UNIVERSITY OF CAMBRIDGE

SHALE OIL EXTRACTION AND CO2 SEQUESTRATION BY A NOVEL METHOD OF HOT GAS INJECTION

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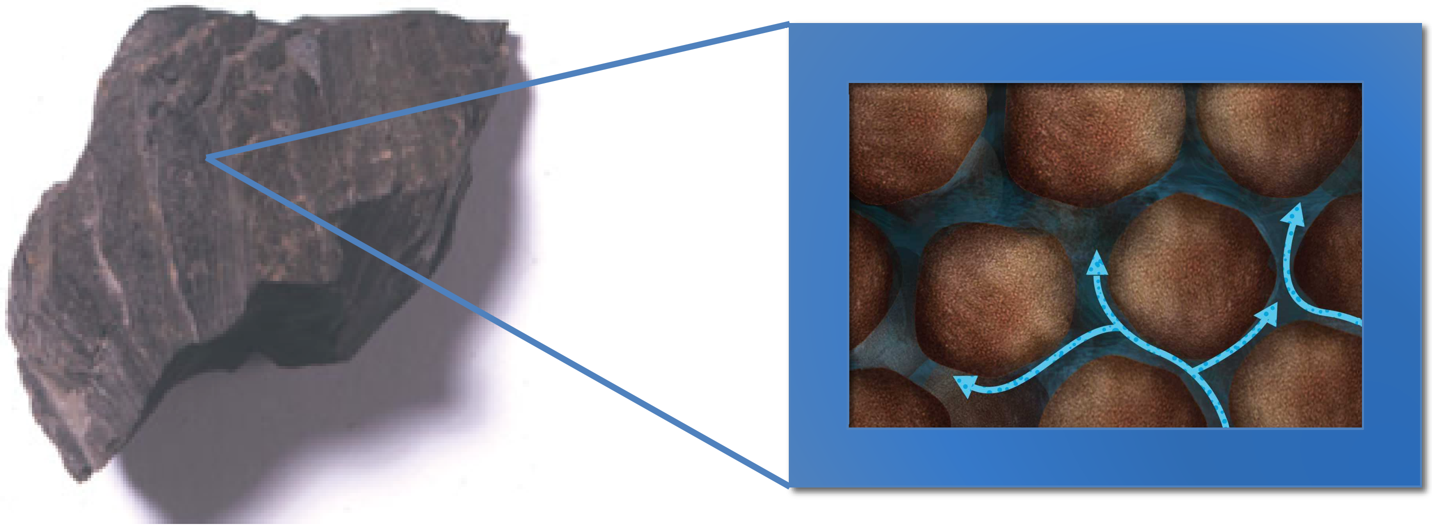
What is Shale Oil?

- Shale rock contains organic material called **Kerogen**
- When you heat it, Kerogen decomposes to **Oil** and **Gas**



