



UNCONVENTIONAL RESERVOIR ENGINEERING PROJECT
COLORADO SCHOOL OF MINES



Analytical Model for Multiwell Interference

(SPE 215031 – Pressure- and Rate-Transient Model for an Array of Interfering Fractured Horizontal Wells in Unconventional Reservoirs)

Erdal Ozkan

Colorado School of Mines



Introduction

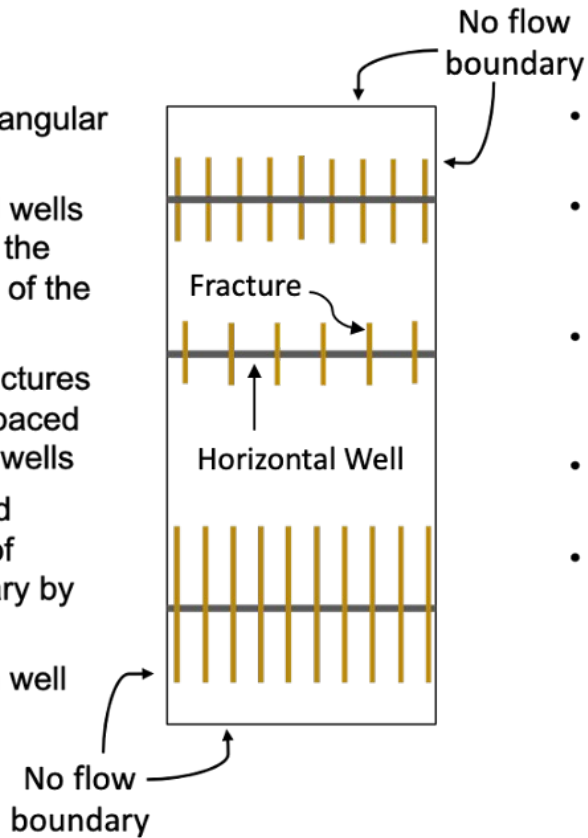
- Analytical model for pressure-transient and production behavior of interfering horizontal wells in unconventional reservoirs
- Arbitrary number of parallel, hydraulically fractured horizontal wells of equal length in single file
- Wells with different fracture stages and properties
- Each well has different SRV and ORV properties
- SRVs and ORVs can have fracture networks
- Varying production and shut-in schedules
- Unequal starting times of wells



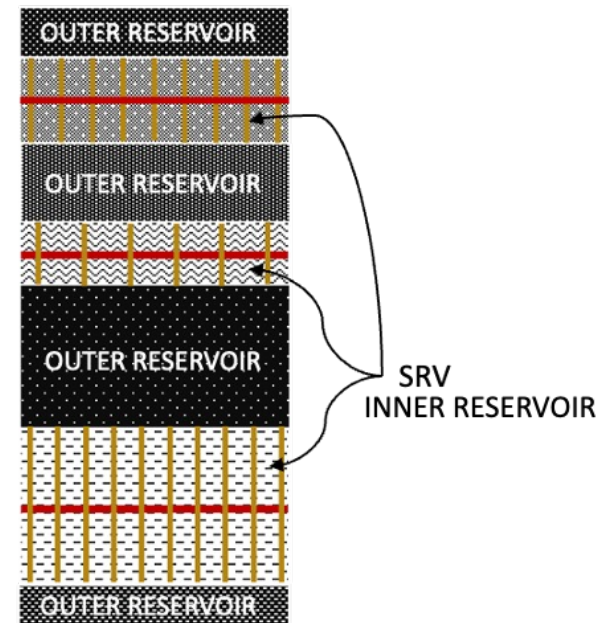
Schematic of the model

Layout

- Closed rectangular reservoir
- 3 horizontal wells penetrating the entire width of the reservoir
- Identical fractures uniformly spaced along each wells
- Number and properties of fractures vary by well
- Nonuniform well spacing

