Some aspects and current needs for geothermal reservoir modeling
First results obtained with ComPASS platform

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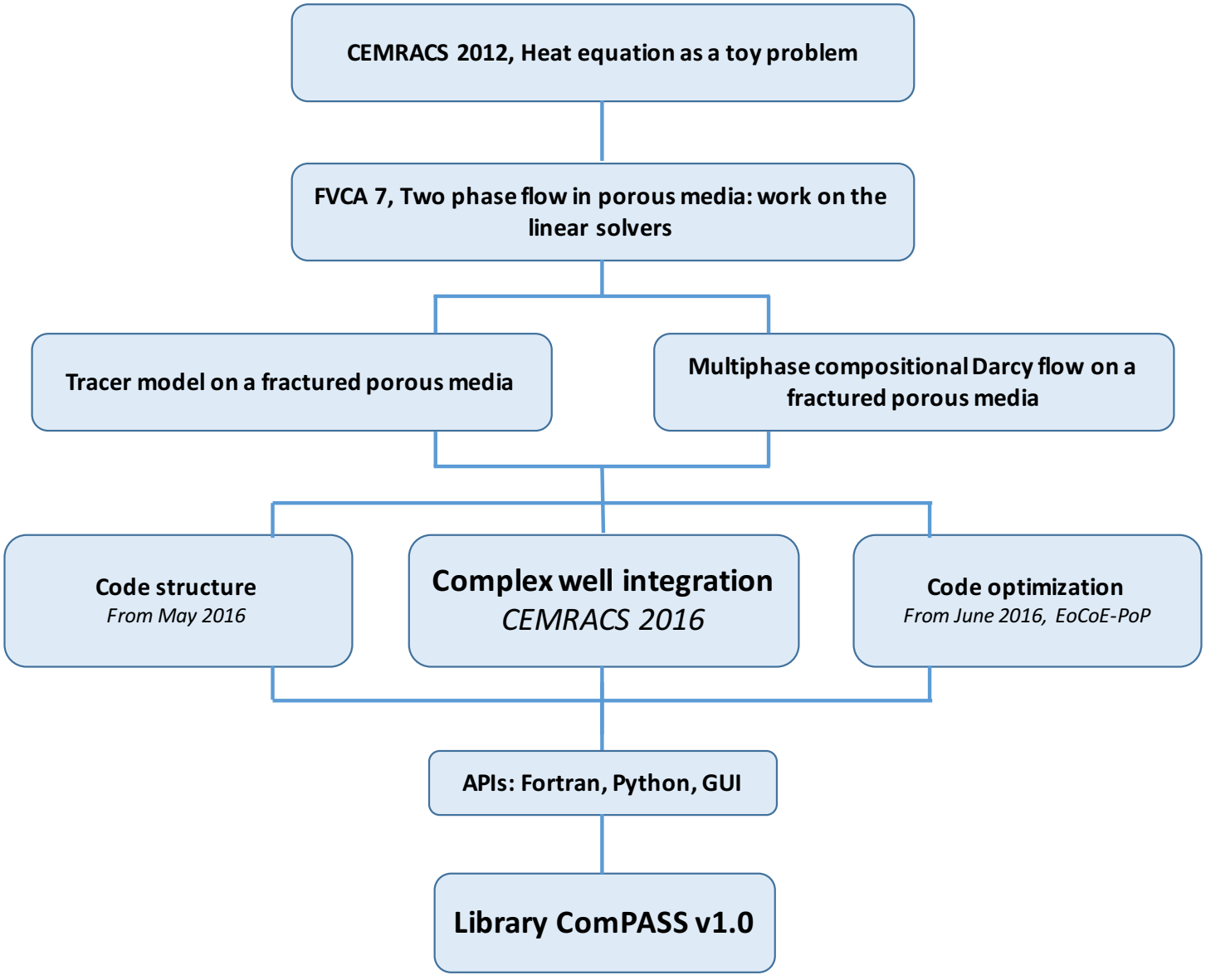
Motivation

To answer the needs, we need to do something both in mathematics and in computer science.