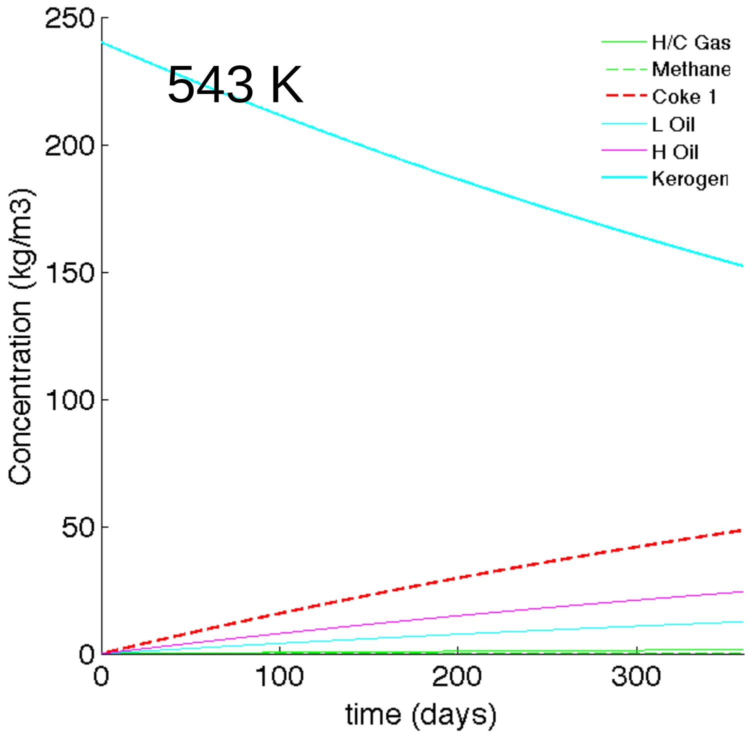
$O(10^{-6}m)$

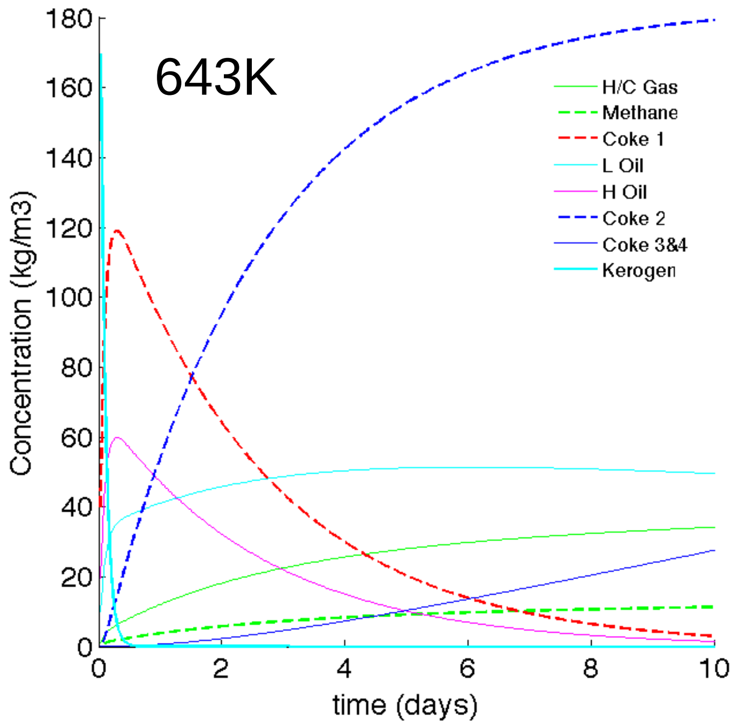
- There are about 2 - 4 trillion barrels worth of shale oil in the USA alone . . **400 years** of oil supply!!

Reaction Mechanism [Burnham and Braun (1991)]

- Kerogen + Energy→ Heavy Oil + Light Oil + Gas + Char
- Heavy Oil + Energy → Light Oil + Gas + Char

- Light Oil, Gas and Solid residue **decomposition** reactions…





Novel (simple) Extraction Technique

- Inject **hot, pressurized CO_2** to heat shale underground (in situ heating)
- Current **inefficiencies** of extraction have a lot to do with
  - Large timescales for extraction due to conduction heating (3 – 5 years) [Fan et al. (2009), White et al. (2010)]
  - Inefficient thermal waves due to conduction heating (Low EROI)
  - Huge environmental costs (Retorting of Shale) [Brandt (2008)]
- **Gas injection** may solve these issues:
  - As a fluid it will travel relatively quickly through the reservoir
  - It will carry the thermal wave with it [Jupp & Woods (2003)]
  - It can be sequestered directly underground after heating

Governing equations [Chen et al. (2006)]

- **Multiphase flow** in a reservoir: Oil and Gas
- Darcy's Law to find phase velocities – (each phase)

$$V_\alpha = -\frac{kk_{r\alpha}}{\phi\mu_\alpha}\left(\nabla P_\alpha + g\nabla z\right)$$

- Mass conservation – (each phase)

$$\frac{\partial}{\partial t}\sum_j \phi\rho_\alpha S_\alpha y_{j,\alpha} + \nabla \bullet \sum_j \rho_\alpha y_{j,\alpha} \mathrm{u}_\alpha + \rho_\alpha S_\alpha D_{j,\alpha} \nabla y_{j,\alpha} + q_c = 0,\ \ j = 1, \ldots n_c$$

$$\text{″}_{j}\ y_{j,!} = 1,\ \ \text{for all } j \qquad \text{″}_{n}\ S_{!} = 1$$

Governing equations [Woods & Jupp (2003)]

- Dynamic Pressure Equation – (liquid phases)

$$\frac{\partial}{\partial t}\left(\frac{P}{T}\right) = \frac{k}{\phi\mu}\nabla\bullet\left(\frac{P}{T}\nabla P\right)$$