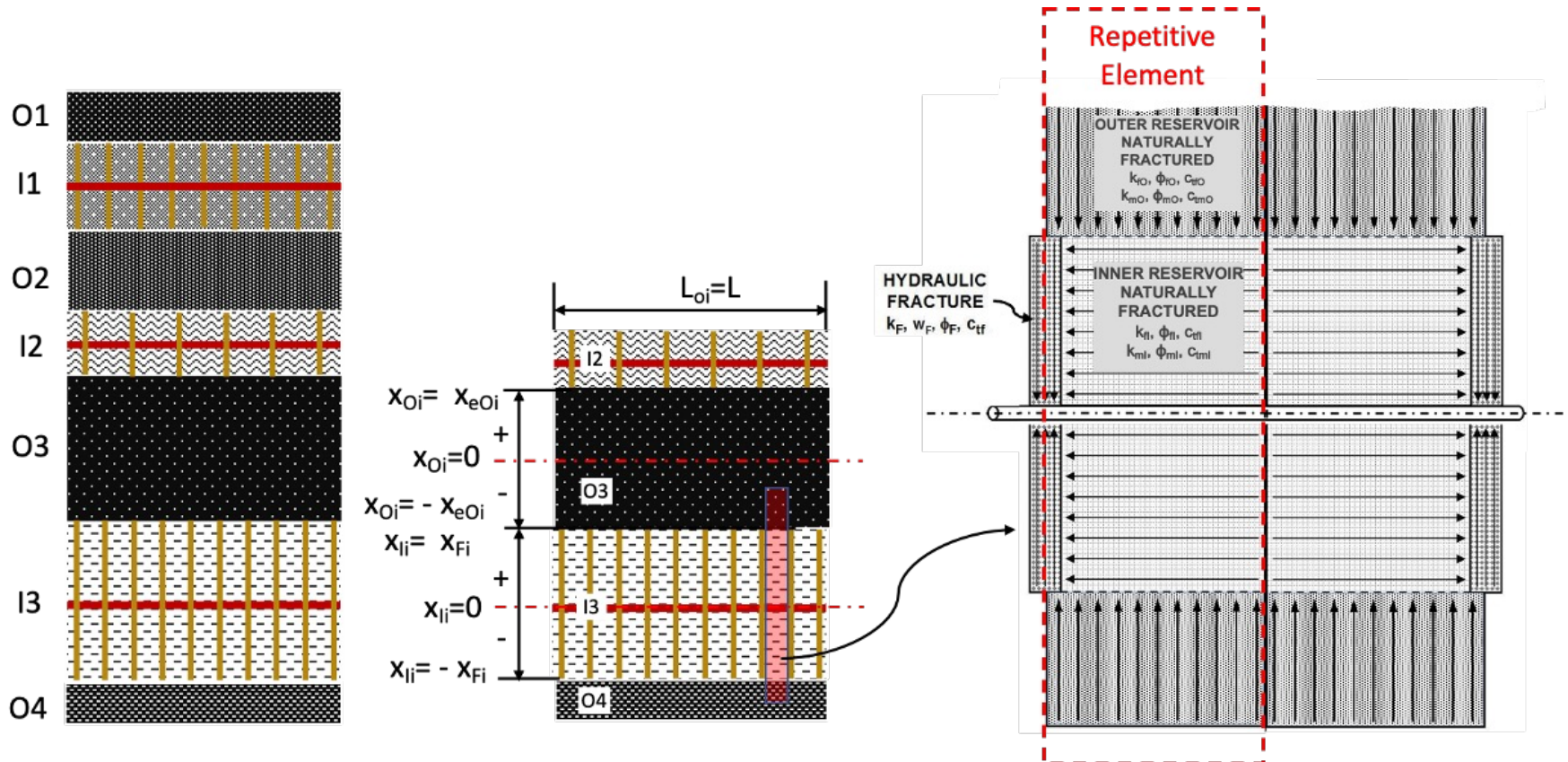


- There is an SRV around each well
- SRV boundary is at the tip of the fractures
- All reservoir blocks can be single- or dual-porosity
- Each reservoir block is internally uniform
- Each block is in perfect contact with its neighbor except for the outermost, closed boundaries



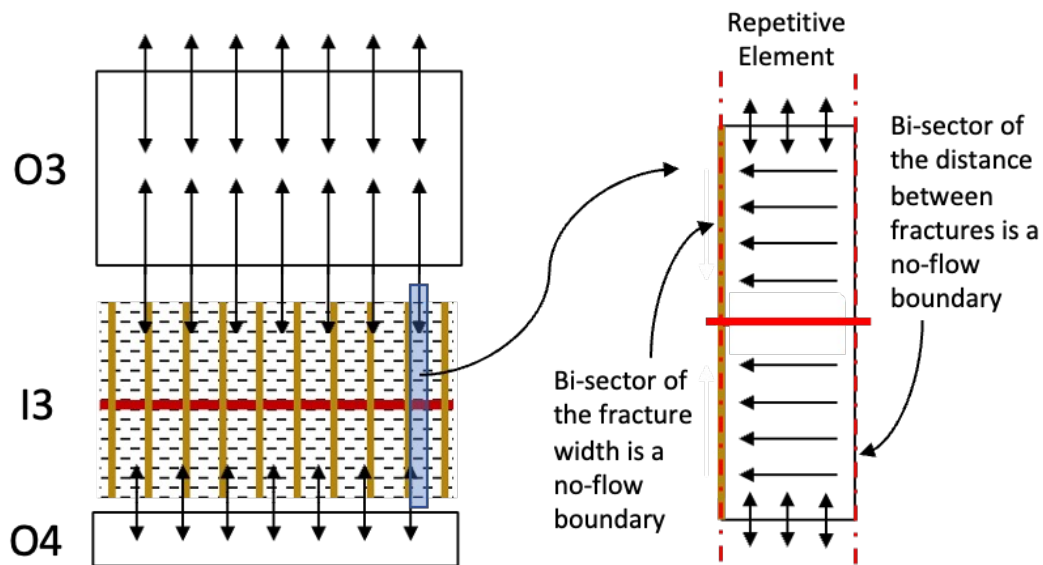
Schematic of the model

Hydraulic Fractures



Model development

Coupled reservoir blocks



Reservoir is divided blocks of SRVs and ORVs

Hydraulic fractures are represented by blocks

Flow in each block is 1D (trilinear flow)

