Geothermal Simulation Using MRST

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Introduction

- Hot underground aquifers are appealing resources for energy production and storage
  - Renewable 51 Always on 51 Available anywhere 51
- Viability depends a number of factors (Glassley [2010], Stober and Bucher [2013])
  - Efficiency, storage capacity, operational and drilling costs, legal regulations, ...
- Assessment requires solid system knowledge (Andersson [2007])
  - Aquifer/aquiclude geology, groundwater chemistry, flow properties, ...

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> Complexity and size typically renders numerical simulations the only viable option (O'Sullivan et al. [2000], Lee [2010], Stober and Bucher [2013])

Introduction

	Geothermal	Oil & Gas
Physical complexity		
Flexible gridding		
Realistic well modelling		
Efficient linear/nonlinear solvers		

Introduction

	Geothermal	Oil & Gas
Physical complexity	51	
Flexible gridding	55	
Realistic well modelling	55	
Efficient linear/nonlinear solvers	55*	

- Geothermal simulation software (COMSOL, ANSYS, SEAWAT, FEFLOW, TOUGH2, ...)
  - High degree of physical complexity (EOS, compositional, geochemistry, etc.)
  - Less flexible/lacks complex gridding, realistic well modelling and efficient solvers

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- Oil & Gas simulation software (ECLIPSE, INTERSECT, ECHELON, tNavigator, Nexus, ...)
  - Flexible and complex gridding, well modelling and efficient solvers
  - Physics limited to those involved in hydrocarbon recovery
- Large and active research community
  (Scott et al. [2017], Weis et al. [2014], Vehling et al. [2018], Wang et al. [2020], Wong [2018], ...)

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Here: Present ongoing work on implementing low- to moderate-temperature geothermal simulation capabilities in the the open-source MATLAB Reservoir Simulation Toolbox (MRST)

Governing equations and discretization

- Single-phase conservation of mass on semi-discrete, implicit form

$$R_f^{n+1} = \frac{1}{\Delta t^n}(M_f^{n+1} - M_f^n) + \nabla \cdot \vec{V}_f^{n+1} - Q_f = 0$$

Mass — Flux — Sources/sinks

  - Mass flux from Darcy's law: $\vec{V}_f = -\frac{\rho_f}{\mu_f}\mathbf{K}(\nabla p - \rho_f \vec{g})$

Governing equations and discretization

- Conservation of energy on semi-discrete, implicit form

$$R_e^{n+1} = \frac{1}{\Delta t^n}\left([M_f u_f + M_r u_r]^{n+1} - [M_f u_f + M_r u_r]^n\right) + \nabla \cdot (\vec{V}_f h_f + \vec{H})^{n+1} - Q_f h_f^{n+1} = 0$$

Internal energy — Advective heat flux — Conductive heat flux — Enthalpy

  - Heat flux from Fourier's law: $\vec{H} = -(\lambda_f + \lambda_r)\nabla T$

Governing equations and discretization

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Enthalpy

Internal energy

Advective heat flux

Conductive heat flux

  - Heat flux from Fourier's law: $\vec{H} = -(\lambda_f + \lambda_r)\nabla T$

- Finite-volume + implicit timestepping → stable over wide range of parameters

Newton's method: make system $R(x) = 0$, linearize, neglect higher-order terms

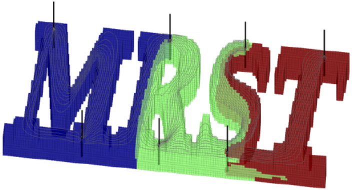
$$x^{k+1} = x^k + \Delta x, \quad -\frac{\partial R}{\partial x}\Delta x = R(x^k)$$

Governing equations and discretization

MATLAB Reservoir simulation Toolbox
`mrst.no`

- Open-source → *full source code access*
- Flexible, fully-unstructured grid format
- Industry-grade well modelling and control
- `C++` accelerated backends, compiled linear solvers
- Discrete operators + automatic differentiation

Governing equations and discretization



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$$\nabla \cdot \vec{H} \qquad \vec{H} = -(\lambda_f + \lambda_r)\nabla T$$

```
div(H)      H = -(lambdaF + lambdaR).*grad(T)
```

Automatic differentiation: Combine chain rule and elementary differentiation rules by means of operator overloading to analytically evaluate all derivatives → Computing Jacobians amounts to writing down residual equations.