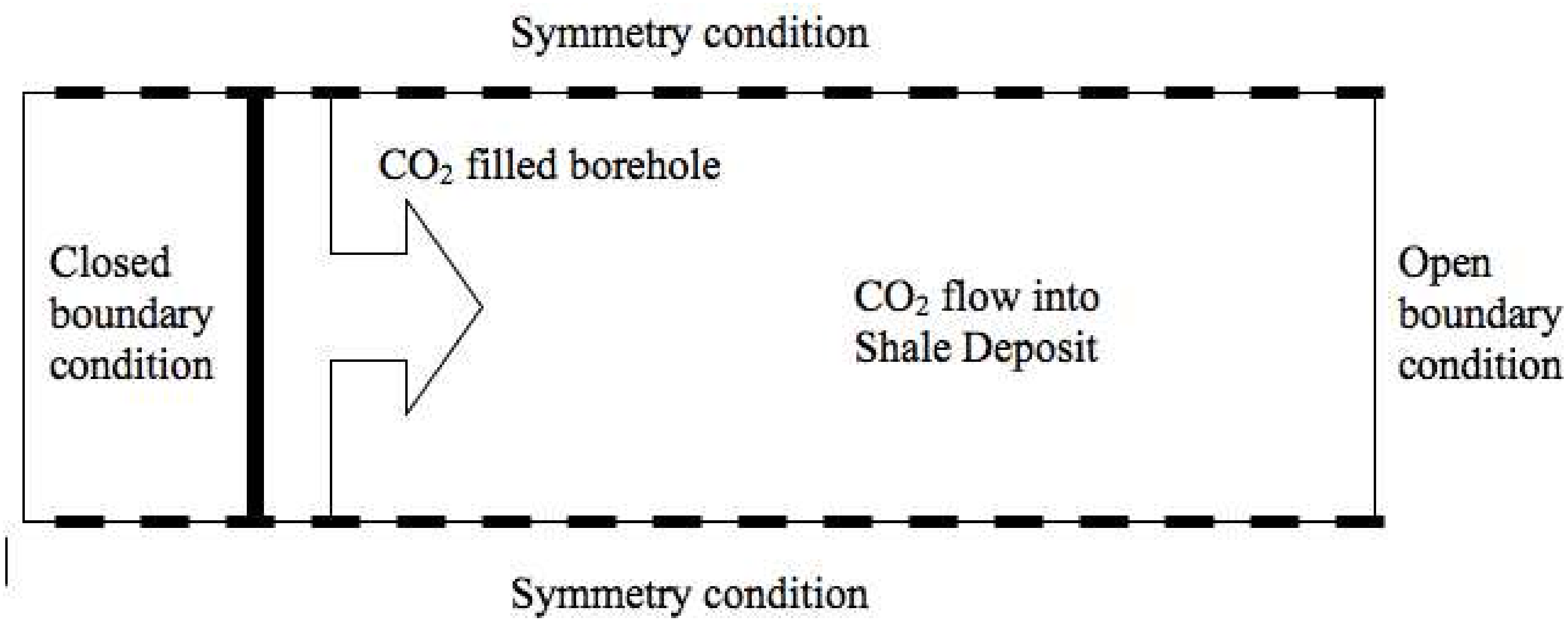
- Reservoir Energy/Temperature equation – (all phases)

$$\frac{\partial T}{\partial t} + \left(\frac{(\rho c_p)_f}{(\rho c_p)_m}\right)(Q/r)\frac{\partial T}{\partial r} = \frac{\alpha}{r}\frac{\partial^2 T}{\partial t^2} + QH_{rxn}$$

Ratio of specific heat capacity of fluids to that of solids

Problem Description

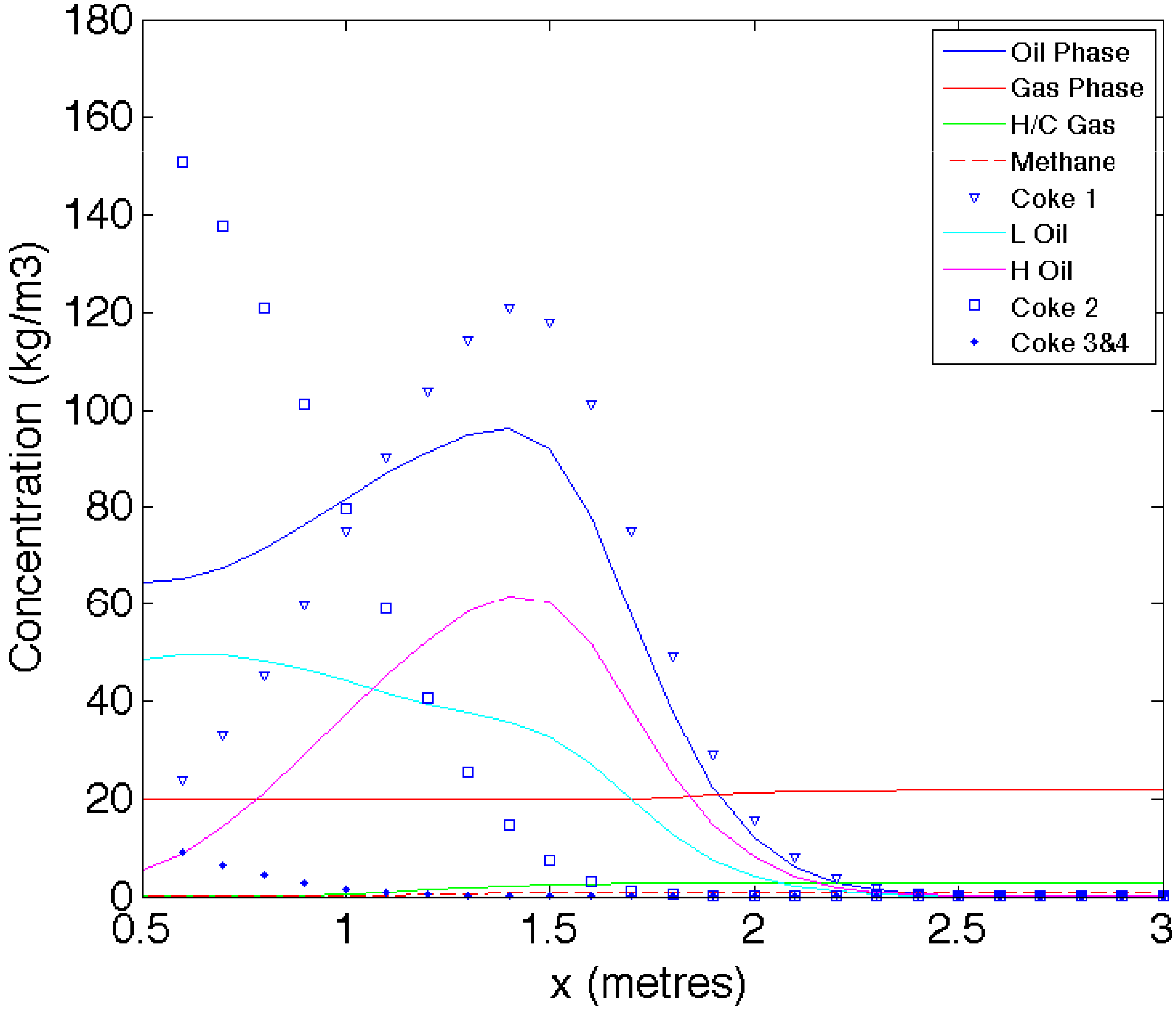
- 1D Cylindrical coordinates
- **Injected CO2:** 230 bar, 573K
- **Reservoir:** Porosity = 0.1, Permeability = 5mD,
  Richness = 30 gal/ton, Pressure = 100 bar