ComPASS : Computing Parallel Architecture to Speed up Simulations



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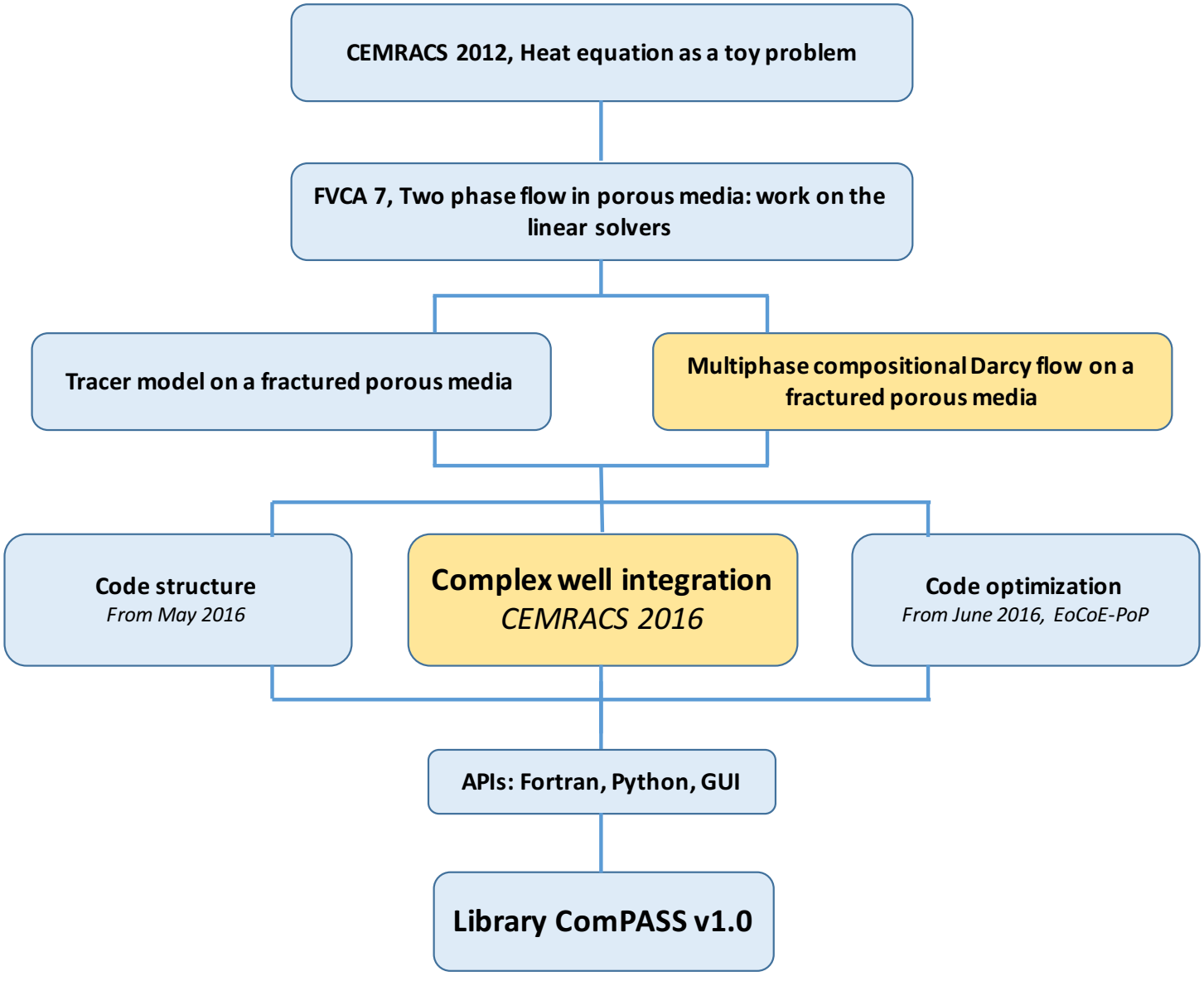