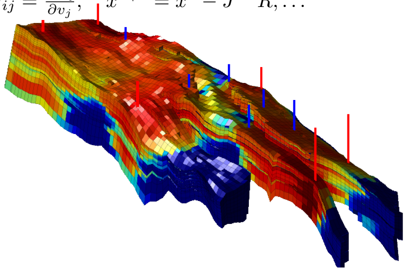
Governing equations and discretization

1) Define continuous residual equations

$r_i = \frac{\partial m_i}{\partial t} + \nabla \cdot \vec{v} - q_i = 0$

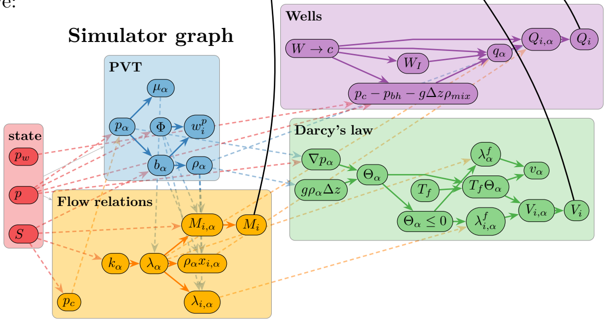
3) Differentiate discrete residual with AD and solve:

$J_{ij} = \frac{\partial R_i}{\partial v_j}, \quad x^{k+1} = x^k - J^{-1}R, \ldots$



2) Create *simulator graph* to discretize equations

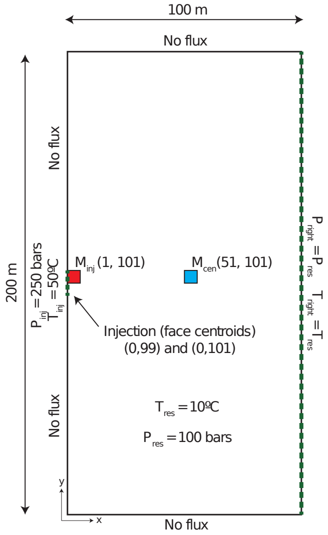
$$R_i = \frac{1}{\Delta t}\left(M_i^{\,n+1} + M_i^{\,n} \right) + \nabla \cdot V_i - Q_i$$



4) Post: Make decisions, compute sensitivites, ...

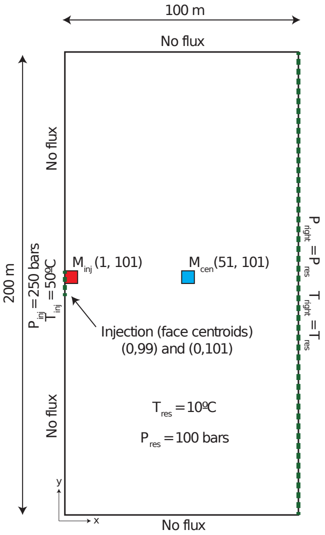
Simulation on graphs	Graph of functions for multiphysics problems Easy to modify, extend and understand Smart automatic differentiation for high performance

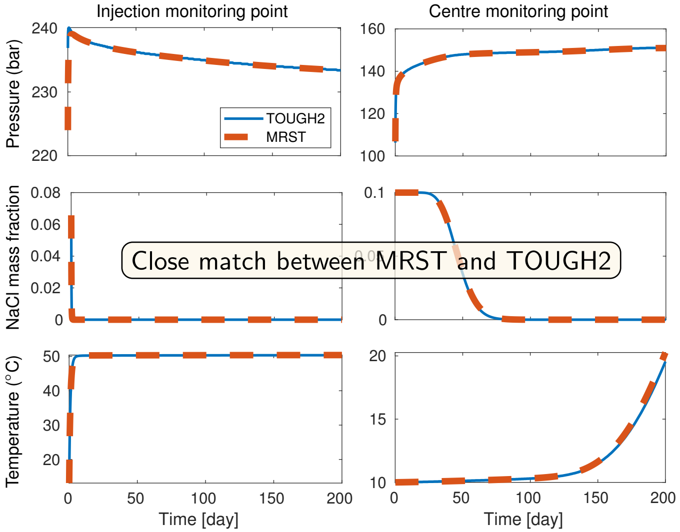
Example: TOUGH2 validation



- Injection of H_2O into $H_2O + NaCl$
- Injection temperature: 50°C, reservoir temperature: 10°C
- Two monitoring points: injection boundary and center