Continuity of pressure and flux at block boundaries

Hydraulic fractures have finite conductivity

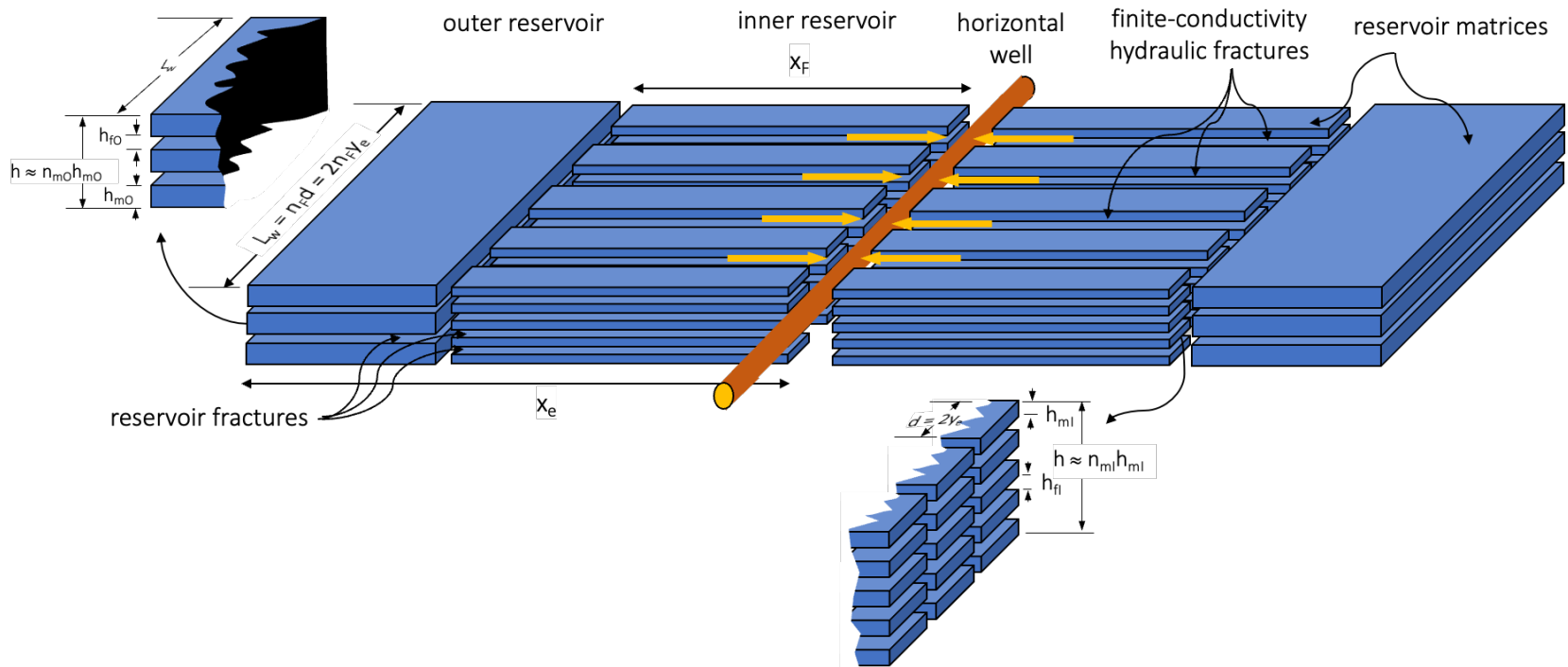
Repetitive elements are used for SRV solutions