Outline

- Model introduction
- ComPASS
- Numerical results
- ComPASS - CEMRACS 2016

Model introduction - recall - Two phase immiscible

Mass conservation

$$\begin{cases} \partial_t(\phi\zeta^w S^w) + \mathrm{div}(\mathbf{V}^w) = 0, & (H_2O) \\ \partial_t(\phi\zeta^o S^o) + \mathrm{div}(\mathbf{V}^o) = 0, & (HC) \end{cases}$$

together with the Darcy flow

$$\begin{cases} \mathbf{V}^w = -\dfrac{\zeta^w k_{r_w}}{\mu^w}\Lambda\nabla P, \\ \mathbf{V}^o = -\dfrac{\zeta^o k_{r_o}}{\mu^o}\Lambda\nabla P, \end{cases}$$

and closure equation

$$S^w + S^o = 1,$$

where P is pressure, Λ is permeability, ϕ is porosity and

	water phase	oil phase
Saturation (volume fraction)	S^w	S^o
Molar density	ζ^w	ζ^o
Viscosity	μ^w	μ^o
Relative permeability	k_{r_w}	k_{r_o}

Model introduction - recall - Two phase immiscible

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- $\mathcal{C} = \{H_2O, HC\}$, $\mathcal{P} = \{\mathrm{water}, \mathrm{oil}\}$,
- $M_{CP} = \begin{matrix} \\ H_2O \\ HC \end{matrix} \overset{\begin{matrix} \text{water} & \text{oil} \end{matrix}}{\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}}$

Model introduction - recall - Black oil

- $\mathcal{C} = \{H_2O, HC\}$, $\mathcal{P} = \{\text{water}, \text{oil}\}$
- $M_{CP} = \begin{array}{c} \begin{matrix} \text{water} & \text{oil} \end{matrix} \\ \begin{pmatrix} 1 & 0 \\ 1 & 1 \end{pmatrix} \begin{matrix} \rightarrow & H_2O \\ \rightarrow & HC \end{matrix} \end{array}$

Mass conservation

$$\begin{cases} \partial_t n_{H_2O} + \operatorname{div}\Big(\sum_{\alpha \in Q \cap \{w\}} C^w_{H_2O} \mathbf{V}^w \Big) = 0, \quad (H_2O) \\ \partial_t n_{HC} + \operatorname{div}\Big(\sum_{\alpha \in Q \cap \{w\}} C^w_{HC} \mathbf{V}^w \Big) + \operatorname{div}\Big(\sum_{\alpha \in Q \cap \{o\}} C^o_{HC} \mathbf{V}^o \Big) = 0, \quad (HC) \end{cases}$$

	water phase	oil phase
Molar composition	$C^w_{H_2O}$, C^w_{HC}	$C^o_{HC} = 1$
Saturation (volume fraction)	S^w	S^o

where $Q \subset \{w, o\}$ is set of present phases and the mole of H_2O (HC) are

$$n_{H_2O} = \phi \zeta^w S^w C^w_{H_2O}, \quad n_{HC} = \phi \zeta^w S^w C^w_{HC} + \phi \zeta^o S^o C^o_{HC}$$

together with the Darcy flow and the algebraic equilibrium.

Model introduction - recall - vapor liquid two phase thermal model

- $\mathcal{C} = \{H_2O\}$, $\mathcal{P} = \{\text{water}, \text{gas}\}$

  water gas
- $M_{CP} = \begin{pmatrix} 1 & 1 \end{pmatrix}$

Mass conservation

$$\partial_t n_{H_2O} + \operatorname{div}\Big(\sum_{\alpha \in Q} C^{\alpha}_{H_2O} \mathbf{V}^{\alpha} \Big) = 0, \quad (H_2O)$$

Energy conservation

$$\partial_t E + \operatorname{div}\Big(\sum_{\alpha \in Q} h^{\alpha} \mathbf{V}^{\alpha} - \lambda \nabla T \Big) = 0,$$

where the energy is

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

together with Darcy flow $\mathbf{V}^{\alpha}$ and algebraic equilibrium, where h^{α}: molar enthalpy, λ: thermal conductivity, e^{α}: internal energy.

