Research Summary

INTERPRETING WELL PRESSURE TRANSMITTED BY FIBER OPTICS USING A MATHEMATICAL MODEL

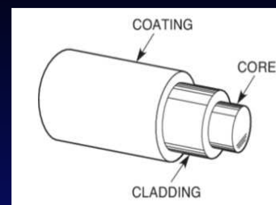
Chayapod Beokhaimook

Overview

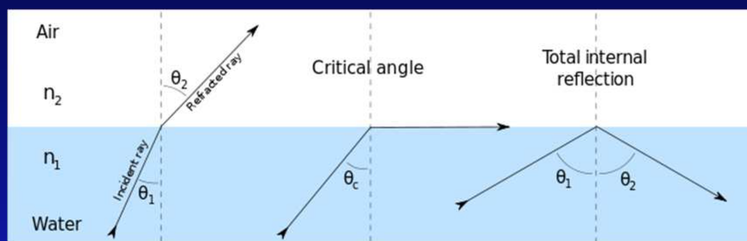
- Main Goal: Calculate reservoir permeability variation along the wellbore using pressure data transmitted by fiber optics
- Methodology: Construct a 1D mathematical model to calculate reservoir permeability using the measured pressures along the wellbore

Fiber Optics Fundamentals

- Components
  - Core
  - Cladding
  - Coating
- Transmission: Total Internal Reflection



www.newport.com/t/fiber-optic-basics



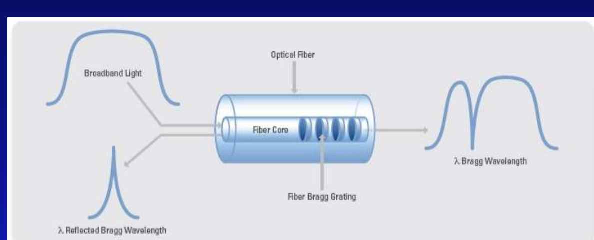
https://upload.wikimedia.org/wikipedia/commons/thumb/5/5d/RefractionReflextion.svg/660px-RefractionReflextion.svg.png

Measurements with Fiber Optics

- Optical fibers are installed inside/outside the wellbore and the pressure sensors measures pressure inside the wellbore
- Measurements are based on the wave length shift in the fiber Bragg gratings (FBG):

$$\lambda_B = (2n_{eff})\Lambda$$

λ_B: *Bragg wavelength*
n_{eff}: *Effective refractive index*
Λ: *Bragg grating spacing*



www.ni.com/white-paper/11821/en/

Measurements with Fiber Optics

Temperature and Strain Sensing

$$\frac{\Delta\lambda_B}{\lambda_{B,0}} = (1 - p_e)\epsilon + (\alpha_T + \alpha_n)\Delta T$$

λ_B: Bragg wavelength
p_e: strain − opitc coefficient
ϵ: strain
α_T: thermal expansion coefficient
α_n: thermo − optic coefficient
ΔT: temperature change

Pressure Sensing

$$\frac{\Delta\lambda_B}{\lambda_{B,0}} = \left[-\frac{1-2\nu}{E} + \frac{n_{eff}^2}{2E}(1-2\nu)(2p_{12} + p_{11})\right]\Delta P$$

ν: Poisson's ratio
E: Young's modulus
n_{eff}: effective refractive index
p_{11}, p_{12}: components of a strain − optic tensor
ΔP: pressure change

Model Assumptions

- Pressure measurements from fiber optics are accurate enough!
- The change in fluid properties within the wellbore are insignificant
- Fluid accumulation in the wellbore is negligible compared to the net influx into the wellbore

3D, Single-Phase Numerical Model

- Flow in Reservoir

$$\nabla \cdot \frac{k}{\mu}(\nabla P_{res} - \gamma \nabla D) + \hat{q} = \phi c_t \frac{\partial P_{res}}{\partial t}$$

- Flow in Wellbore

$$\frac{\partial q_{wb}}{\partial x} - J_s(p_r - p_{wb}) = 0$$

$$\frac{\partial p_{wb}}{\partial x} - \gamma = 0$$

$$J_s = -\frac{2\pi k}{\mu}\frac{1}{\ln\left(\frac{r_b}{r_w}\right) - \frac{3}{4} + s_d}; r_b = \sqrt{\frac{\Delta x \Delta z}{\pi}}$$

3D Water-Oil Numerical Model

- Flow in Reservoir

$$\nabla \cdot (k\lambda_o)(\nabla p_o - \gamma_o \nabla D) + \hat{q}_o = \phi\left[S_o(c_\phi + c_o)\frac{\partial p_o}{\partial t} + \frac{\partial S_o}{\partial t}\right]$$

$$\nabla \cdot (k\lambda_w)(\nabla p_o - \gamma_w \nabla D - \nabla p_{cwo}) + \hat{q}_w = \phi\left[S_w(c_\phi + c_w)\frac{\partial p_w}{\partial t} + \frac{\partial S_w}{\partial t}\right]$$