Single or dual-porosity in SRVs and ORVs



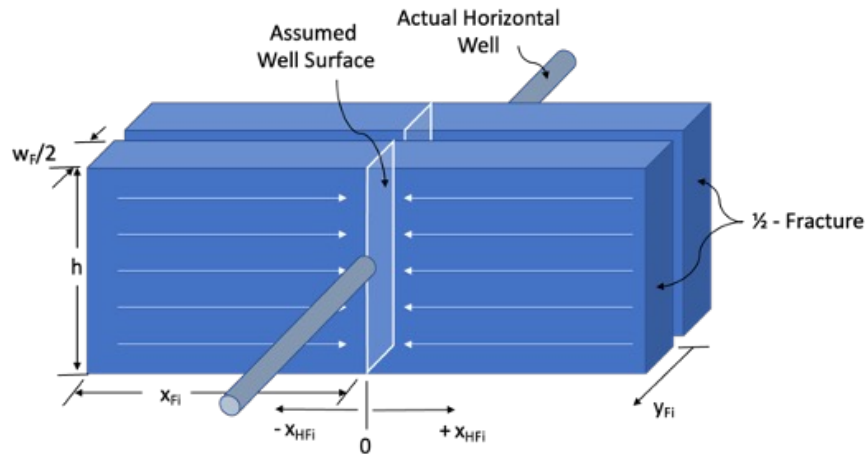
Schematic of the model

Representation of wells, hydraulic fractures, SRVs, and ORVs

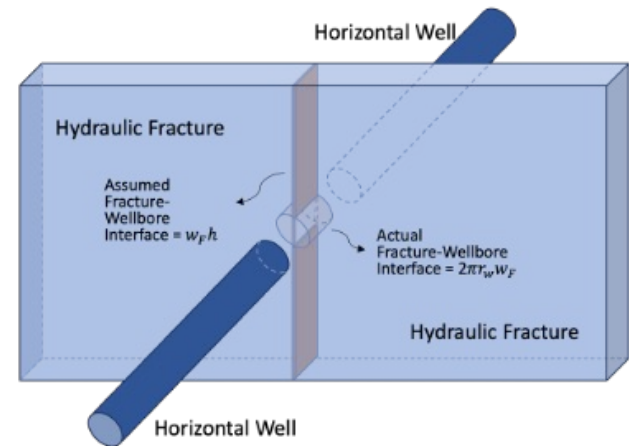


Model development

Hydraulic fracture model

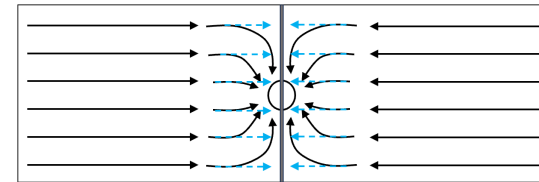


Flow choking



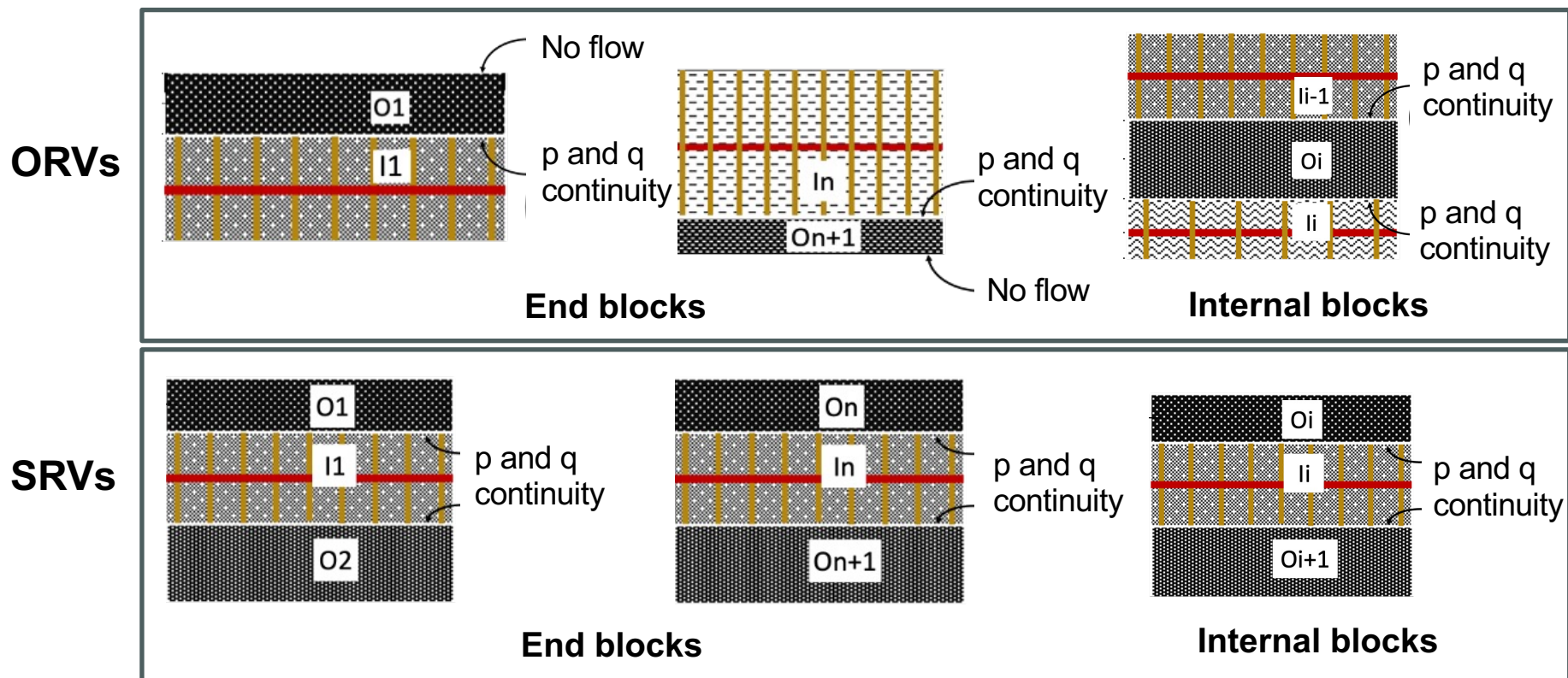
Choking skin

$$s_{cF} = \frac{\psi_1 k_{fI} h}{q_F B \mu} \Delta p_{cF} = \frac{k_{fI} h}{k_F w_F} \left[\ln \left(\frac{h}{2r_w} \right) - \frac{\pi}{2} \right]$$