Multiphase compositional thermal Darcy flow model

Extended Coats' formulation

- Set of phases: $\mathcal{P}$
- Set of components: $\mathcal{C}$
- Model matrix: $M_{CP} \in \{0,1\}^{\#\mathcal{C}\times\#\mathcal{P}}$

- Mass conservation

$$\partial_t n_i + \operatorname{div}\Big(\sum_{\alpha\in Q} C_i^\alpha \mathbf{V}^\alpha\Big) = 0,\ \ i \in \mathcal{C},$$

- Energy conservation

$$\partial_t E + \operatorname{div}\Big(\sum_{\alpha\in Q} h^\alpha \mathbf{V}^\alpha - \lambda\nabla T\Big) = 0,$$

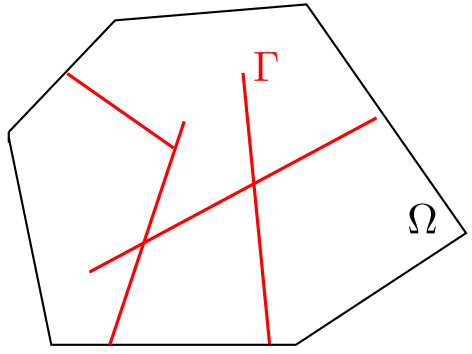
with the energy

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

- Thermal dynamic equilibrium

Physical specifications

- Multiphase compositional thermal Darcy flow model
- 2D discrete fracture or fault network coupled with the surrounding 3D matrix domain



Hybrid dimensional models for Discrete Fracture Network
dim(Γ)=dim(Ω)-1, $d_f \ll \mathrm{diam}(\Omega)$, [Alboin-Jaffré-Roberts-Serres 2002]

Mesh

- General meshes (polyhedral cells, possibly non planar faces)

Challenges

- Non-linear strong coupling
  - elliptic/parabolic for pressure and temperature, hyperbolic for saturation
  - phase appearance and disappearance

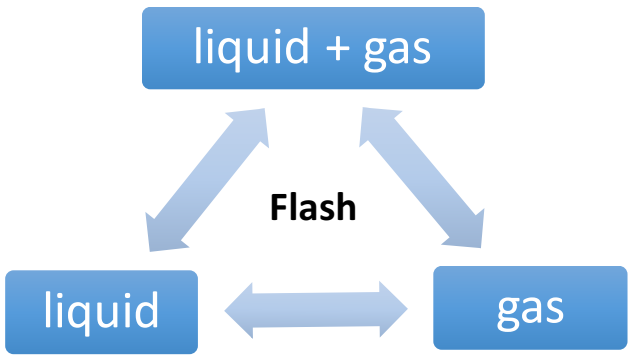


Figure: Example: vapor liquid two phases thermal model.

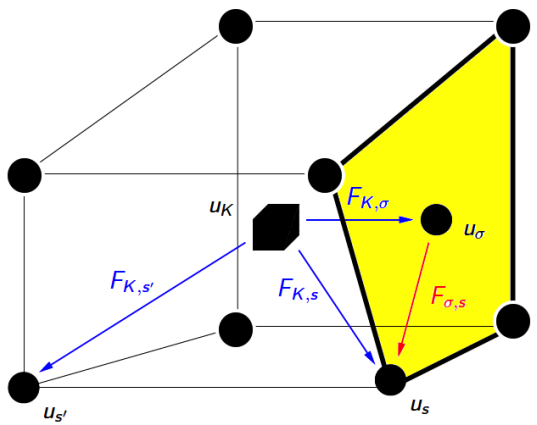
Challenges

- Strong heterogeneity
  - matrix-fracture geometry
  - strong contrast of matrix and fracture:

$$\text{ratio} = \frac{\text{Permeability in fractures}}{\text{Permeability in matrix domain}} \text{ can be very large } (ex.10^6)$$

Numerical specifications - discretization

- Fully implicit in time
- Parallel Vertex Approximate Gradient (VAG) scheme accounting for the flow in the 3D matrix and the 2D fault network
  - ⋆ Unknowns:
    cells, nodes, fractures faces
  - ⋆ Flux:
    In the matrix : $F_{K,\mathbf{s}}$, $F_{K,\sigma}$ nodes and fracture faces connected to cell.
    In the fracture : $F_{\sigma,\mathbf{s}}$ nodes connected to fracture face.