- Flow in Wellbore

$$\frac{\partial q_{o,wb}}{\partial x} - q_{o,wb_{s,R}} = 0$$

$$\frac{\partial q_{w,wb}}{\partial x} - q_{w,wb_{s,R}} = 0$$

$$\frac{\partial p_{wb}}{\partial x} - \gamma = 0$$

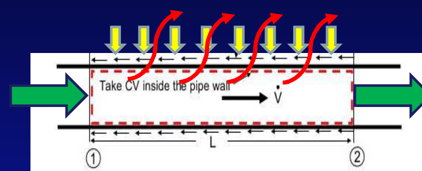
1D Single-Phase Semi-Analytical Model

- Pressure in the drainage area is assumed constant
- SPE-135223-PA (Farshbaf Zinati et al., 2012)

$$\frac{\partial q_{wb}}{\partial x} - J_s(p_r - p_{wb}) = 0$$

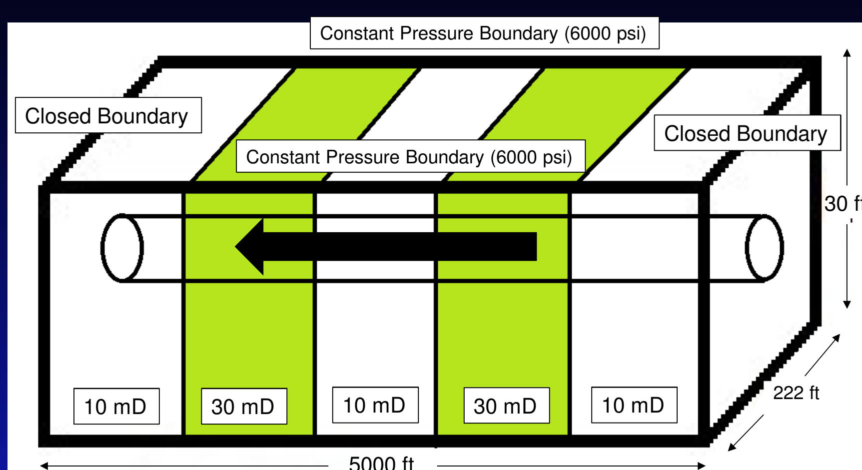
$$\frac{\partial p_{wb}}{\partial x} - \gamma = 0$$

$$J_s \approx \frac{4\pi k}{\mu}\left[ln\left(\frac{cosh\frac{\pi w_R}{h_R}-1}{cosh\frac{\pi d}{h_R}-1}\right)\right]^{-1} \quad (Jansen)$$

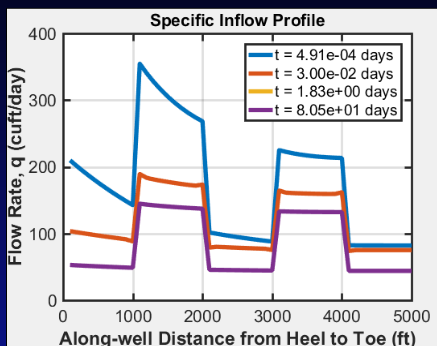


https://image.slidesharecdn.com/slidefluid-140504101515-phpapp02/95/flow-in-pipes-9-638.jpg?cb=1399198575

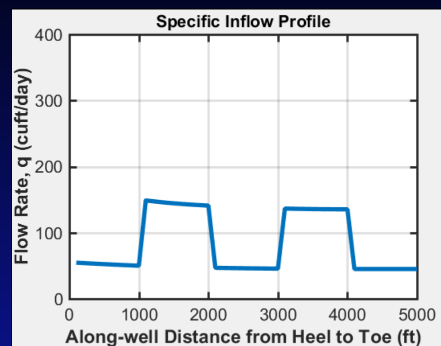
Model Comparison: Reservoir



Model Comparison: Constant Pressure BC



Our 3D Numerical Model



1D Steady-State Model

Inverse Modeling to Calculate Reservoir Permeability

- We will minimize the square difference between the fiber optics measured pressure and the model pressure:

$$W = (Y - D)^T P_y^{-1} (Y - D)$$

$W: Objective\ function$
$Y: Model\ predicted$ pressure
$D: Fiber\ optics\ measured\ pressure$
$P_y: Covariance\ matrix\ of\ the\ measurement\ error$

Issues with the Model

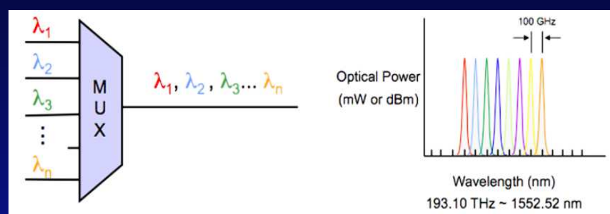
- Friction factor correlation issues
  - Doesn't take into account the influx from perforation
  - Multiphase flow is even more complicated
- Effects from temperature and strain can affect pressure measurements
  - In calculating the Bragg shift, the optical fiber material properties change with temperature, but we assume insignificant at this point
- Measurement noise may not be negligible!

