Two-Dimensional COMSOL Simulation of Heavy-Oil Recovery By Using Electromagnetic Heating

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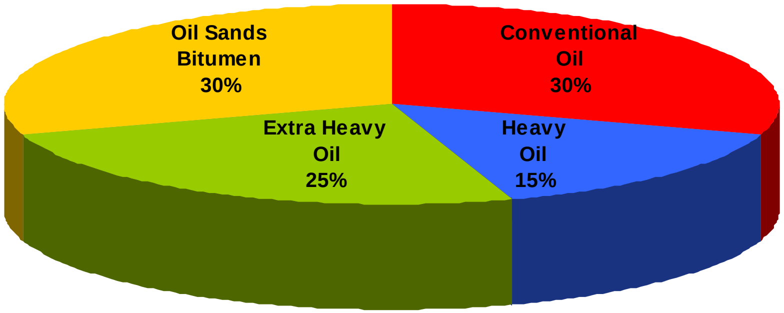
Why EM Heating



Process	Typical Ult. Recovery % OOIP
Steam (Drive and soak)	50-65
Combustion	10-15
SAGD	>60
Various EM	Like steam

- EM offers a wider range of application than steam injection
- EM heating has never been optimized
- Need for unconventional technology to recover hydrocarbons from non-conventional reservoirs

