Let’s Combust - Fossil Fuels

And if there is bit of time left

Fossils

Energy Resources Engineering
Institute for Computational & Mathematical Engineering
Stanford University

Woudschoten 2015
HEAVY OIL
Decline of easiest to produce reservoirs pushes industry to

- Invest in Enhanced Oil Recovery (EOR) techniques
- Move into more hostile environments (off-shore, North)
- Explore and produce non-conventional oils, including heavy oils
Worldwide Heavy Oil Production by Country (www.slb.com)
Worldwide Heavy Oil Resources by Country (www.slb.com)
**Heavy Oils Require Stimulation**

All heavy oils

1. are rather difficult to produce
2. are gucky

**Thermal stimulation common**

- Steam Flooding
- Steam-Assisted Gravity Drainage
- In-Situ Combustion
GIVE IT SOME AIR AND COMBUST

1. Burned out zone
2. Air and vaporized water
3. Burning front/combustion zone
4. Coking zone
5. Steam/vaporizing zone
6. Condensing zone/hot water
7. Oil bank
8. Cold combustion gases
Great Idea, Big Headache

An attractive method for unlocking heavy-oil resources:

- Steam generated in-situ
- Oil upgrading possible

Multiple phases, multi-components, thermal, compressible, strongly nonlinear,
And most definitely and strongly multi-scale
Lab Tools & Virtual Lab Tools

- Kinetic Cells (100-5000 psi)
- Combustion Tube (up to 100 psi)
- X-ray CT scanning

- Virtual Kinetic Cell (homebrew)
- Virtual Combustion Tube (homebrew)
- 2D small scale models (homebrew, commercial)
- 3D industrial scale reservoir model (in collaboration with 3DSL)
Can we Cluster Reactions?

Quite often we see three regimes

**Low Temperature Oxidation Reactions**
Forms heterogeneous gas/liquid of partially oxygenated compounds and few carbon oxides. Increases oil viscosity and fuel content

**Cracking/pyrolisis**
Fuel "coke" formation (solid hydrocarbon, H/C 0.6-2), CO₂, CO

**High Temperature Oxidation**
Surface (and gas?) reactions of solid fuel. Highly exathermic Needs to be maintained by sufficient air flux
What’s Your Favorite Scheme?

Crookston Model (Crookston 1979) – no LTO/HTO distinction

Heavy Oil + O\textsubscript{2} → Inert Gas + Water  (Heavy Oil Oxidation)
Light Oil + O\textsubscript{2} → Inert Gas + Water  (Light Oil Oxidation)
Heavy Oil → Light Oil + Coke  (Heavy Oil Cracking)
Coke + O\textsubscript{2} → Inert Gas + Water  (Coke Oxidation)

Three Reaction Model (Dechelette 2006) – no light oil/heavy oil distinction

Oil + O\textsubscript{2} → Coke\textsubscript{1}  (Heavy Oil Cracking)
Coke\textsubscript{1} + O\textsubscript{2} → CO + CO\textsubscript{2} + Water + Coke\textsubscript{2}  (Low Temperature Oxidation)
Coke\textsubscript{2} + O\textsubscript{2} → CO + CO\textsubscript{2} + Water  (High Temperature Oxidation)

In each project, model is selected/calibrated based on lab data
Primary reactions, phase behavior, flow behavior (viscosity reduction), interaction with rock
Modeling at the Lab Scale

Transport & energy equations (accumulation = flow + well + reaction)

\[
\frac{\partial C_i}{\partial t} + \nabla \cdot \mathbf{q}_i^m = Q_i^{m,\text{well}} + Q_i^{m,\text{reac}} \quad \text{(Mass transport for i-th component)}
\]

\[
\frac{\partial U_t}{\partial t} + \nabla \cdot \left( q^{h,\text{adv}} + q^{h,\text{cond}} \right) = Q^{h,\text{well}} + Q^{h,\text{reac}} \quad \text{(Energy transport)}
\]

Combined with a volume balance equation (pressure equation)

and thermodynamic equilibrium equations

Components typically include heavy oil, light oil, \( O_2 \), \( CO_2 \), \( CO \), \( H_2O \)

At lab scale chemical reactions modeled with Arrhenius

\[
\frac{dC_f}{dt} = K p_{O_2}^a C_f^b, \quad K = A e^{-E_a/RT}
\]

\( C_f \) = fuel concentration, \( p_{O_2} \) = partial pressure \( O_2 \), \( T \) = temperature

\( A \) = pre-exponential factor, \( E_a \) = activation energy
Hard to Resolve Front — Even in 1D

Resolving thin reaction front requires grid step sizes < 1cm

or *constant recalibration of reaction parameters*

Semi-affordable grid sizes in commercial reservoir simulation? ~ 10m
Challenge 1: Upscale Kinetics

Da number
- at laboratory scale \( \sim 10^{3-4} \)
- at reservoir scale \( \sim 10^{7-8} \)

Typical approach is to use the lab reaction models at the reservoir scale

.... and twiggle the pre-exponential factors and reaction rates

Because of scale mismatch this leads to strong grid sensitivity

\[ \text{Temperature [°C]} \]

\[ N = 600 \]

\[ N = 10 \]
Challenge 2: Upscale permeability

- ISC is essentially a gas drive:
  Highly mobile gases (air, steam and inert gases) displace hardly mobile oil
- Combustion/coking highly dependent on oxygen/steam transport

Challenge 3: Subgrid heterogeneity
Challenge 4, 5, 6, 7, ……

Sensitivity to initial oil, initial water, relative permeability,
Viscosity-temperature relations, phase behavior, …………. 
**What Were We Thinking (6-8 years ago)?**

“We will tackle ISC in 4D. Easy”

- **Adaptive Mesh Refinement**
  - to resolve critical fronts (combustion, steam, oil bank)
  - to capture important perm variations
  Required flexible AMR method and appropriate permeability/transmissibility upscaling techniques

- **Operator splitting**
  to separate fast kinetics from transport and reduce stiffness

- **Specialized kinetics integrators with phase change detection**
START

Pressure

Heat Eq.