Conclusions

- Reservoir permeability can be quantified using a coupled wellbore to reservoir flow model
- 1D semi-analytical model is a good approximation because during a calculation the reservoir pressure in the draingage volume does not significantly
- Significant model issues
  - Friction factor correlation
  - Effects of temperature on Bragg wave length shift
  - Measurement noise

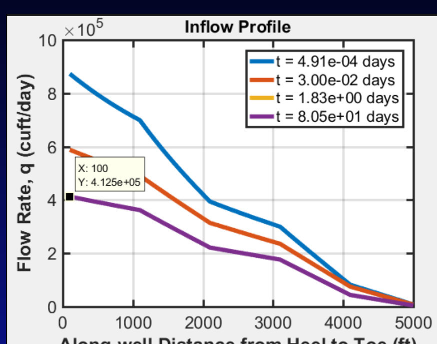
Wavelength Division Multiplexing (WDM)

- Install FBG sensors at multiple locations
- Each sensor has its own unique range of Bragg wavelength

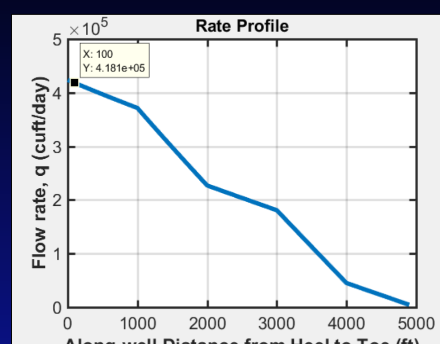


(https://www.nanog.org/meetings/nanog57/presentations/Monday/mon.tutorial.Steenbergen.Optical.39.pdf)

Model Comparison: Constant Pressure BC

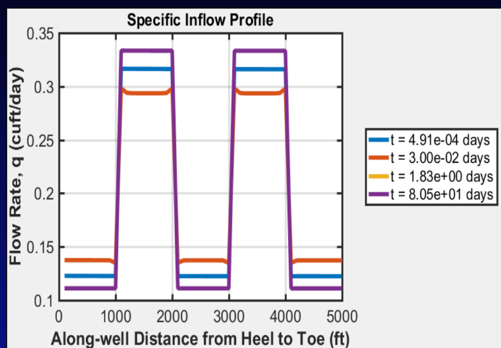


Our 3D Numerical Model

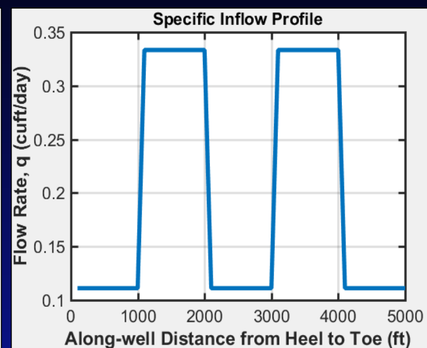


1D Steady-State Model

Model Comparison: Constant Rate BC

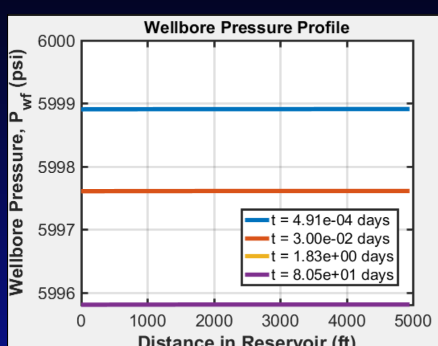


Our 3D Numerical Model

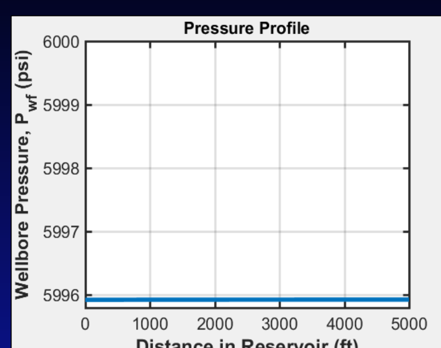


1D Steady-State Model

Model Comparison: Constant Rate BC



Our 3D Numerical Model



1D Steady-State Model