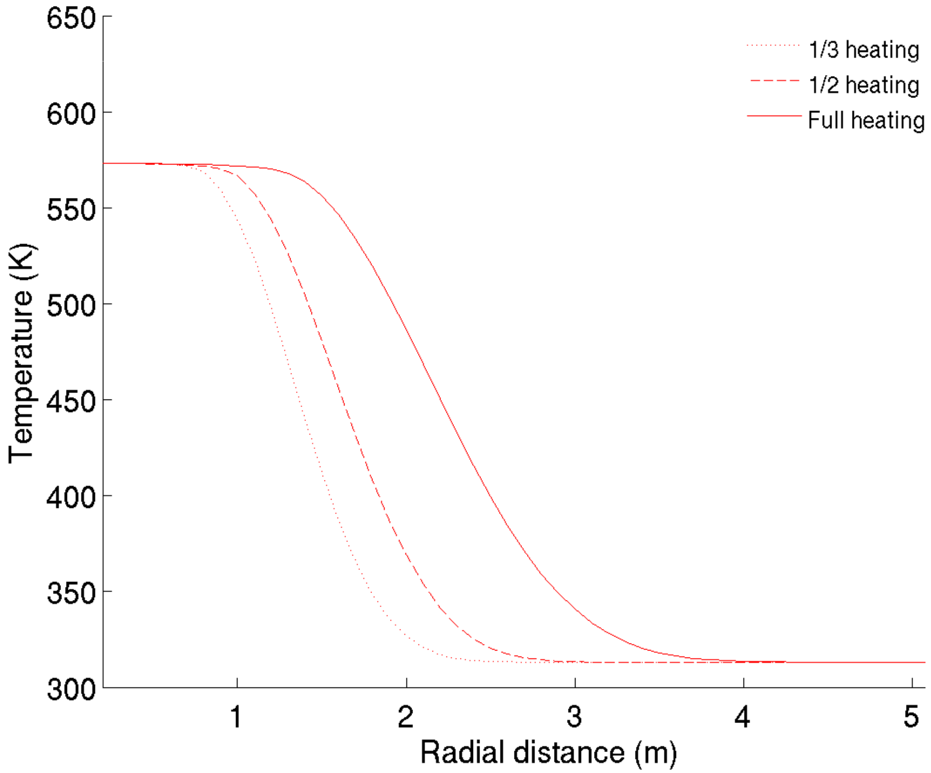
Numerical Method

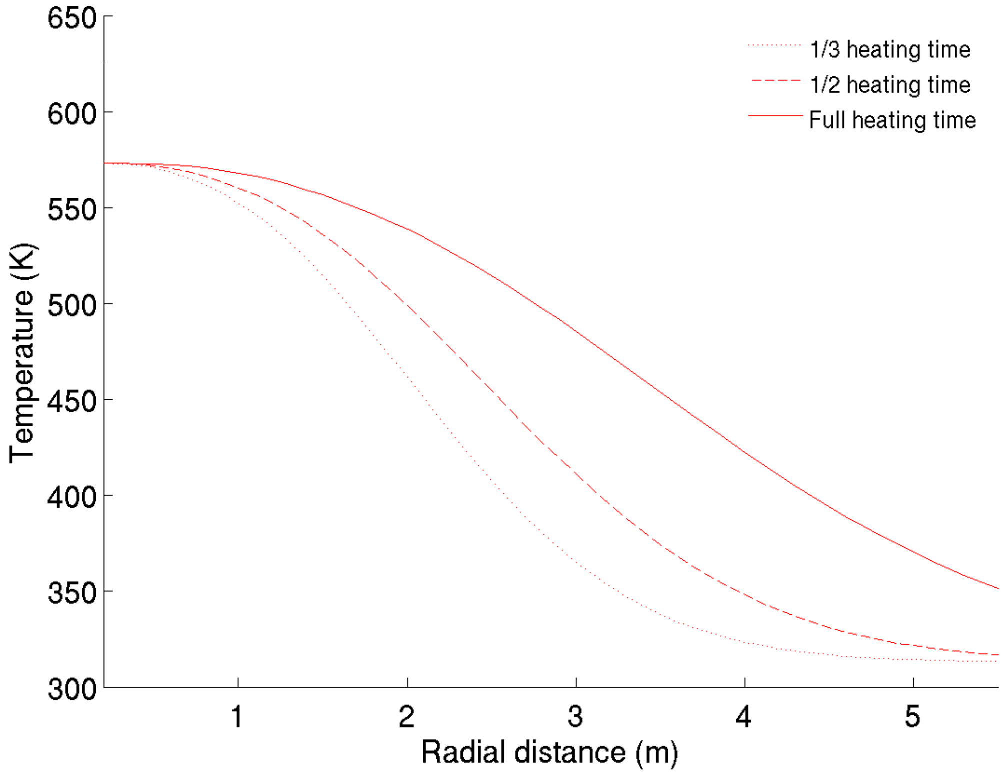
- Discretized PDE’s and fed them as ODE’s to **DVODPK**
- Second order **upwind differencing** for advection terms
- Second order **centered differencing** for diffusion terms