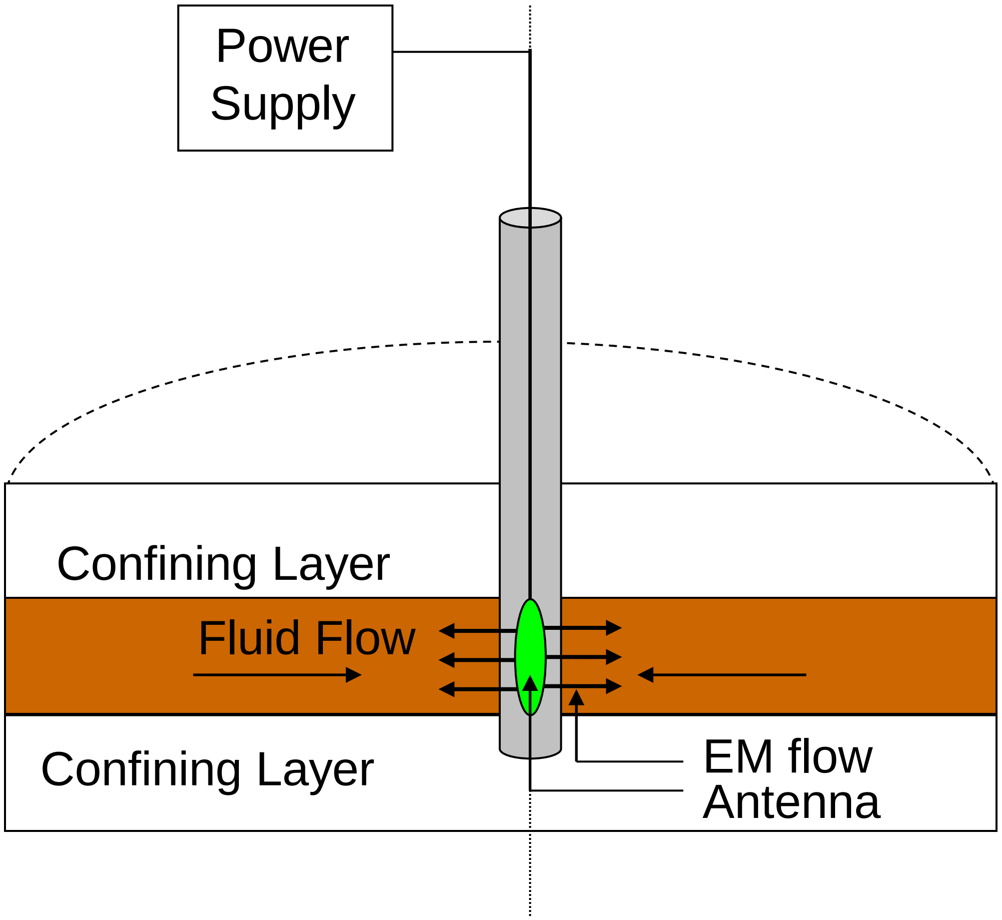
Why COMSOL

- Flexible for coupling ***Multiphysics***
- Easy EM heating

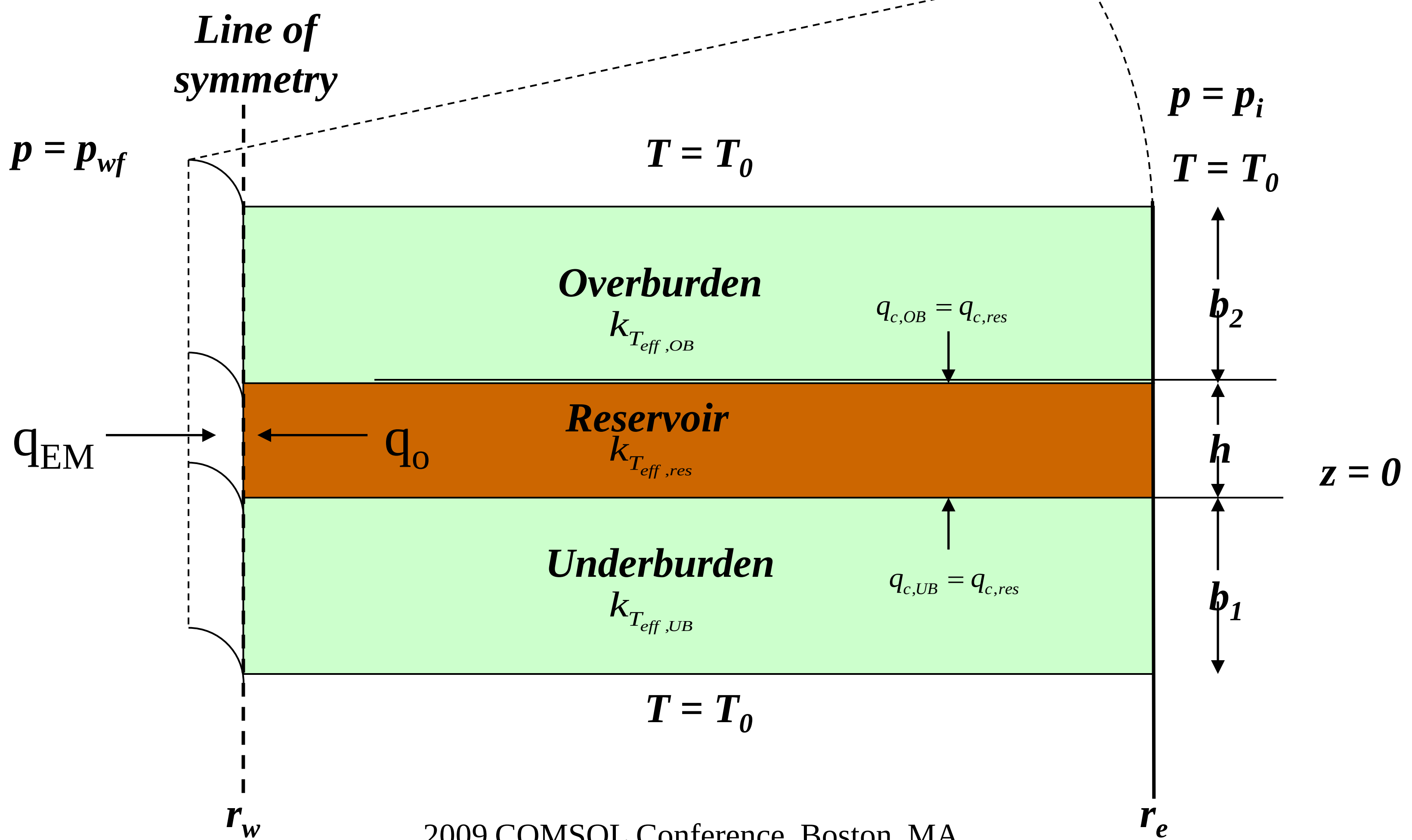
- No commercial simulator available up to date to model environment for complex ***PDE*** formulation
- Property updating via ***Sub-domain Expressions*** and ***Functions*** using the dependent variables
- No need for finite differencing formulation, more time to focus on the equations and physics

EM Heating Scheme

Schematic view of counter-current flow



Model Geometry and Boundary Conditions



Model Formulation

Assumptions:

