Current Research in Heavy Oil Modeling

Zhangxing Chen

University of Calgary
Xi’an Jiaotong University
Outline

• Research Background

• Current Research on Heavy Oil Modeling

• Current Research of my Group
Modeling and Simulation Applications

- Resource exploration
- Resource evaluation
- Resource recovery process design and optimization
- Production, prediction and management
Integrated Basin/Reservoir Simulation

From Basin Modeling to Reservoir Filling to Reservoir Simulation
Basin Modeling

- Study of burial of sediments
- Study of thermal evolution of these sediments
- Study of Generation, migration, and preservation of hydrocarbons
Reservoir Filling

- Fluid continuity
- Fluid compartments
- Charge history
- Oil quality
- Compositional equilibration
Reservoir Simulation

- Prediction of future performance of a field
- Finding ways and means to optimize oil recovery
Recent Books

- Computational Methods for Multiphase Flows in Porous Media
  - Year 2006
  - Z. Chen, G. Huan and Y. Ma
  - 1st Edition Out
Recent Books (cont’d)

- Reservoir Simulation: Mathematical Techniques in Oil Recovery
- Year 2007
- Z. Chen
- NSF Summer School
- 1st Edition Out
Recent Books

• Finite Element Methods and Their Applications
• Z. Chen
• Year 2005
• Over 1,500 copies sold
• Worldwide Texts and Scientific Research Reference
• Research Background

• Current Research on Heavy Oil Modeling
Outline

• Why? – Importance of the Research
• Enhanced Recovery Methods:
  - CSS (cyclic steam stimulation)
  - SAGD (steam assisted gravity drainage)
  - VAPEX (vapor extraction)
• Problems in Oil Recovery from Heavy Oil/Oil Sands
• Mathematical Tools and Modeling Challenges
Importance of the research

- Conventional oil & gas in decline and must be replaced by unconventional resources
- Reserves of unconventional oil are enormous worldwide and important to economy
- New technology needed to reduce risk and costs and make environmentally sustainable
- Mathematical modeling important for process design & optimization
Importance of the research (cont’d)

- About 10 trillion barrels of heavy oil resources worldwide
- Roughly triple the combined world reserves of conventional oil and gas
Global crude reserves by country

Canada, with 174 billion barrels in Oil Sands reserves, ranks second only to Saudi Arabia in global oil reserves

Source: Canadian Heavy oil Association
<table>
<thead>
<tr>
<th>Country</th>
<th>Mil BOPD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Russia</td>
<td>9.6</td>
</tr>
<tr>
<td>Saudi Arabia</td>
<td>8.5</td>
</tr>
<tr>
<td>USA</td>
<td>5.3</td>
</tr>
<tr>
<td>Iran</td>
<td>4.1</td>
</tr>
<tr>
<td>China</td>
<td>3.8</td>
</tr>
</tbody>
</table>
## Oil Classification

<table>
<thead>
<tr>
<th></th>
<th>Viscosity (cp)</th>
<th>Density (kg/m³)</th>
<th>Density (API)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conv. oil</td>
<td>&lt;100</td>
<td>&lt;934</td>
<td>&gt;10</td>
</tr>
<tr>
<td>Heavy oil</td>
<td>100-10,000</td>
<td>934-1,000</td>
<td>10-20</td>
</tr>
<tr>
<td>Bitumen</td>
<td>&gt;10,000</td>
<td>&gt;1,000</td>
<td>&lt;10</td>
</tr>
</tbody>
</table>
## Examples of heavy oil/bitumen

<table>
<thead>
<tr>
<th></th>
<th>API Range</th>
<th>Consistency Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold lake bitumen</td>
<td>11</td>
<td>1-30,000 cp</td>
</tr>
<tr>
<td>Peace river bitumen</td>
<td>9-10</td>
<td>200,000 cp</td>
</tr>
<tr>
<td>Athabasca bitumen</td>
<td>8-9</td>
<td>2-5 million cp</td>
</tr>
</tbody>
</table>
What is oil sands?

• Composition
  ▪ Inorganic material (75-80%, of which 90% quartz sand)
  ▪ Water (3-5%)
  ▪ Bitumen (10-12%)

• Unconsolidated, crumbles easily in hands
The principal obstacle in heavy oil recovery is the high viscosity (>100 cp). Any reduction in viscosity will increase the oil mobility.