Base Case – 20 days of heating



Base Case – 20 days of heating

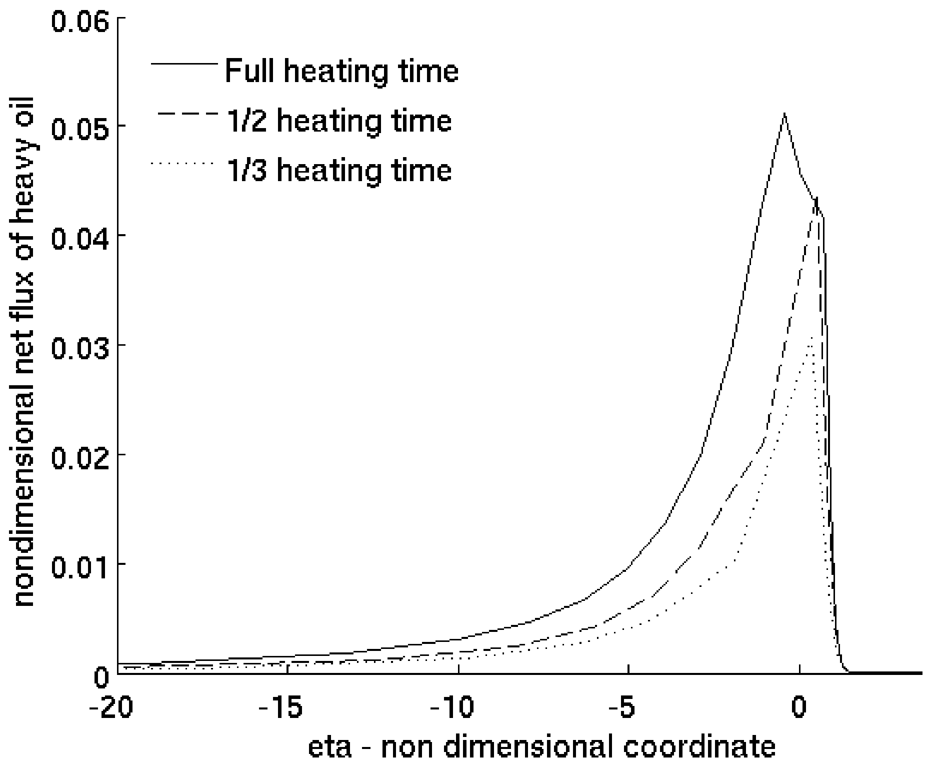


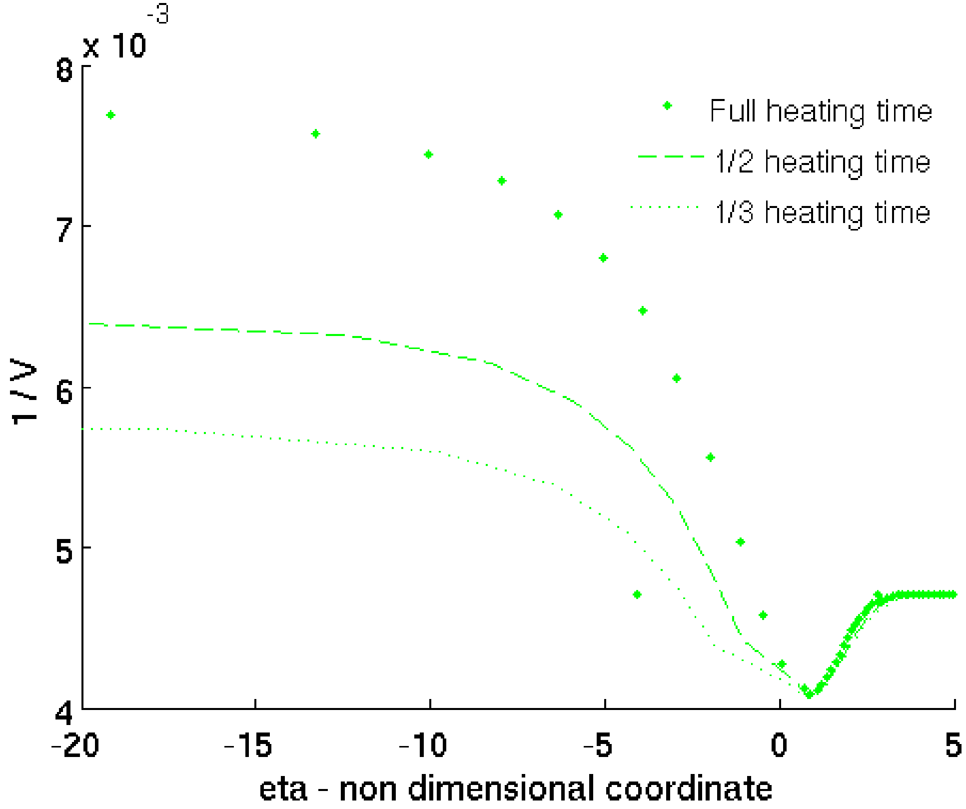


- Steep thermal profiles for gas injection (**LEFT**)
- Long thermal tails for conduction (**RIGHT**)