- Single phase (oil)
- 3 layer 2D model with axial symmetry (r,z)
- Constant properties ($k, \rho C_t$), except oil viscosity (μ_o), and thermal conductivity (k_t) as a function of temperature
- Single heating well at $r = r_w$
- Electrical properties vary only with Temperature

Model Formulation

Assumptions:

- Fluid flow occurs only in the middle layer in radial direction

- Vertical heat loss is included

Model Equations

- Mass conservation equation

$$\frac{\partial}{\partial t}\left(\phi\rho_o\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r\rho_o u_o\right)=0$$

- Darcy's Law (Momentum Equation)

$$u_o=-\frac{k_o}{\mu_o}\left(\frac{\partial p_o}{\partial r}+\rho_o g\nabla z\right)$$

Andrade's Equation (1979)

$$\mu_o = De^{(F/T)}$$

- Energy conservation equation for middle layer (reservoir)

$$\left(\rho C_p\right)_T\frac{\partial T}{\partial t}=-\left(\rho C_p\right)_o u_o\frac{\partial T}{\partial r}+\frac{1}{r}\frac{\partial}{\partial r}\left(k_T r\frac{\partial T}{\partial r}\right)+k_T\frac{\partial^2 T}{\partial z^2}+\alpha q^r$$

Model Equations

- Electromagnetic source equation (antenna)

$$q_{EM}(r) = \frac{P_0 e^{-\alpha(r - r_w)}}{r}$$

where

$$\alpha = 2\omega\sqrt{\frac{\varepsilon\mu'}{2}}\left[\sqrt{1+\left(\frac{\sigma}{\varepsilon\omega}\right)^2} - 1\right]^{1/2}$$

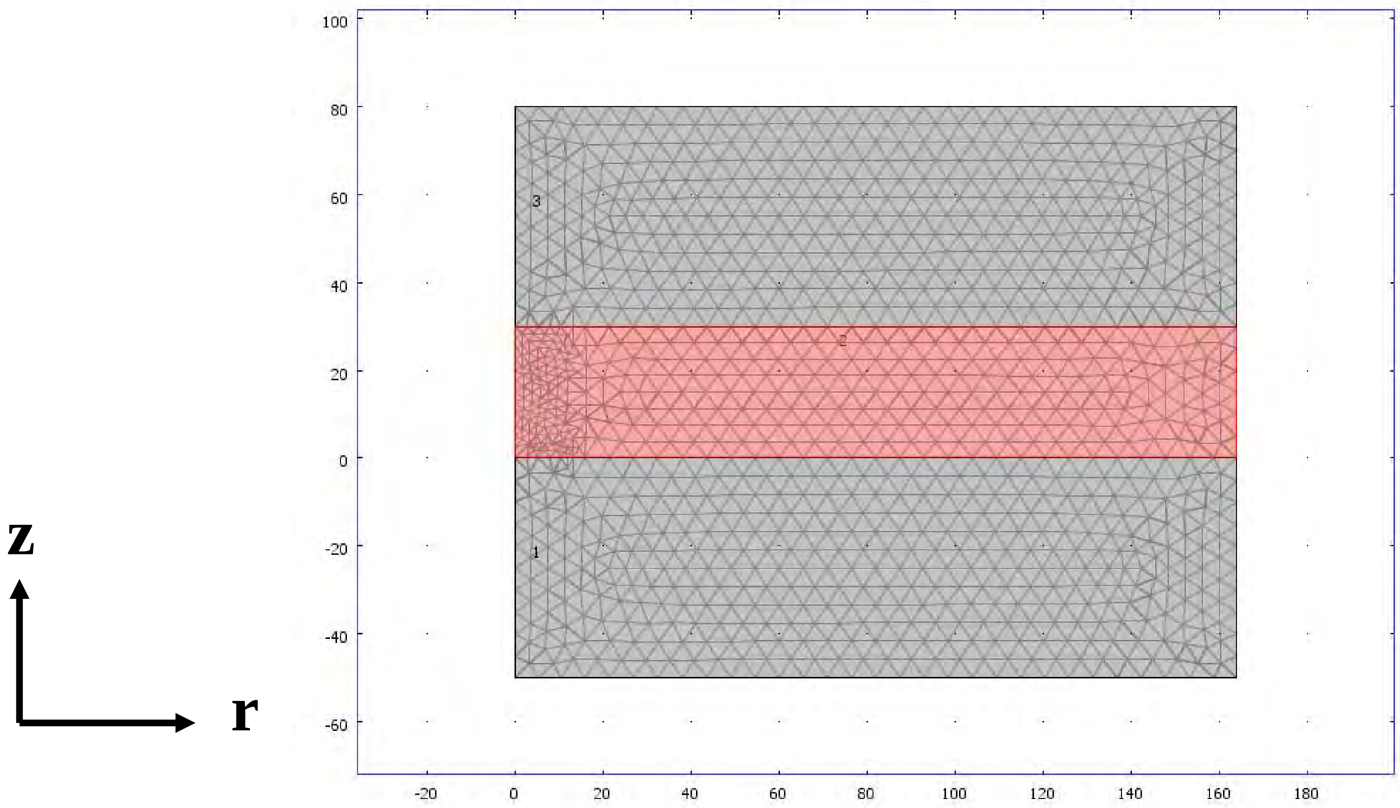
- Energy conservation equation for top and bottom layer