**Enhanced recovery methods of heavy oil reservoirs**

- **Thermal methods**
  - CSS
  - Steamflooding
  - Hot waterflooding
  - In-situ combustion (THAI)
  - SAGD

- **Non-thermal methods**
  - Waterflooding (polymers)
  - Chemical flooding
  - Immiscible CO₂ flooding
  - Solvents injection
  - VAPEX
Enhanced recovery methods: CSS

- CSS was accidentally discovered in 1957 when Shell Oil Company of Venezuela was testing a steam drive in the Mene Grande field.
Problems in oil recovery from oil sands

- In-place hydrocarbons (bitumen): too viscous and thus immobile.
- No communication between injection and production wells.
- Oil sands in shallow formations that do not contain superimposed injection pressures.
Partial solutions

- The viscosity can be lowered by application of heat in the form of:
  - Steam injection
  - In situ combustion
  - Conduction heating
  - Electrical heating
  - In situ upgrading
Oil phase effective permeability is a control on oil flow rate.

\[ U_o = -\frac{k_o}{\mu_o} \nabla (P_o - \rho_o g z) \]

Oil phase viscosity is the other.
Partial solutions (cont’d)

The lack of communication between injection and production wells can be rectified by:

- Fracturing
- Use of steam stimulation of individual wells
- Use of an existing bottom water zone linking the wells
Partial solutions (cont’d)

- Insufficient overburden is related to injection pressure requirements:
  - Reduction of well spacing to compensate for overburden
  - Use of horizontal wells

Source: http://www.cnrl.com/assets/north_american_crude_oil_and_liquids/thermal/
Enhanced recovery methods: SAGD

- CSS low recovery rate: 30% of initial oil in place
- Relatively new thermal concept: SAGD (steam assisted gravity drainage) by Butler in 1977-78
SAGD (cont’d)

- Uses heating for viscosity reduction
- Drive energy comes from gravity
- Process is driven by heat transfer between steam and cold oil
- Heat can pass through rock grains
- Thin shale layers are not a big barrier to heat transfer
• Up to 70% recovery
• Commercial steam/oil ratio under favorable conditions
• High operating costs and environmental impact
Enhanced recovery methods: VAPEX

• Similar to SAGD, VAPEX (vapor extraction) involves injection of light hydrocarbon vapors such as propane, butane, or mixture of them as solvent into a reservoir to dilate and recover bitumen (late Butler, 1989).
Enhanced recovery methods: VAPEX (cont’d)
Unresolved issues & challenges of VAPEX

- Lower oil rate than SAGD
- Loss of solvent to untargeted zones
- Accumulation of non-condensable gas in the vapor chamber
- Formation damage by asphaltenes precipitation
- Hydrate formation
### Examples of heavy oil/bitumen (cont’d)

<table>
<thead>
<tr>
<th>Type</th>
<th>API Grade</th>
<th>Viscosity (cp)</th>
<th>Recovery Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold lake bitumen</td>
<td>11 API</td>
<td>1-30,000 cp</td>
<td>CSS</td>
</tr>
<tr>
<td>Peace river bitumen</td>
<td>9-10 API</td>
<td>200,000 cp</td>
<td>CSS</td>
</tr>
<tr>
<td>Athabasca bitumen</td>
<td>8-9 API</td>
<td>2-5 million cp</td>
<td>Mining/SAGD</td>
</tr>
</tbody>
</table>
Mathematical Tools

Journeying to the Reservoir

- Geomodels
- Upscaling
- Gridding
- Software Research
- Solvers & Parallelization
- Numerical Methods
Basic Models

• **Mass conservation**

\[
\sum_{j=1}^{N_p} \left( \int_V \frac{\partial}{\partial t} (\phi s_j \rho_j z_{ij}) dV + \int_S (\rho_j z_{ij} v_j) dS \right) + q_i = 0, \quad i = 1, 2, \ldots, N_c
\]

• **Darcy law**

\[
v_j = -\frac{1}{\mu_j} k_j (\nabla p_j - \rho_j g \nabla z), \quad j = 1, 2, \ldots, N_p
\]

• **Energy conservation**

\[
\int_V \frac{\partial}{\partial t} \left( \phi \sum_{j=1}^{N_p} \rho_j s_j u_j + (1 - \phi) \rho_{\text{rock}} C_p (T - T_{\text{int}}) \right) dV + \int_S (q_{i,h} + q_{i,c}) dS + Q_{i,c} + Q_{i,t} = 0
\]
Modeling Challenges

- Reservoir heterogeneities
- Heterogeneities in fluid properties
- Moving thermal fronts--thin
- For thermal-solvent processes, moving mobile solvent-rich oil layers are thin
- Dependence of relative permeability on temperature
- Phase behavior important (e.g., VAPEX)
- Presence of mud and shale layers, vertical flow barriers
- Geomechanics important (e.g., shearing of sand at chamber edges)
- Reactions (in situ combustion and upgrading)
- Thin diffusion
Modeling challenges (cont’d)

