# High Performance simulation of geothermal systems


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# Outline

- Introduction
- Well modeling and implementation
- Validation tests
- Conclusions

## Geothermal loop

- Extract multiphase flows at the production wells (hot water + gas).
- Inject a single phase flow into a reservoir (cold water).

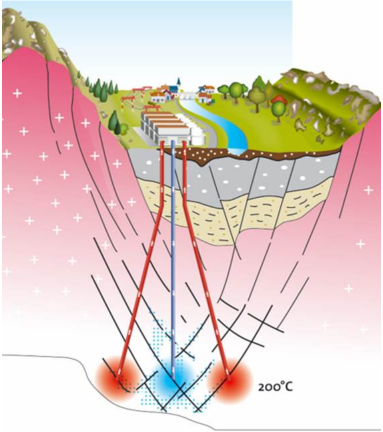



Figure: An example of geothermal wells.

# Model introduction

- $\mathcal{C} = \{H_2O\}$, $\mathcal{P} = \{\mathrm{water}, \mathrm{gas}\}$
- Set of present phases $Q \subset \mathcal{P}$

- Mass conservation

$$\partial_t n_{H_2O} + \mathrm{div}\Big( \sum_{\alpha \in Q} C^{\alpha}_{H_2O} \mathbf{V}^{\alpha} \Big) = q_{H_2O}, \quad (H_2O)$$

together with the Darcy flow

$$\mathbf{V}^{\alpha} = -\frac{\zeta^{\alpha} k_{r_{\alpha}}}{\mu^{\alpha}} \Lambda \nabla P,$$

where $n_{H_2O}$ is the mole of $H_2O$

$$n_{H_2O} = \phi \zeta^{w} S^{w} C^{w}_{H_2O} + \phi \zeta^{o} S^{g} C^{g}_{H_2O}.$$

| | water phase | gas phase |
|---|---|---|
| Molar composition | $C^{w}_{H_2O} = 1,$ | $C^{g}_{H_2O} = 1$ |
| Saturation (volume fraction) | $S^{w}$ | $S^{g}$ |

# Model introduction

- Energy conservation

$$\partial_t E + \operatorname{div}\Big( \sum_{\alpha \in Q} h^\alpha \mathbf{V}^\alpha - \lambda \nabla T \Big) = q_e,$$

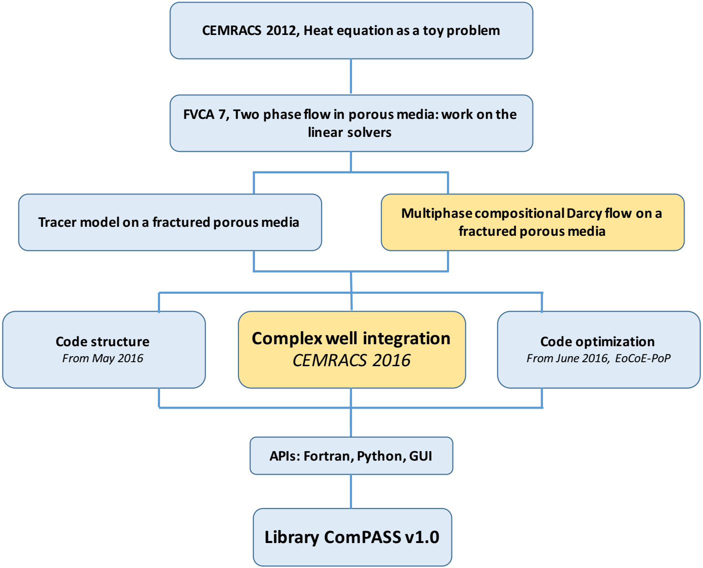
where the energy is

$$E = \phi \sum_{\alpha \in Q} \zeta^\alpha e^\alpha S^\alpha + (1-\phi)\zeta^r e^r,$$

and $h^\alpha$: molar enthalpy, $\lambda$: thermal conductivity, $e^\alpha$: internal energy.

- The system is closed with some closure equations.

# ComPASS : Computing Parallel Architecture to Speed up Simulations



*We focus on thermal well integration in code ComPASS, which is a central feature of geothermal exploitation.*

## Well modeling

- Physical well model (Bibliography),
- Geometry of wells: the well consists of multiple oriented edges, describing a connected and acylic graph (tree).

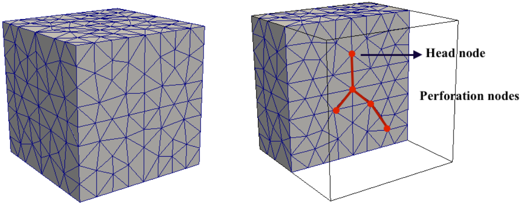



Figure: Simple example with one vertical well (mesh, well, slice view).