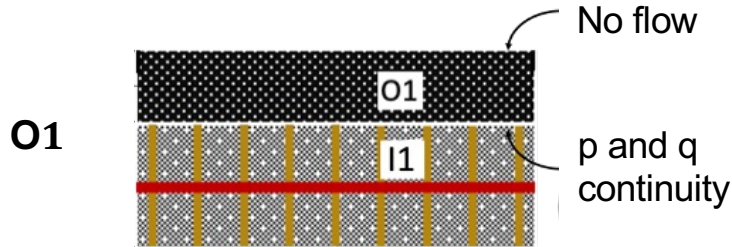
Model development

Solution for each block by Green's function

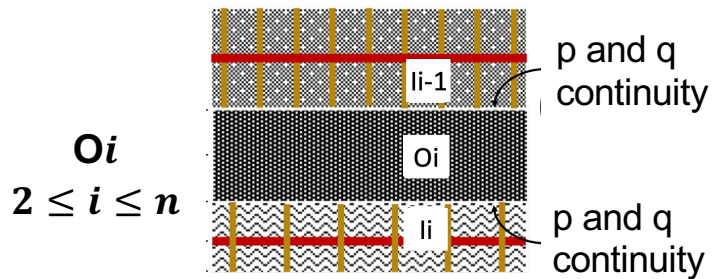


Model development

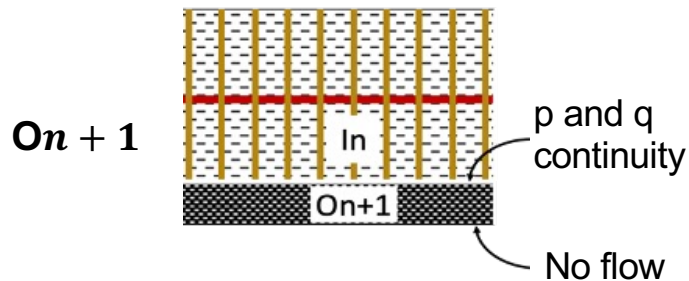
Outer reservoir solutions



$$\bar{p}_{fO1D}(x_{O1D}) = (\bar{p}_{fI1D})_{x_{F1D}} \frac{\cosh[\sqrt{u_{O1}}(x_{O1D} - x_{eO1D})]}{\cosh(2\sqrt{u_{O1}}x_{eO1D})}$$



$$\begin{aligned} \bar{p}_{fOiD}(x_{OiD}) &= \{ [e^{\sqrt{u_{Oi}}(x_{OiD} - x_{eOiD})} + e^{-2\sqrt{u_{Oi}}(x_{eOiD})}] \bar{p}_{fIi-1D}(x_{Fi-1D}) \\ &\quad - \bar{p}_{fIiD}(x_{FiD}) \} \frac{\sinh[\sqrt{u_{Oi}}(x_{OiD} - x_{eOiD})]}{\sinh[2\sqrt{u_{Oi}}(x_{eOiD})]} \end{aligned}$$



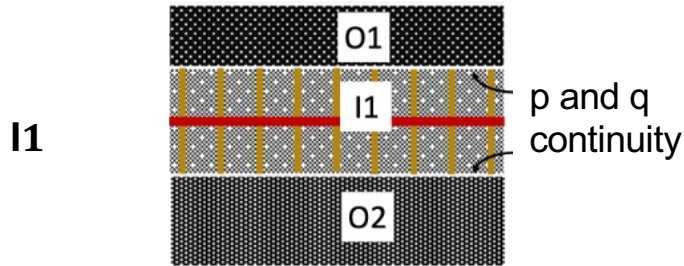
$$\bar{p}_{fOn+1D}(x_{On+1D}) = \bar{p}_{fInD}(x_{FnD}) \frac{\cosh[\sqrt{u_{On+1}}(x_{On+1D} + x_{eOn+1D})]}{\cosh(2\sqrt{u_{On+1}}x_{eOn+1D})}$$

$$u_{Oi} = s_{Oi} f_{Oi}(s_{Oi}) \quad f_{Oi}(s_{Oi}) = \omega_{Oi} + \frac{\lambda_{Oi}(1 - \omega_{Oi})}{3s_{Oi}} \tanh \left(\sqrt{\frac{3(1 - \omega_{Oi})s_{Oi}}{\lambda_{Oi}}} \right)$$

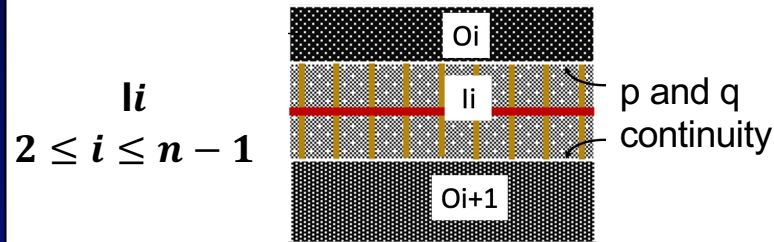


Model development

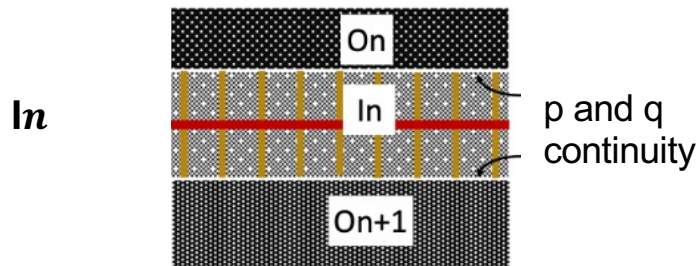
Inner reservoir solutions



$$\begin{aligned} & \bar{p}_{fliD}(y_{liD}, s) \\ &= \frac{\cosh[\sqrt{\alpha_{oi}}(1 - y_{liD})]}{\cosh(\sqrt{\alpha_{oi}})} \bar{p}_{fliD}(0, s) \\ &+ \frac{1}{\alpha_{oi}} \left\{ \frac{\cosh[\sqrt{\alpha_{oi}}(1 - y_{liD})]}{\cosh(\sqrt{\alpha_{oi}})} - 1 \right\} \bar{h}_i(s) \end{aligned}$$



$$\bar{h}_i = \begin{cases} \frac{\gamma_{012}}{2} \bar{p}_{f12D,avg} & i = 1 \\ \frac{\gamma_{0ii-1}}{2} \bar{p}_{fli-1D,avg} + \frac{\gamma_{0ii+1}}{2} \bar{p}_{fli+1D,avg} & 2 \leq i \leq n-1 \\ \frac{\gamma_{0nn-1}}{2} \bar{p}_{fIn-1D,avg} & i = n \end{cases}$$