Reservoir NOT Homogeneous

Clearwater Core Samples
### Modeling challenges (cont’d)

<table>
<thead>
<tr>
<th>Location</th>
<th>API Range</th>
<th>Consistency (cp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold lake bitumen</td>
<td>11 API</td>
<td>1-30,000 cp</td>
</tr>
<tr>
<td>Peace river bitumen</td>
<td>9-10 API</td>
<td>200,000 cp</td>
</tr>
<tr>
<td>Athabasca bitumen</td>
<td>8-9 API</td>
<td>2-5 million cp</td>
</tr>
</tbody>
</table>
Modeling challenges (cont’d)

- Current simulation models do not have sufficient physics for heavy oil/bitumen.
- Need detailed simulation models and robust algorithms that can capture physics.
- Need fast tools because hundreds to thousands of simulations are run for process design and uncertainty analysis.
Outline

• Research Background

• Current Research on Heavy Oil Modeling

• Current Research of my Group
Current Research

- Mathematical models
- Simulation software
- Lab
- Validation and applications
- History matching and optimization

Journeying to the Reservoir

ADVANCED DYNAMIC MODELING AND SIMULATION
Current Research (cont’d)

• Design of new (oil, gas, and coal) recovery processes (lab experiments, pilot tests, and feasibility study)

• **Geo-modeling** (well logging, seismic data, geologist’s knowledge, lab experiments, and field data)

• Field scale modeling and simulation

• Risk analysis, optimization, and prediction
Our research group is becoming a major player and global leader in the modeling and simulation of:

- Heavy oil/bitumen recovery
- Underground coal gasification (UCG)
THAI Modeling
SAGD Modeling
Water+ASP Modeling
Important Players

- Federal funding agencies (6)
- Industrial sponsor members (9)
- Current students (31)
- Research associates and post-docs (4)
- Project manager
- Administrative and technical support staff
- A number of faculty collaborators at the University of Calgary and worldwide
Research Resources

- Research and commercial simulation software
- High performance computing hardware – IBM cluster
- Computer server room
- CMG simulation laboratory
- Visualization centre (i-Centre)
- Advanced oil recovery laboratories
HQP Training

4 Post Doctoral Fellows per year
Supervisors: Collaborators and Dr. Chen

12 PhD Students per year
Supervisors: Collaborators & Dr. Chen

Interdisciplinary Reservoir Characterization Program
MEng 24 Students per year

CHAIR PROGRAM

8 MSc Students per year
Supervisors: Collaborators & Dr. Chen
Multidisciplinary Program

- Mathematics and Statistics
- Computer Science
- Geology (Geophysics)
- Chemical and Petroleum Engineering
Lab Collaborators

THE CHAIR RESEARCH PROGRAM

Cold production: Dr. Ron Sawatzky

In situ Upgrading: Dr. Pedro Pereira

Phase behavior: Jalal Abedi

Relative Permeability: Dr. Mingzhe Dong

In situ Combustion: Drs. Gord Moore and Raj Mehta

EOR: Dr. Brij Maini
Chair Research (cont’d)

THAI Model

Complex Flow Due to Heterogeneous Geology

Modelling Complex Layers & Slanted Wells

Modelling of a Reservoir
Sponsors

• Federal support:
  - NSERC (Natural Science and Engineering Research Council of Canada)
  - AERI (Alberta Energy Research Institute)
  - iCORE (Informatics Centre of Research Excellence)
  - CFI (Canada Foundation for Innovation)
  - AAET (Alberta Advanced Education and Technology)
  - IBM CAS (Center for Advanced Studies) in Alberta

• Industrial participants:
  - Current: CMG, ConocoPhillips, IBM, Nexen, PetroCanada, CNPC-I, Shell, StatoilHydro, Synergia
Applications (cont’d)

Fluid mixing

- Unstable displacement
- Fingering, instability
- Advection, diffusion, gravity segregation, and viscosity
- Compositional variation
Demo 1 – Assessing development projects
Demo 2 – Management of reservoirs

Simulation with shales
Applications (cont’d)

- **Demo1** – Well architecture
- **Demo2** – Adaptive grids
- **Demo3** – Corner point correction
- **Demo4** – Streamlines
- **Demo5** – Fault treatment
Conclusions

• Thermal/solvent processes for heavy oil/bitumen are difficult to simulate. With sufficient physics and good geological characterization, significant improvement in modeling and simulation will be made.

• With all the new tools (gridding, solvers, parallelization, and computer hardware) significant improvements in simulation robustness and speed and optimization algorithms will be made.

• All these mean significant savings in capital costs.
Modeling challenges (cont’d)

Reservoir NOT Homogeneous