## Numerical methods - Reservoir

- Fully implicit in time schema
- VAG scheme for space discretization (a type of finite volume method)

$\Rightarrow$ In the reservoir, the unknowns are

$$P_s, T_s, S_s^w, S_s^g, C^w_{s,H_2O} = 1, C^g_{s,H_2O} = 1,$$

where $s$ is cell, node and fracture faces.

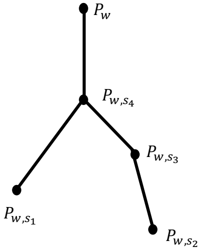
# Numerical methods

## Numerical methods - Well

- One unknown is introduced for each well: $P_w$ (Pressure of head)
- The pressure on the perforation nodes are computed using an explicit way

$$P_{w,s} = P_w + \Delta P_{w,s}^{n-1}$$

where $\Delta P_{w,s}^{n-1}$ is computed with the data from the previous time step.



## Numerical methods - Well and reservoir intersection

- Flux between the well and the reservoir
  - Injection well:

$$\frac{\zeta^l k_{r_l}}{\mu^l}(P_{w,s}, T_w, C^l_{H_2O}) \cdot WI_{w,s} \cdot (P_s - P_{w,s})^-$$

  - Production well:

$$C^\alpha_{H_2O} \frac{\zeta^\alpha k_{r_\alpha}}{\mu^\alpha}(P_s, T_s, C^\alpha_{H_2O}) \cdot WI_{w,s} \cdot (P_s - P_{w,s})^+$$

where $WI_{w,s}$ is the well index.


Figure: Injection well and production well.

## Numerical methods

- Newton Raphson algorithm including the wells pressure
  - Jacobian matrix
  - Phase appearance and disappearance

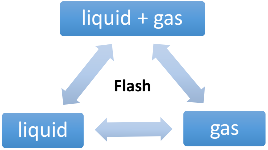
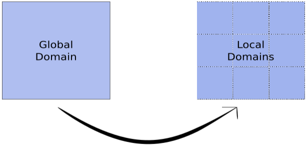



Figure: Example: vapor liquid two phases thermal model.

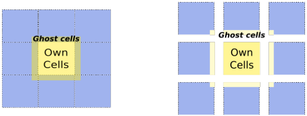
# Implementation

## Implementation specifications

- Mesh partitioning with METIS library (with one layer ghost cells)




*Cell Decomposition*
*done with METIS*




*Adding ghost cells to*
*the initial METIS distribution*

- The nodes (fracture faces) are partitioned into local sub domains. Each sub domain contains own nodes and ghost nodes.

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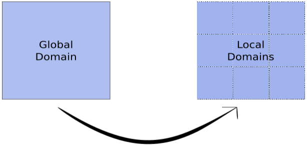


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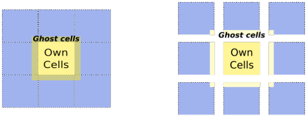



*Adding ghost cells to the initial METIS distribution*

- The nodes (fracture faces) are partitioned into local sub domains. Each sub domain contains own nodes and ghost nodes.
- The well is own to one sub domain $\Longleftrightarrow$ its head node is an own node of this sub domain.

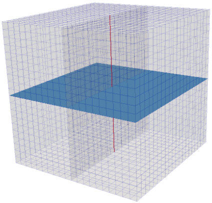
# Implementation

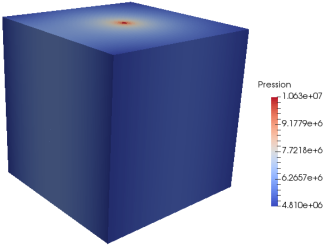
## Implementation including the wells

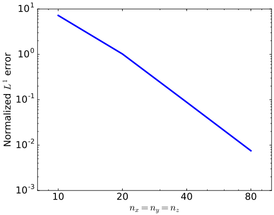
- Linear solver libraries PETSc
  - Iterative linear solver with CPR-AMG preconditioner:
    AMG for pressure part + ILU(0) for complete system (multiplicative)
- Visualization with VTK
- Checkpointing with HDF5

# Validation step

We validate the code with an analytic solution in the case of single-phase (liquid) isothermal flow with a radial injector or producer.

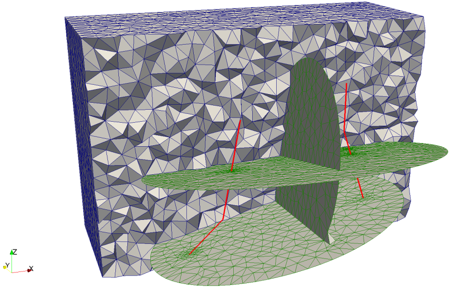




# Production step

Production tests with a more completed test case.



## Brief conclusions

**What we have done**

- Thermal well model (Bibliography).
- Well geometry.
- Including the wells in code ComPASS (coding).
- Validation tests (partially).

**What we are going to do**

- production tests,
- ...

**Thanks for your attention!**

MORE http://compass.gforge.inria.fr