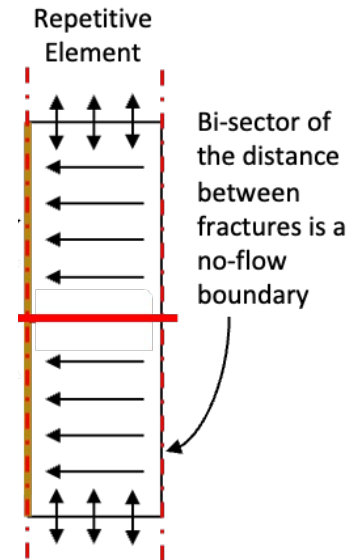
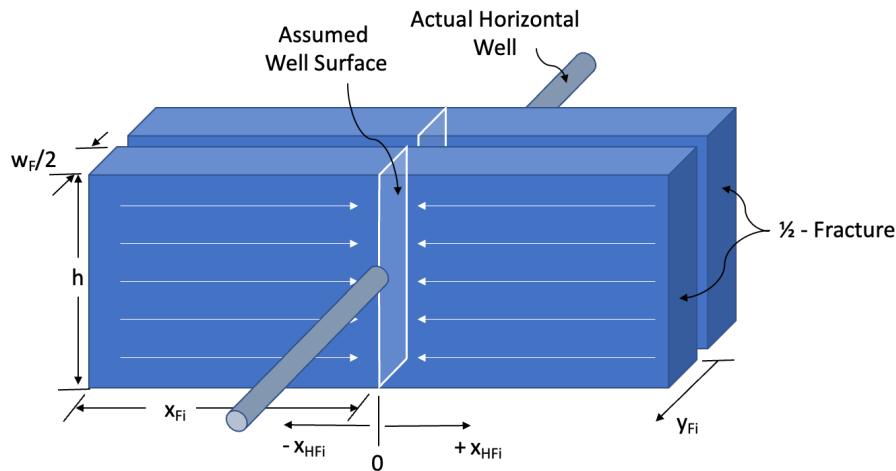


$$\bar{p}_{fliD,avg}(s) = \int_0^1 \bar{p}_{fliD}(y_{liD}, s) dy_{liD}; \quad i = 1, n$$



Model development

Hydraulic fracture solution



$$\bar{p}_{FiD}(x_{HFiD}, s) = \frac{\gamma_{Fi}}{\alpha_{Fi}} \left[\sum_{j=1}^n \psi_{Fij} \bar{p}_{FjD}(s) \right] + \frac{\pi \bar{q}_{iD}}{n_{Fi} C_{FiD} k_{fLiD} x_{FiD} \sqrt{\alpha_{Fi}}} \frac{\cosh[\sqrt{\alpha_{Fi}}(x_{FiD} - x_{HFiD})]}{\sinh(\sqrt{\alpha_{Fi}} x_{FiD})}$$



Solution

Dimensionless Pressure for Well i

$$\bar{p}_{wiD} = \frac{\gamma_{Fi}}{\alpha_{Fi}} \left[\sum_{j=1}^n \psi_{Fij} \bar{p}_{wjD} \right] + \frac{\pi \bar{q}_{iD}}{n_{Fi} C_{FiD} k_{fIiD} x_{FiD} \sqrt{\alpha_{Fi}} \tanh(\sqrt{\alpha_{Fi}} x_{FiD})} + s_{cFi}$$

Nested solution in dimensionless variables

Reservoir, well, fracture properties enter solution via definitions of

\bar{p}_{wiD} , \bar{q}_{iD} , γ_{Fi} , ψ_{Fij} , C_{FiD} , k_{fIiD} , and x_{FiD}

In Laplace domain (inverted numerically)



Solution

Matrix solution for n wells

$$\sum_{j=1}^n a_{ij} \bar{p}_{wjD} = b_i, \quad i = 1, \dots, n$$

$$a_{ij} = \begin{cases} \frac{\gamma_{Fi}}{\alpha_{Fi}} \psi_{Fij} & i \neq j \\ \frac{\gamma_{Fi}}{\alpha_{Fi}} \psi_{Fii} - 1 & i = j \end{cases} \quad b_i = - \left[\frac{\pi}{n_{Fi} C_{FiD} k_{fLiD} x_{FiD} \sqrt{\alpha_{Fi}} \tanh(\sqrt{\alpha_{Fi}} x_{FiD})} + s_{cFi} \right] \bar{q}_{iD}$$

$$\bar{q}_{iD} = \frac{q_{iD}}{s}$$

Constant rate production. Wells starting at the same time and producing at constant rates, q_{iD} , for all times



Solution

Extensions for sandface pressure and rate variations

$$\bar{q}_{iD} = \frac{1}{s} \sum_{k=1}^{K_i} (q_{ikD} - q_{ik-1D}) e^{-st_{ik-1D}}$$

