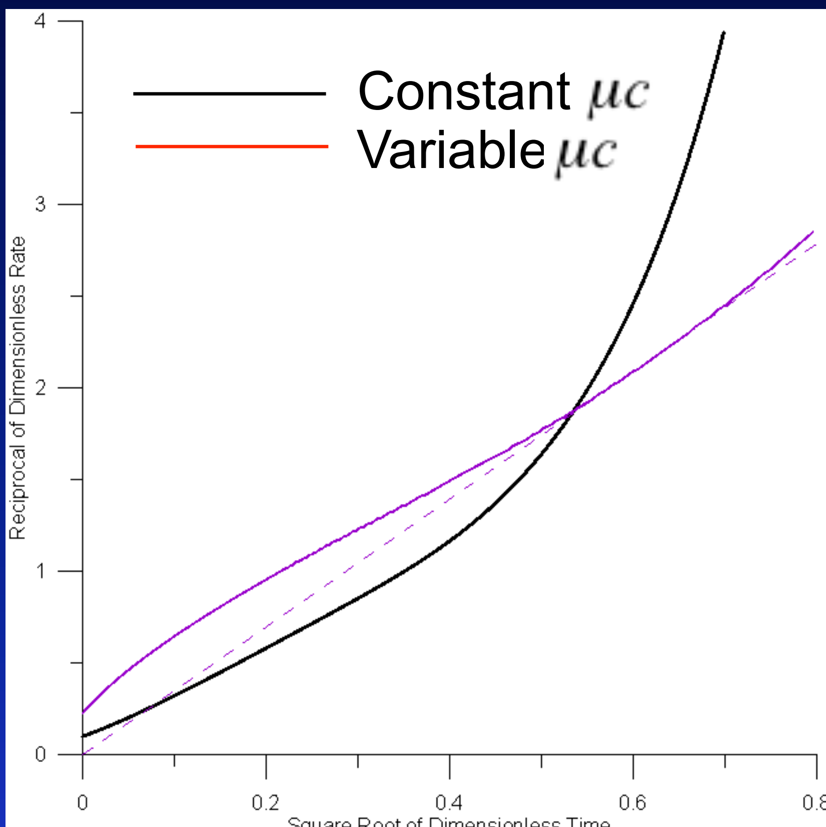
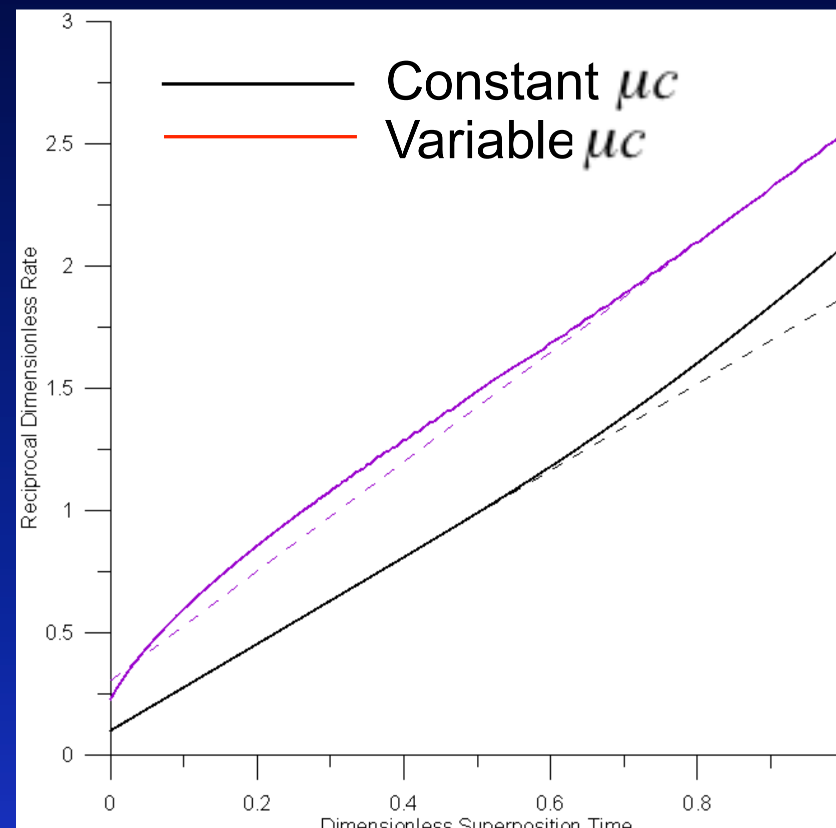
Phase II

Variable $c_g \mu_g$ + ND + Stress dependent Permeability





Work to Continue

Phase III

Extension of the model need to incorporate more physics

- Pressure dependent permeability
- Multiphase flow effects (water, condensate)
- Klinkenberg effect
- Desorption of gas