Numerical specifications - Solver

- Newton Raphson algorithm with phase appearance and disappearance

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- Newton Raphson algorithm with phase appearance and disappearance
- Two ways to reduce the size of the Jacobian system
  - Preelimination of the secondary unknowns before assembly of the Jacobian matrix

    $(P, T, C_i^\alpha, S^\alpha, ...) \rightarrow$ primary unknowns $\cup$ secondary unknowns
  - Schur complement of the Jacobian matrix

    (nodes, fracture faces, cells) $\rightarrow$ (nodes, fracture faces)

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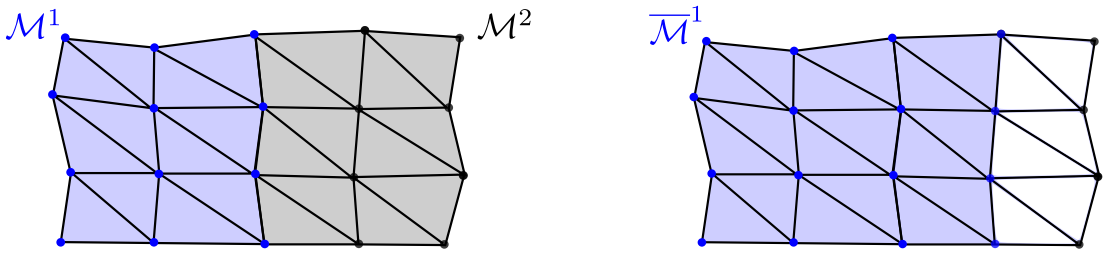
  - Schur complement of the Jacobian matrix

    $$\text{(nodes, fracture faces, cells)} \rightarrow \text{(nodes, fracture faces)}$$
- Iterative linear solver with CPR-AMG preconditioner
  - Multiplicative preconditioner: AMG for pressure part + ILU(0) for complete system

Implementation specifications

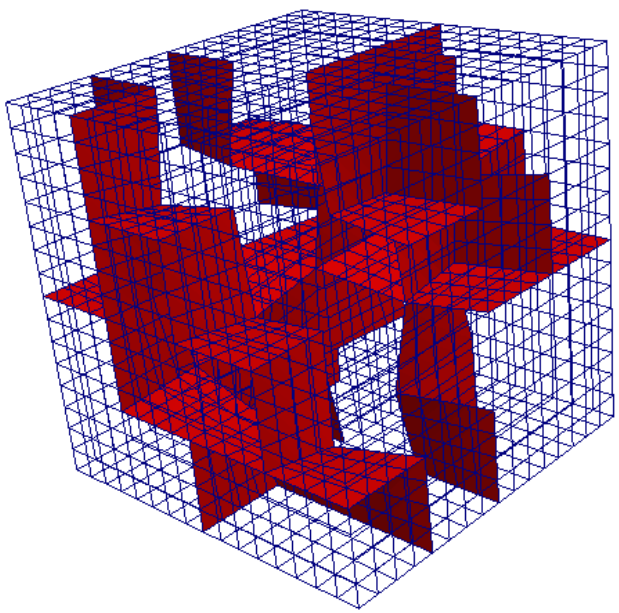
- Parallel programming with MPI using Fortran 2003 and C/C++
- Mesh participation with METIS library
- One layer of ghost cells



- Connected to the linear solver libraries PETSc + Hypre + Trilinos (+Dune)
- Visualization ouputs using parallel vtk format
- Checkpointing using HDF5

Numerical test 1 - Two phase immiscible

- Two phases water and oil and two components H_2O and HC.
- Reservoir of size $100m \times 100m \times 100m$ with fractures of width 1 cm.
- Hexahedral mesh.
- Permeability ratio between the fracture network and the matrix of 10000.
- Reservoir initially saturated with pure water and injection of oil from the bottom boundary with a gravity dominant flow.
- 20000 days of simulation.