Wells start producing at different times, t_{i0} , and have a schedule of K_i rates, including shut-ins

$$\bar{\bar{q}}_{Di} = \frac{1}{s_i^2 \bar{p}_{wDi}}$$

Constant pressure production

$$\bar{q}_{Di} = \left(\frac{1}{s_i \bar{p}_{wDi}} + s C_D \right) \bar{p}_{wD,pi}$$

Variable sandface rate and pressure

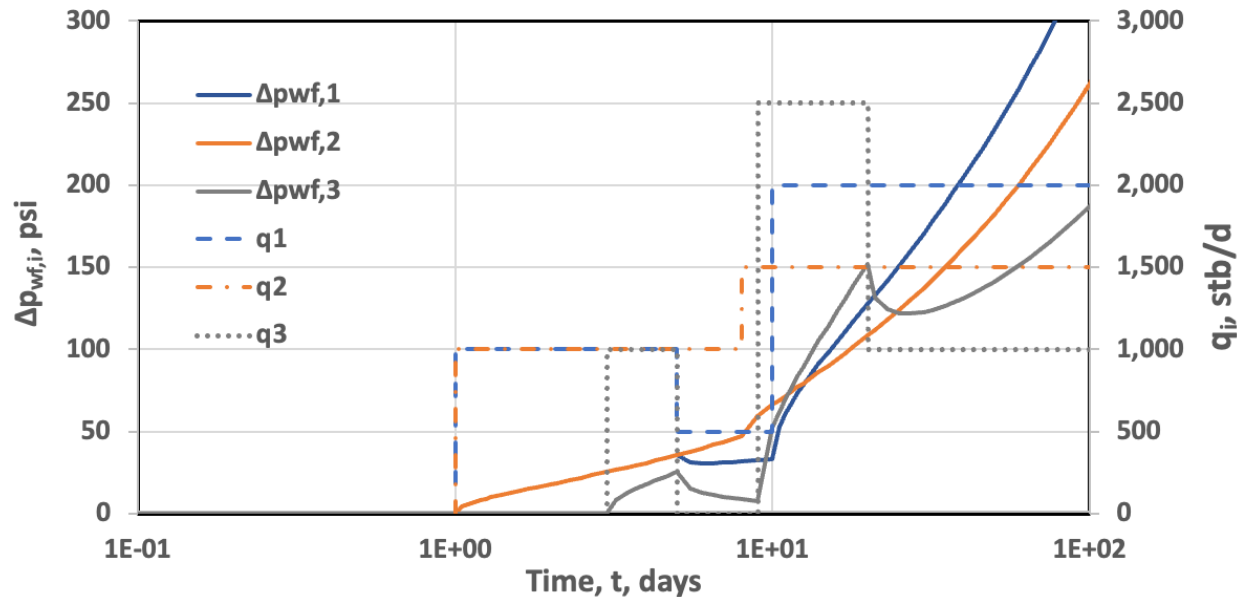
$$\bar{p}_{wiD, storage \& skin} = \frac{\bar{p}_{wiD}}{1 + C_{iD} r_{wiD}^2 s^2 \bar{p}_{wiD}}$$

Wellbore storage and skin



Example 1

Different flow rates and starting times

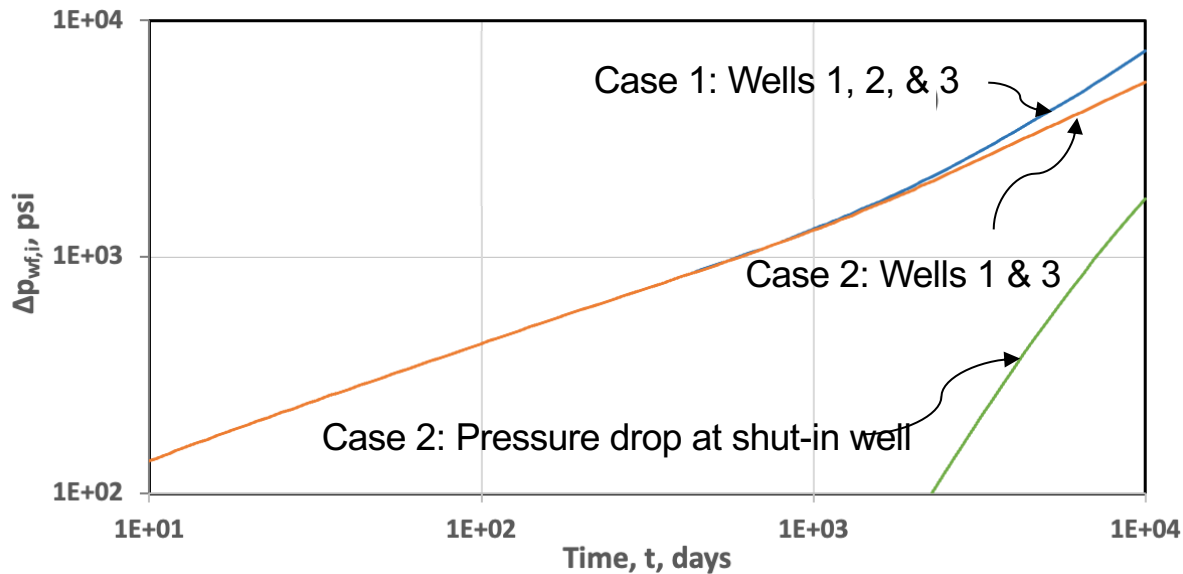


- 3 wells with different production schedules.
- Identical wells
- Same SRV & ORV properties for all wells
- Well 3 undergoes a shut-in period