Base Case – 20 days of heating

- Non dimensional flux of oil (**LEFT**) peaks at thermal wave front

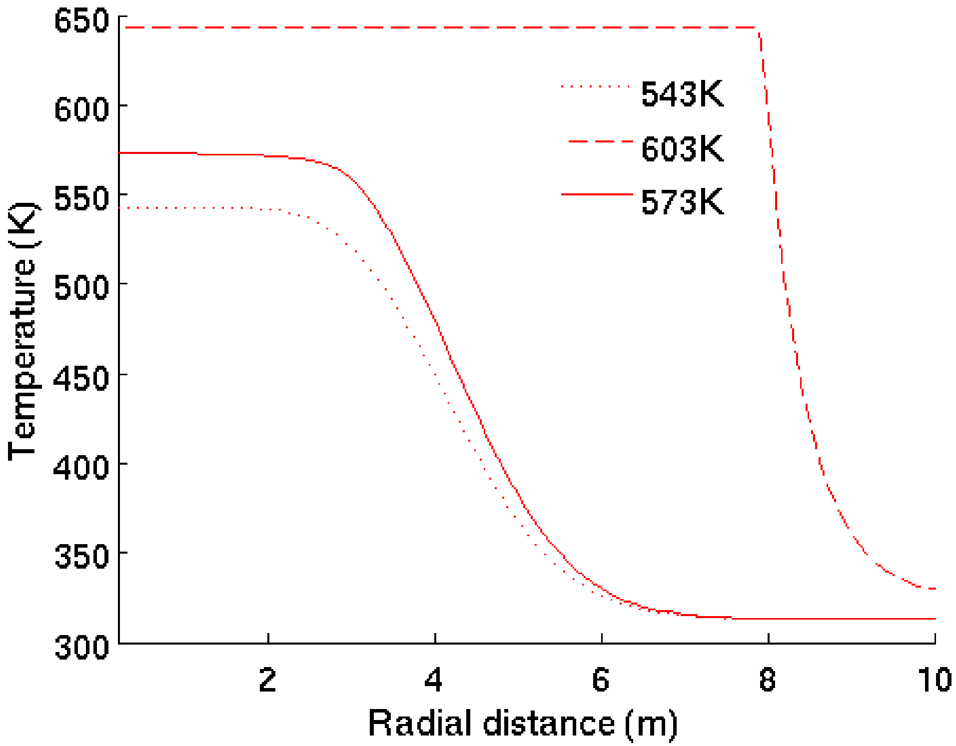


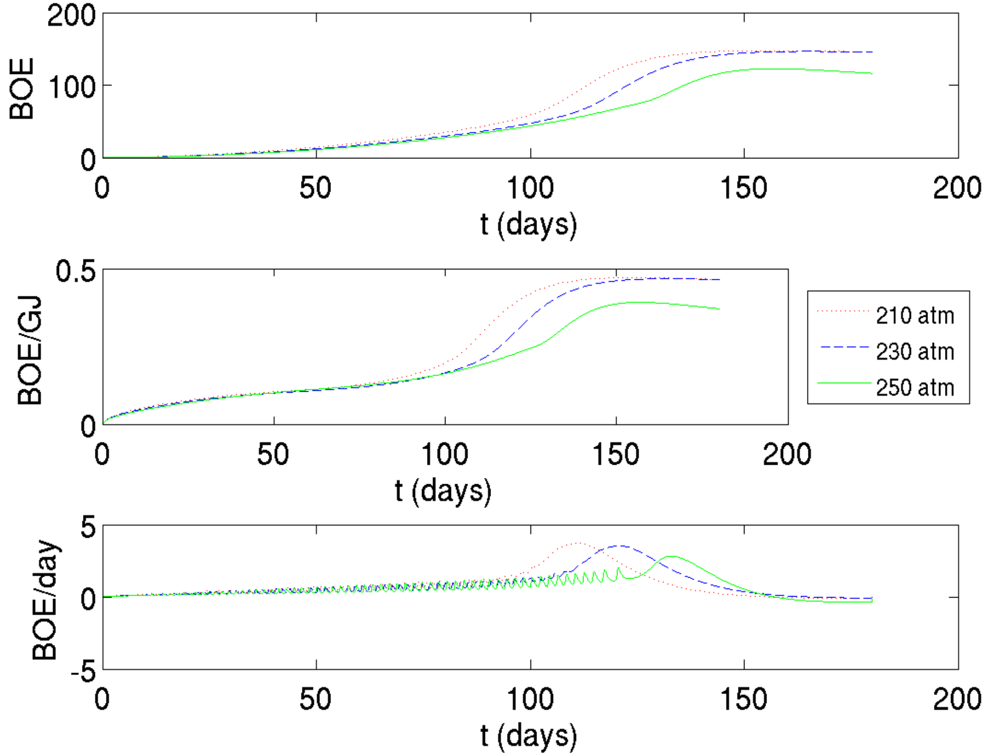


- [Thermal wave speed] / [Fluid speed] (**RIGHT**) minimum follows reaction / thermal front