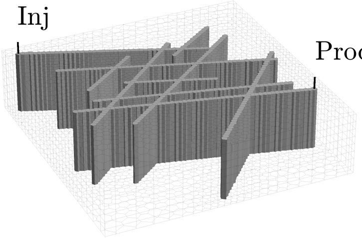
Example: TOUGH2 validation





Close match between MRST and TOUGH2

Example: Enhanced Geothermal System (EGS)



- Fractured, low-perm, high-temp, subsurface rock
- Water circulates through the fracture network
  $\rightarrow$ Fractures act as fins of a heat exchanger
- Here: artificial network in confined, insulated box
- Injection temp: 10 °C, reservoir temp: 95 °C

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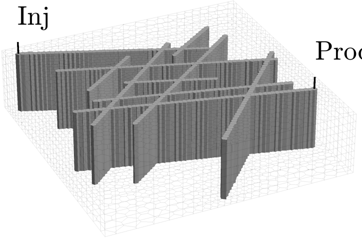

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```
G2D = pebiGrid2D(dx, xmax(1:2), 'cellConstraints', fractures, ... % Fractures
                                'CCRefinement'   , true      , ... % Refine fractures
                                'CCFactor'       , 0.1       );    % Relative fracture size
layers = diff(linspace(0, xmax(3), nlayers + 1));                  % Make layered grid
G = makeLayeredGrid(G2D, layers);
```

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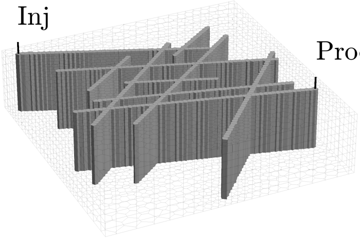

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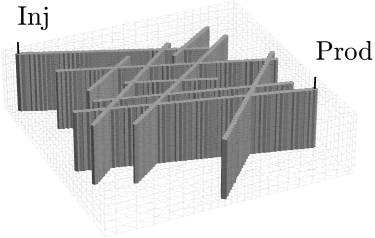
```
fluid = addThermalFluidProps(fluid                                 , ... % Original fluid
                             'Cp'      , 4.2e3*joule/(Kelvin*gram), ... % Heat capacity
                             'lambdaF', 0.6*Watt/(meter*Kelvin)   , ... % Thermal cond