Example 2

Effect of interference



- Identical Wells

- Same SRV & ORV

Case 1:

- 3 identical wells
- Same production rate

Case 2:

- Wells 1 and 3 active
- Well 2 (middle well) is off

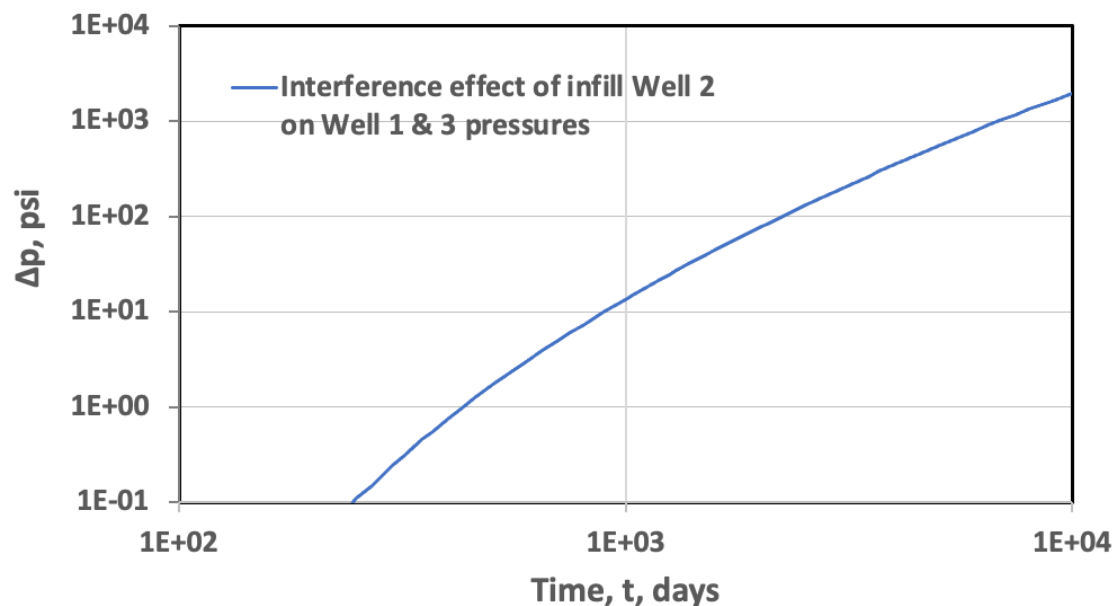


UNCONVENTIONAL RESERVOIR ENGINEERING PROJECT

Advisory Board Meeting, December 14, 2023, Golden, Colorado

Example 2

Effect of interference



Additional pressure drop caused at Wells 1 and 3 because of the production of the infill well (Well 2)

Less than 10 psi for 2.5 years

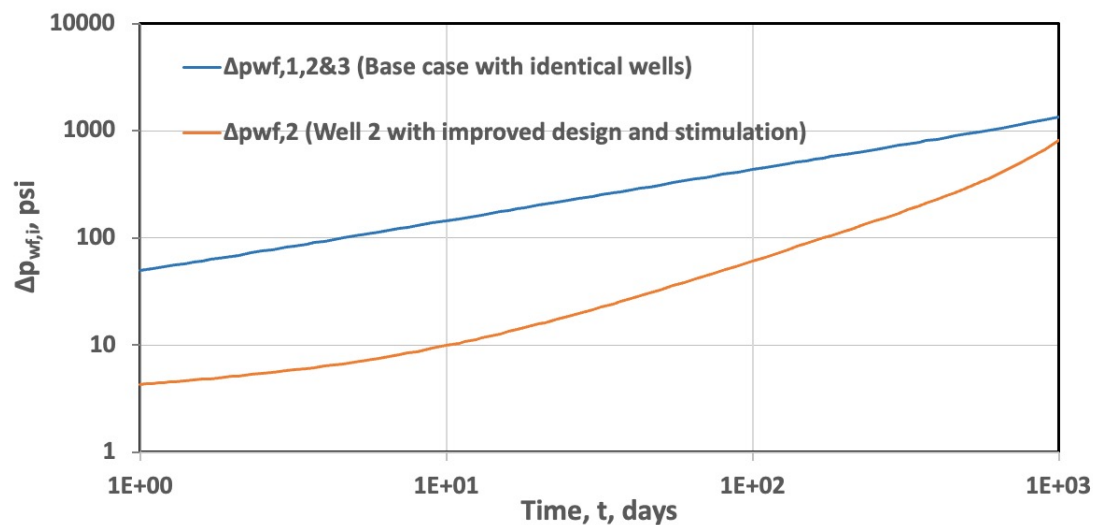
60 psi at the 5th year

854 psi at the 10th year



Example 3

Effect of improved stimulation



Case 1:

Original design with 25 fractures on each well

Case 2:

of Fractures doubled on Well 2
Smaller matrix blocks and higher permeabilities in the SRV of Well 2



Remarks

- A robust and versatile analytical model
- Not intended to be an all-inclusive and high-precision solution.
 - As accurate as the single-well trilinear-flow model, (Brown et al. 2011).
- Should be useful for
 - PTA and RTA applications,
 - production-data analysis and performance predictions
- Helpful tool to make decisions on
 - well-spacing,
 - well design, and
 - hydraulic fracture stimulation treatments.