$$\left(\rho C_p\right)_T \frac{\partial T}{\partial t} = k_s \frac{\partial^2 T}{\partial z^2}$$

COMSOL Method

- PDE application, general form
- Primary variables: Pressure (p), and Temperature (T)
- Use of symmetry, and appropriate form of the equations in radial coordinates (r,z) to simulate flow to a wellbore
- Use of sub-domain expressions to update the oil viscosity (μ_o), and the absorption coefficient (α) with Temperature
- Integration of boundary variables to calculate the oil rate produced

COMSOL Simulation

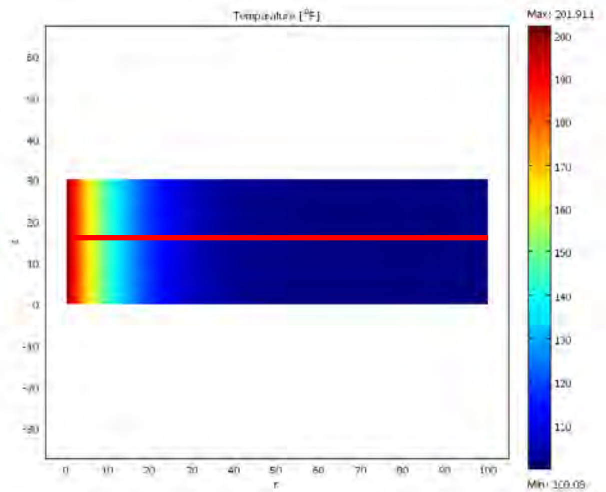


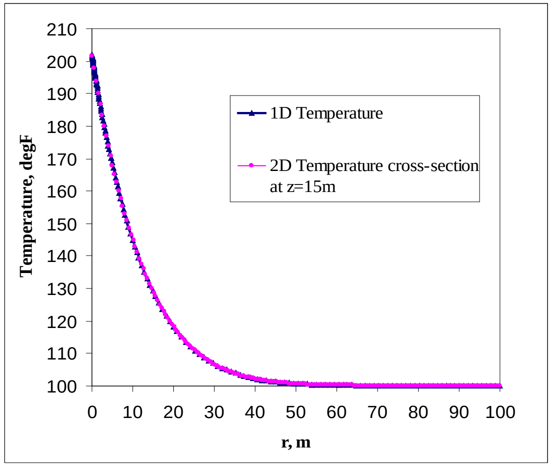
•Number of mesh elements: 2966

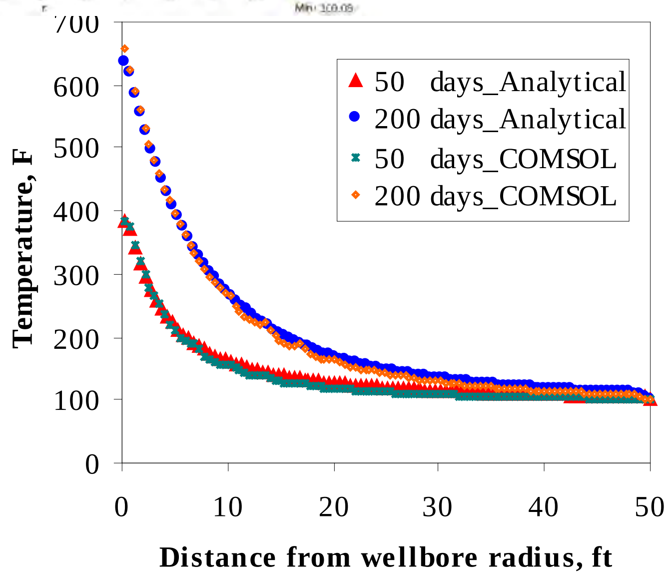
•Refined mesh near the wellbore

Results Simulation_ Validation

1. 1D EM heating solutions



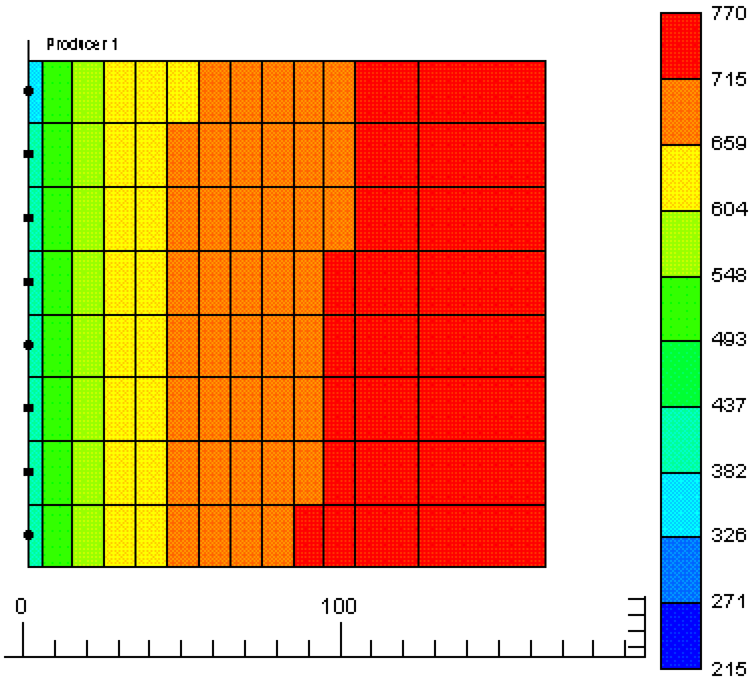


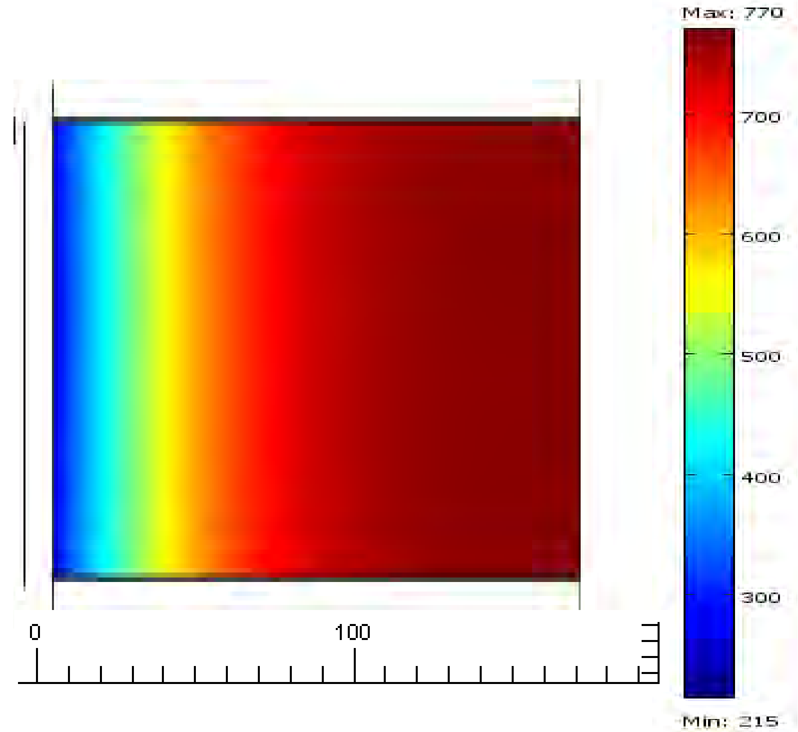


Results Simulation_ Validation

2. 2D COMSOL vs. STARS (Reservoir Simulator)