                             'useEOS'  , true                     );    % Use EOS
```

Example: Enhanced Geothermal System (EGS)



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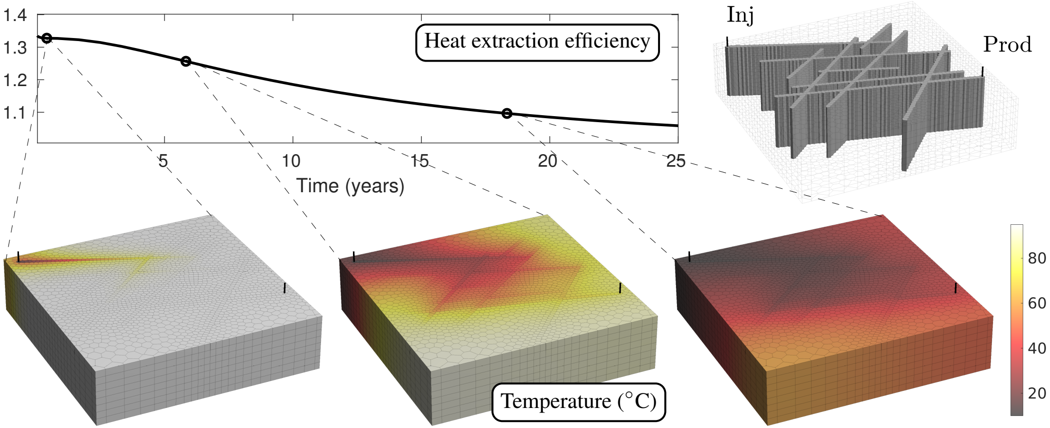
```
rock = addThermalRockProps(rock                                      , ... % Original rock
                           'CpR'     , 1000*joule/(Kelvin*gram), ... % Heat capacity
                           'lambdaR', 2*Watt/(meter*Kelvin        , ... % Thermal conductivity
                           'rhoR'    , 2700*kilogram/meter^3     );     % Rock density
```

Example: Enhanced Geothermal System (EGS)



Example: High-temperature aquifer thermal energy storage (HT-ATES)

- HT-ATES system in artificial but realistic geological model
- Two groups of four wells used to store and extract hot water[1]
  - $\underbrace{\text{4 months storage}}_{\text{summer}}$ – 2 months rest – $\underbrace{\text{4 months production}}_{\text{winter}}$ – 2 months rest
  - Rate-controlled injection, BHP-controlled production

HT-ATES: Flexible, large-scale, subsurface energy storage

- Balance energy supply from multiple temporal resources (wind, hydro, solar, ...)
- Supply extra energy in periods of high demand (store in summer, extract in winter)

[1] Inspired by previous work (Collignon et al. [2020])

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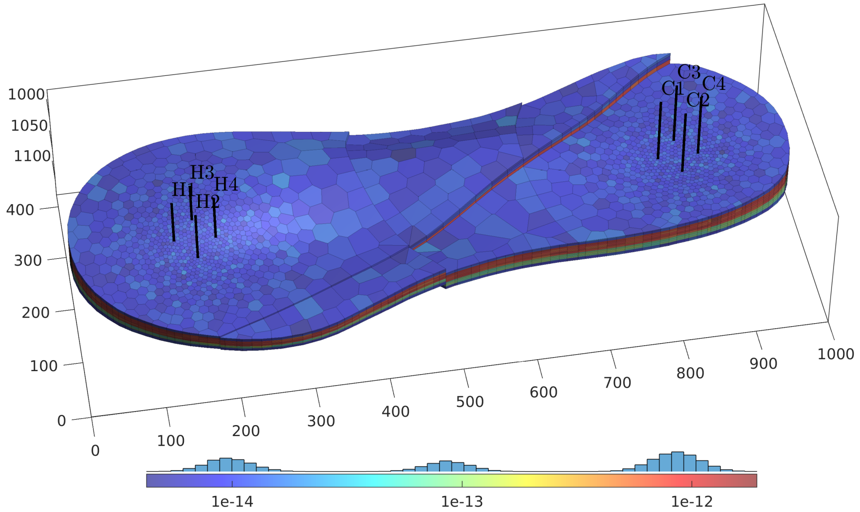