Temperature variations

- Very high temperatures form **strong convective wave**

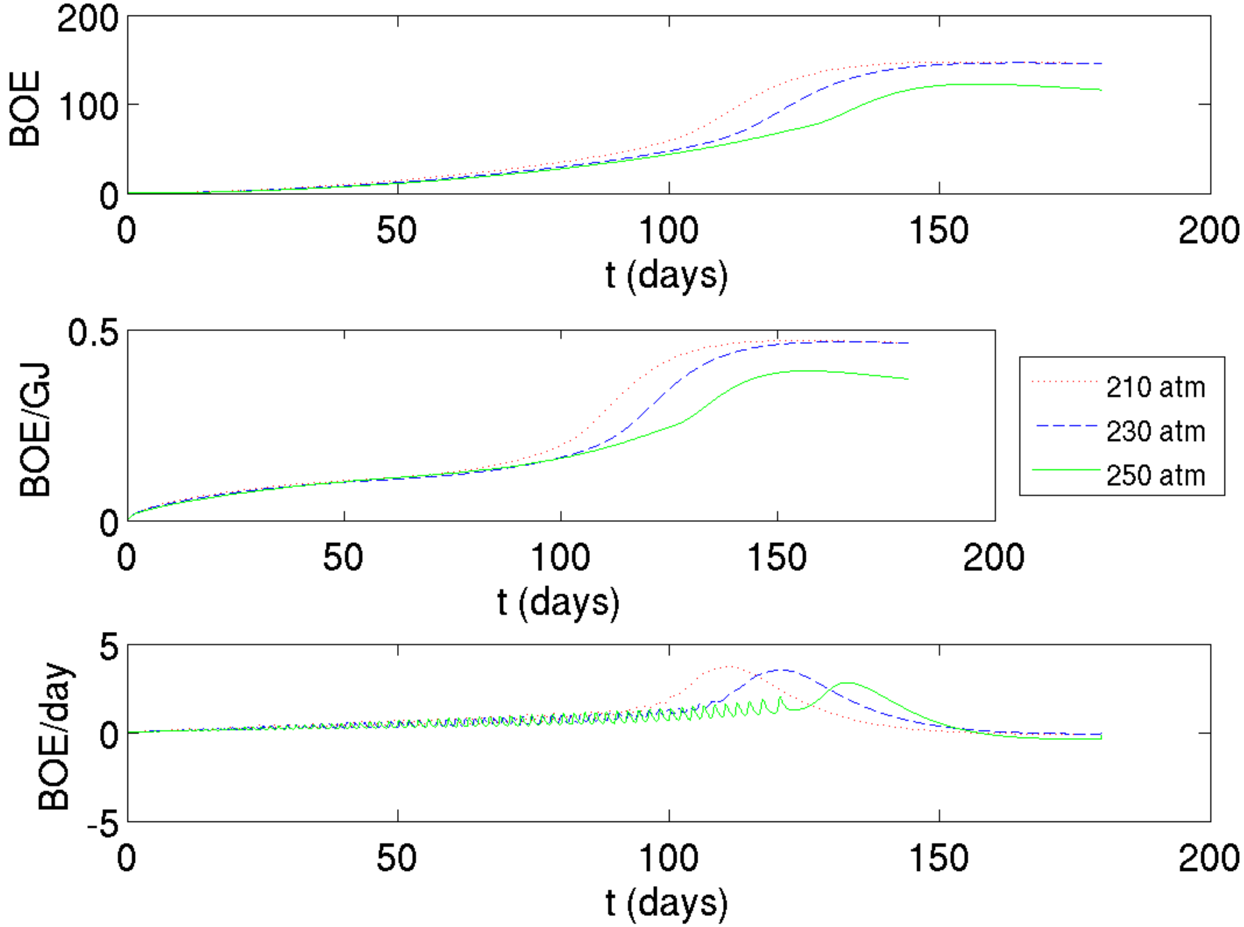




- Lead to rapid **heavy oil decomposition**

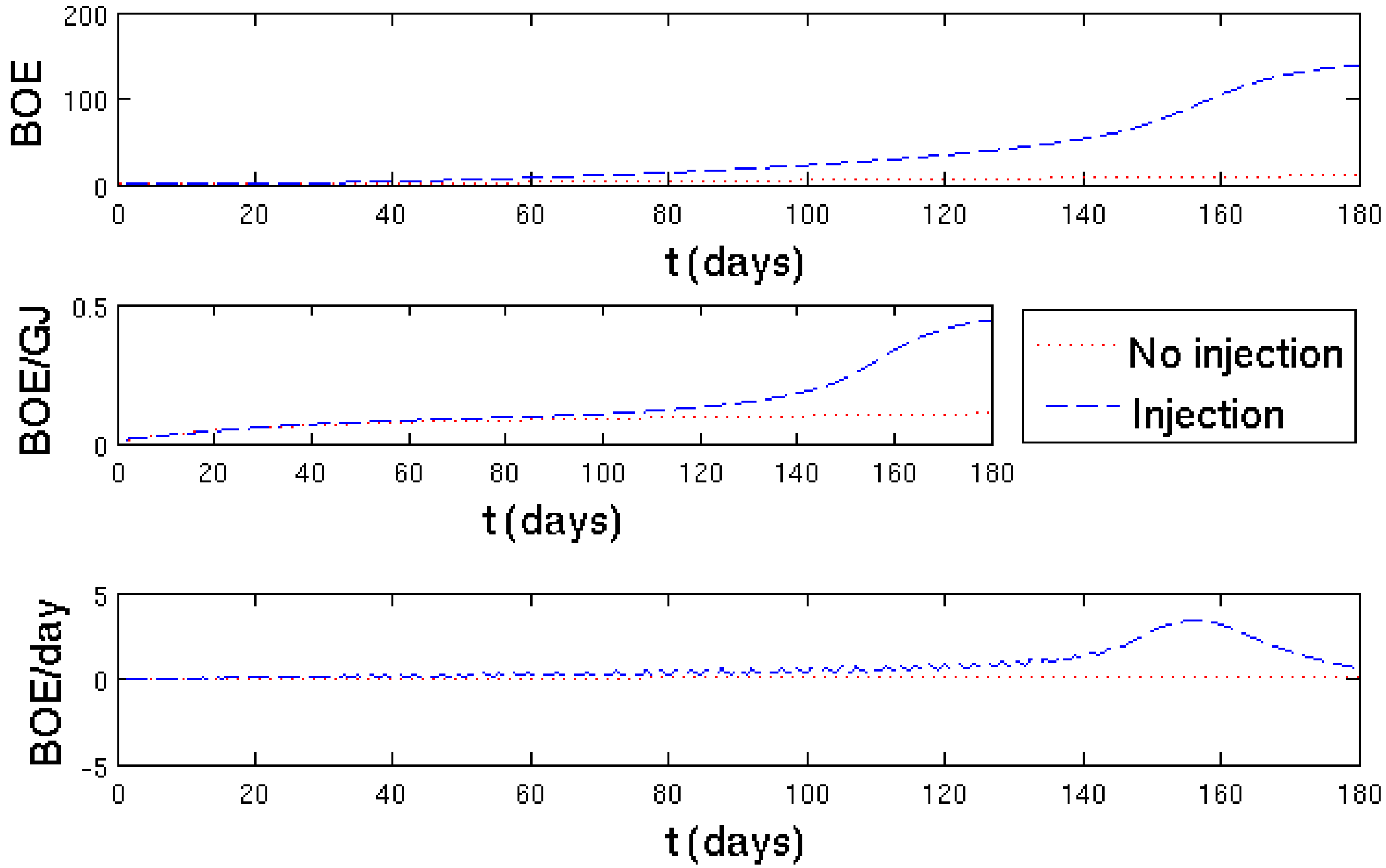
Pressure variations

- High pressures lead to **quick extraction** of oil but require **high energy injection** rates



Thermal conduction vs. Gas injection

- Efficiency graph: injection is **more efficient (EROI 6:1)**, extracts oil quicker.



Future Work

→ Performing a more detailed **Sensitivity Analysis**

→**Lattice Boltzmann** method to explore interaction of shale products on a molecular level

→**In situ combustion** of organic solid residue to produce CO2 for heating other deposits

Thank you very much! Questions?

Bibliography:

1. Burnham and Braun (1991)
2. Chen et al. (2006)
3. Fan et al. (2009)
4. White et al. (2010)
5. Woods & Jupp (2003)

Closure Models [White et al. (2010), Chen et al. (2006)]

- **Permeability** = function(pore pressure, solid content)
- **Porosity** = function(pore pressure)
- **Relative permeability** = function (volume saturation of oil)