Pressure @ t = 100 days

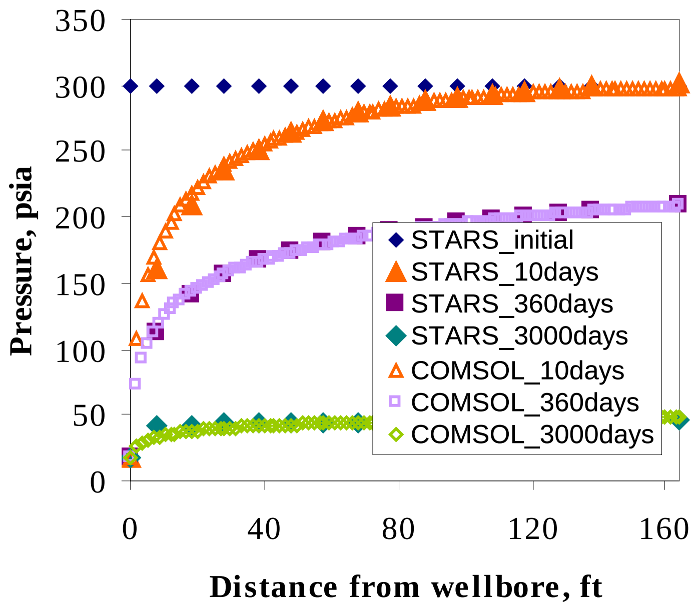




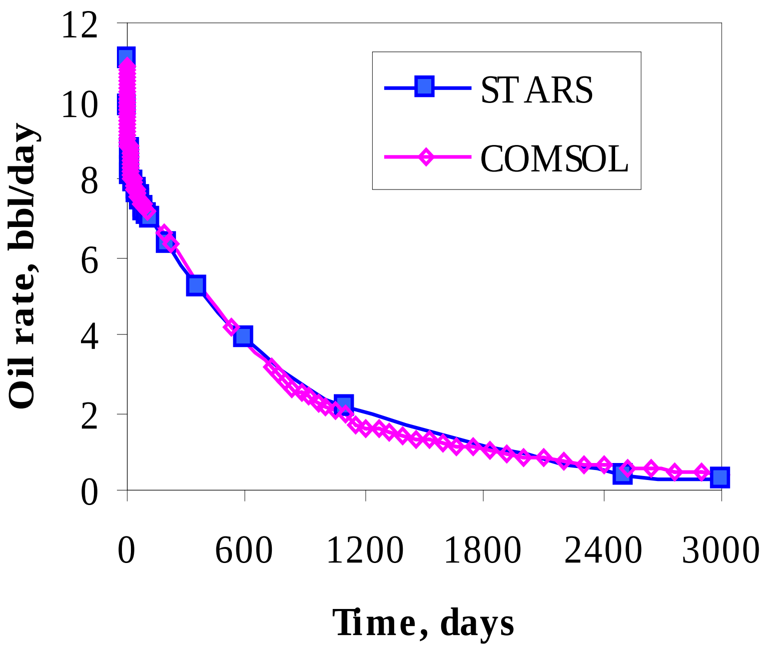
Results Simulation_ Validation

2. 2D COMSOL vs. STARS (Reservoir Simulator)_Cold Production Case

Pressure

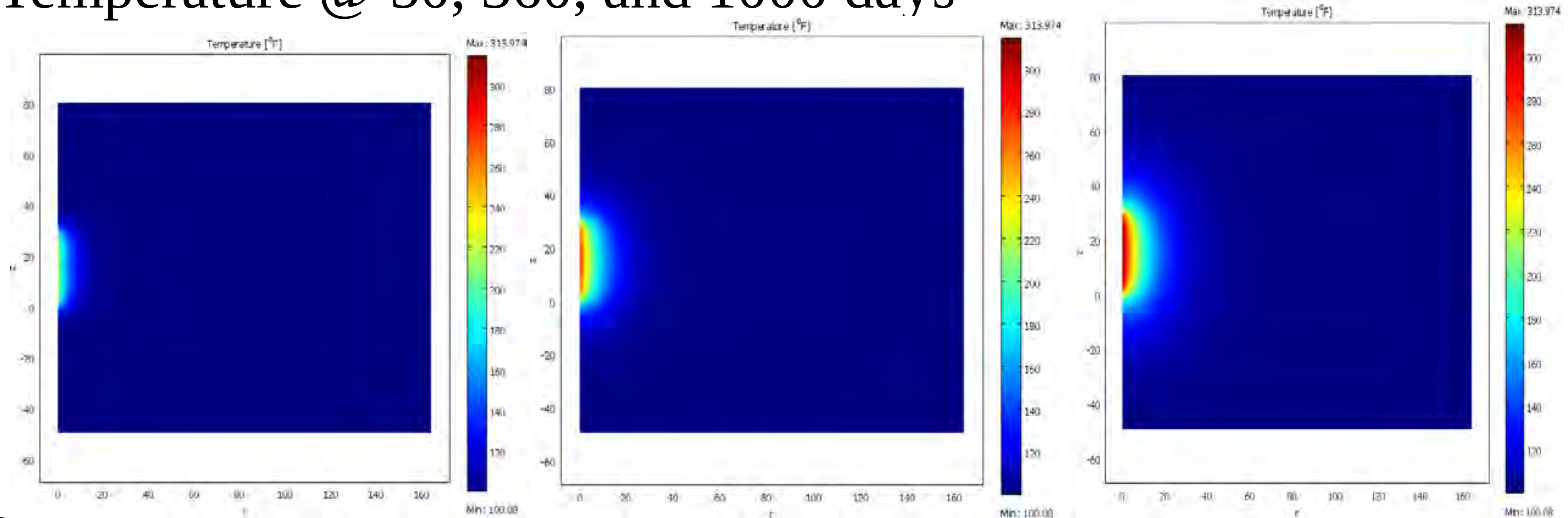


Oil rate

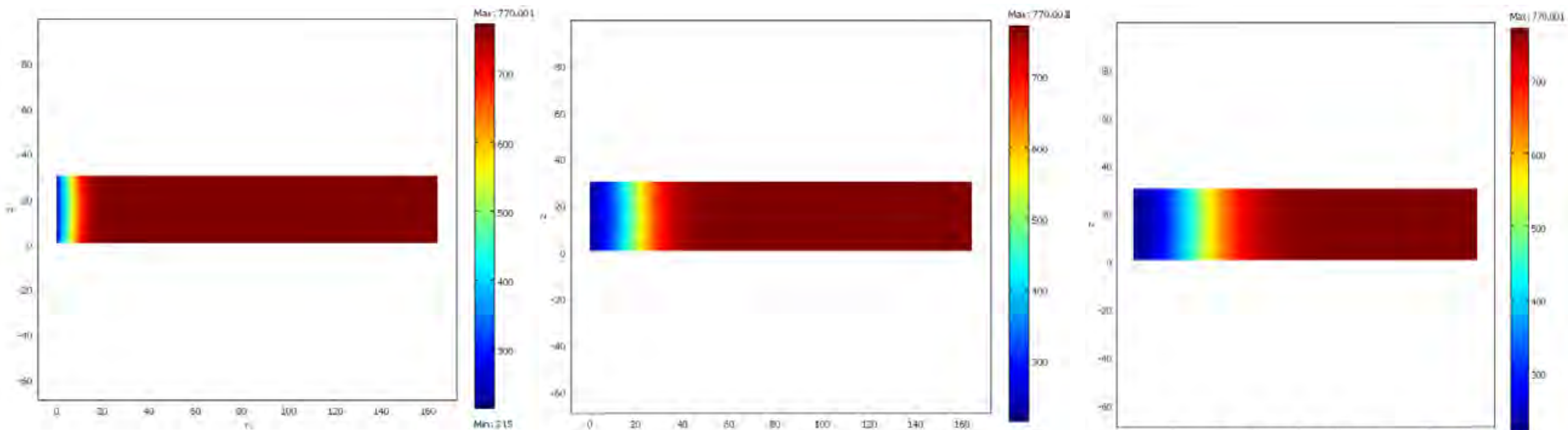