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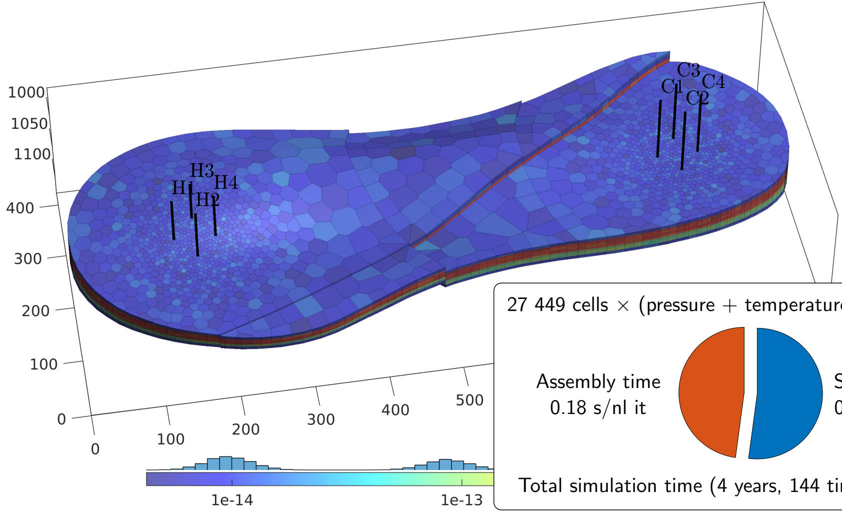
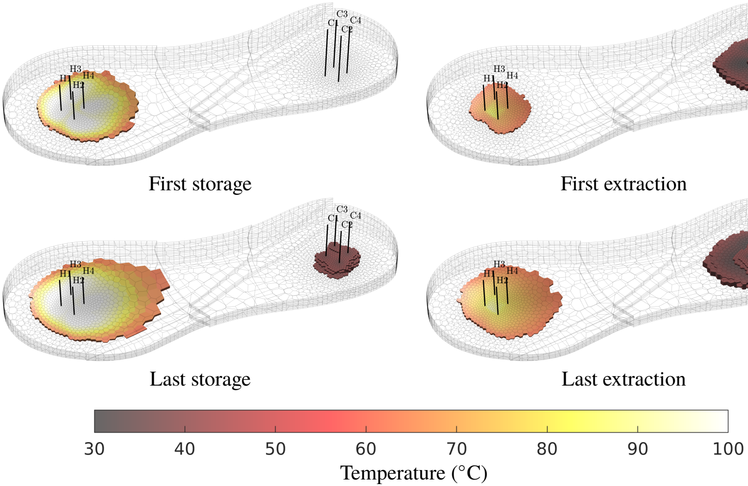


27 449 cells × (pressure + temperature) = 54 898 dofs

Total simulation time (4 years, 144 timesteps): 160 s

Example: High-temperature aquifer thermal energy storage (HT-ATES)



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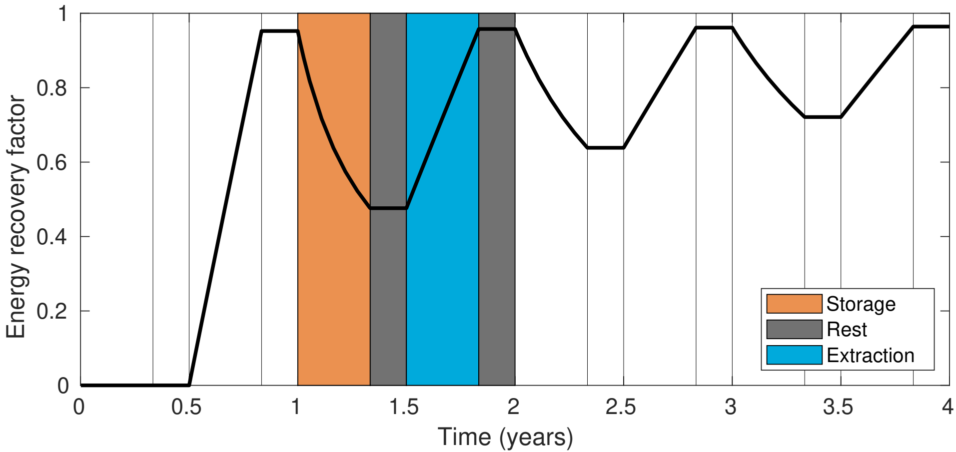

Concluding remarks

What's done?

- First step towards a module for geothermal simulations in MRST
  - *n* salt components, temperature-, pressure- and salinity-dependent EOS
- Applicable to realistic low- to moderate-enthalpy geothermal systems
  - Enhanced geothermal systems (EGS), aquifer thermal energy storage (ATES)

Concluding remarks

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Source code: `mrst.no`
`bitbucket.org/mrst/workspace/projects/MRST`

Concluding remarks

What's next?

- Implement phase transitions (liquid, vapor, halite) and hydrocarbon components
- Combine with tools from O&G reservoir engineering
  - Optimal well control (adjoint), history matching, uncertainty quantification, ...
- Investigate discretizations and solution strategies
  - Splitting, global Newton methods, domain decomposition, ...
- Extensive verification against existing software
  - Already verified against TOUGH2 for simple case with H_2O + NaCl

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