Heat Eq.

Heat Eq.

Pressure

Temperature

Composition (reaction)

Composition (transport)

FINISH

Comp. conservation Eqs.

Comp. conservation Eqs.

Comp. conservation Eqs.

Comp. conservation Eqs.

Time level \( t_{n+1} \)

Time level \( t_n \)
(a) Without phase change detection.

(b) With phase change detection.
Is AMR with traditional models for kinetics an option at the reservoir scale?

- extreme coarsening/refinement to zoom in on combustion front
- high sensitivity to permeability variations leads to ragged front
- workload very skewed (fine cells much more expensive than coarse)
- time-stepping determined by fast kinetics, leading to severe stiffness

After musings and much work, we decided to approach kinetics differently....
Upscaling of Kinetics

Remove need to numerically model fast reactions

- Workload reduction for each time step
- Time step restrictions alleviated

Make kinetics treatment grid size insensitive

- Current "upscaling" done by twiggling until HTO sustained
- Calibration done on some grid size in 1D tests
- When grid step size changed, accuracy rapidly lost
Let’s Think a Bit

What are the essential kinetic impacts on

• kinetics related sources/sinks in PDEs
• phase behavior
• composition
• viscosity
• rock structure
Stuff is Deposited, Stuff Burns, Stuff is Heated, Stuff Moves

- 5-10% of the oil burns after fuel deposition
- Burn complete if air flux sufficient
- Remaining mobile oil flows downstream
Workflow based Upscaling for Grid Independence (WUGI) method

- Find the typical fraction of oil deposited as fuel (the “x”)
- Assume sustained High Temperature Oxidation
- Replace kinetics sources in governing PDEs with appropriate heat release and changes in compositions
- Delivery of oxygen critical: otherwise keep PDEs intact
- Adapt (relative) permeability, porosity, viscosity as appropriate

Fuel left behind for burning – fraction x
Mobile oil pushed down into oil bank

\[ t^n \rightarrow t^{n+1} \]

virgin oil
**X and Subgrid Heterogeneity**

<table>
<thead>
<tr>
<th>Case Number and Description</th>
<th>$S_{o_fuel}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. White Noise</td>
<td>8.1%</td>
</tr>
<tr>
<td>2. Low Permeability Middle Square</td>
<td>9.0%</td>
</tr>
<tr>
<td>3. Low Permeability Squares</td>
<td>9.7%</td>
</tr>
<tr>
<td>4a. Layered System ($K_1/K_2 = 2$)</td>
<td>8.1%</td>
</tr>
<tr>
<td>4b. Layered System ($K_1/K_2 = 10$)</td>
<td>8.7%</td>
</tr>
<tr>
<td>5. Layer 1 of SPE 10 [23]</td>
<td>8.6%</td>
</tr>
<tr>
<td>6. Layer 51 of SPE 10 [23]</td>
<td>13%</td>
</tr>
</tbody>
</table>

Numerical experimentation shows sensitivities but not as strong as feared
In Quest for X, Lab and Numerics Support Each Other

kinetic cell experiments and numerical optimization

Combustion tube experiments and fine scale numerical validation

reaction models, reaction parameters

Field-scale Simulation

Upscaling. Match tube for range of grid sizes

Find equivalent effects, adjust parameters
In One Dimension All Looks Fine

Upscaled ISC model predicts same front location as fine-scale kinetic simulation
Two Dimensions Also OK

Homogeneous permeability, porosity (0.36) and initial oil saturation (0.4)
Upscaled model predicts similar front location as fine-scale kinetic model
Coarsening It Up a Bit More

Front location still predicted correctly by the upscaled model
-> shows no or low grid sensitivity

Kinetic model shows excessive fuel generation and reduced front speed
Oil saturation (upscaled model simulation)

Oil saturation (kinetic model simulation)

Permeability field
**Quenching from Choking**

Small scale heterogeneity causes combustion to quench - coarse scale simulation does not capture this behavior
Sustained Front

Permeability field

Oil saturation

Gas saturation

50X50

10X10
Schlumberger successfully applied WUGI to Suplacu field in Romania. Simulations were done using an improved fuel model in relatively homogeneous permeability fields.
We should relax sustained HTO assumption

Minimal Air Flux threshold is empirical (Nelson 1961, Nodwell & Moore 2000)
Extinction/ignition studied using a Virtual Kinetic Cell (Kristensen & Gerritsen, 2008)
Fuel deposition to vary locally and as function of air flux

What impacts do subgrid scale heterogeneities have?

Does the combustion front "finger" or is it relatively smooth?
Does "choking" occur (swelling oil phase, solid fuel deposition) when heat advection dominates?

What are next critical modeling issues?

Viscosity and relative permeability relations