Results Simulation_ EM Heating

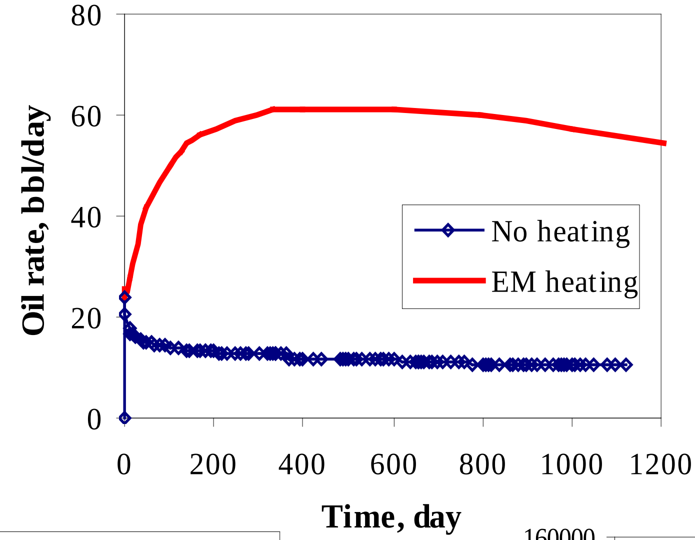
Temperature @ 50, 360, and 1000 days

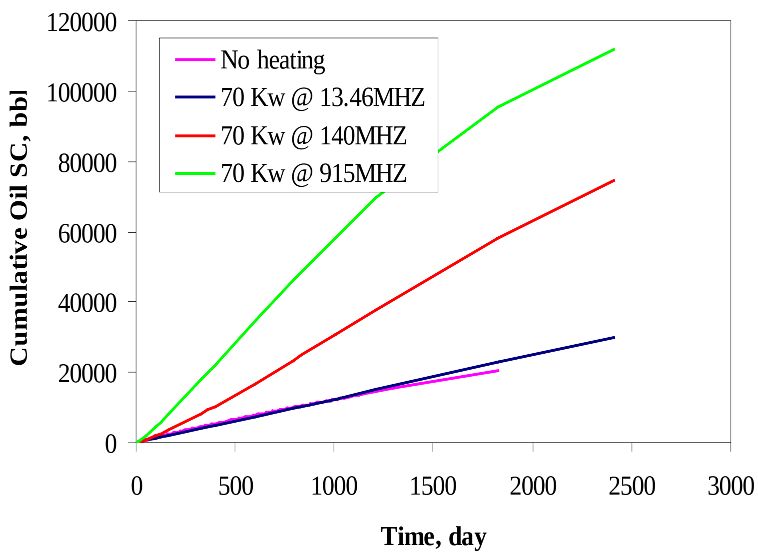


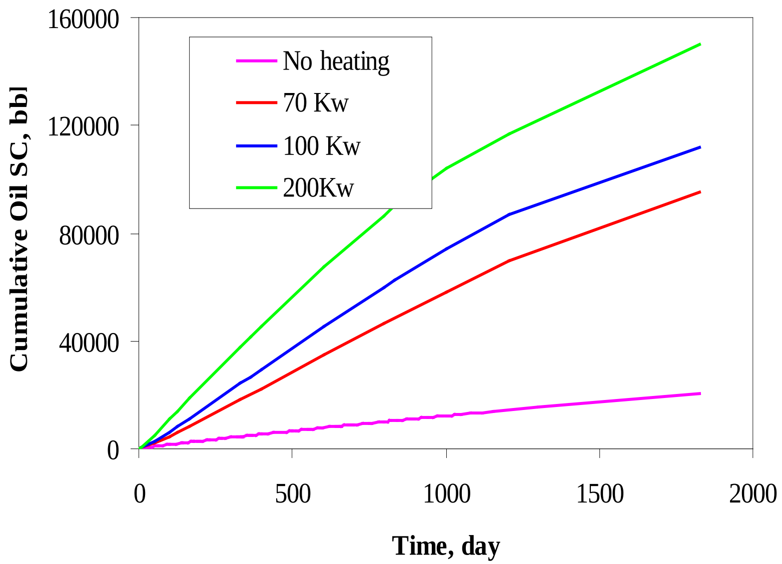
Pressure



Results Simulation EM Heating







Conclusions and current work

- COMSOL has been successfully used to model single-phase flow of heavy oil by EM heating
- COMSOL implementation was validated with analytical solutions.
- Comparison with a commercial reservoir simulator results for a cold fluid production case showed good agreement
- This work is currently being extended to model multiphase flow during EM heating