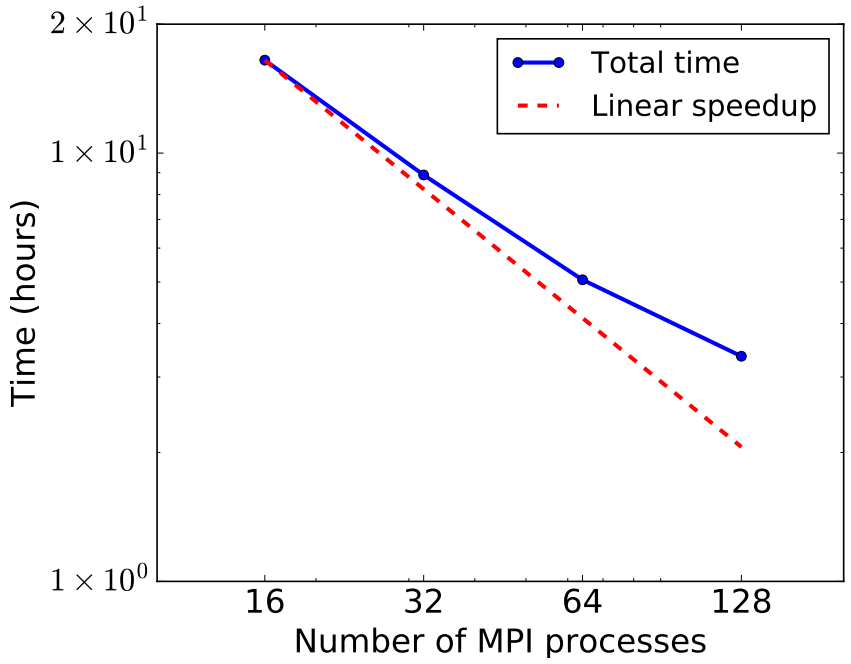


cluster Cicada: `http://calculs.unice.fr/` - 72 Cpu nodes: 16 cores (2 Intel Sandy Bridge E5-2670), 64 GB, GCC 4.9.1, OpenMPI 1.8.2, 1 core/MPI

Numerical test 1 - Two phase immiscible

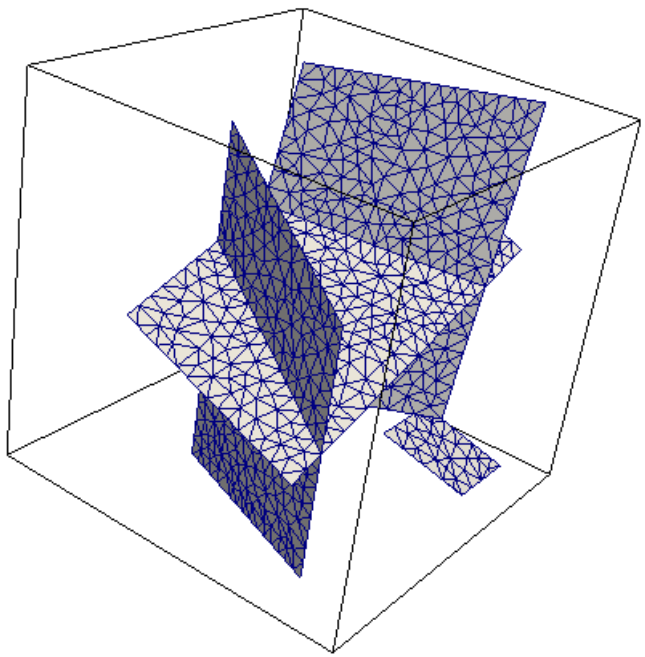
Oil saturation in the matrix and in the fracture network

Numerical test 1 - Two phase immiscible



Numerical test 2 - Black oil

- Two phases water and oil and two components H_2O and HC.
- Dissolution of the HC component in the water phase.
- Reservoir of size $100m \times 100m \times 100m$ with fractures of width 1 cm.
- 3D Mesh with 6×10^6 tetrahedra.
- Permeability ratio between the fracture network and the matrix of 10000.
- Reservoir initially saturated with pure water and injection of oil from the bottom boundary with a gravity dominant flow.
- 10000 days of simulation.

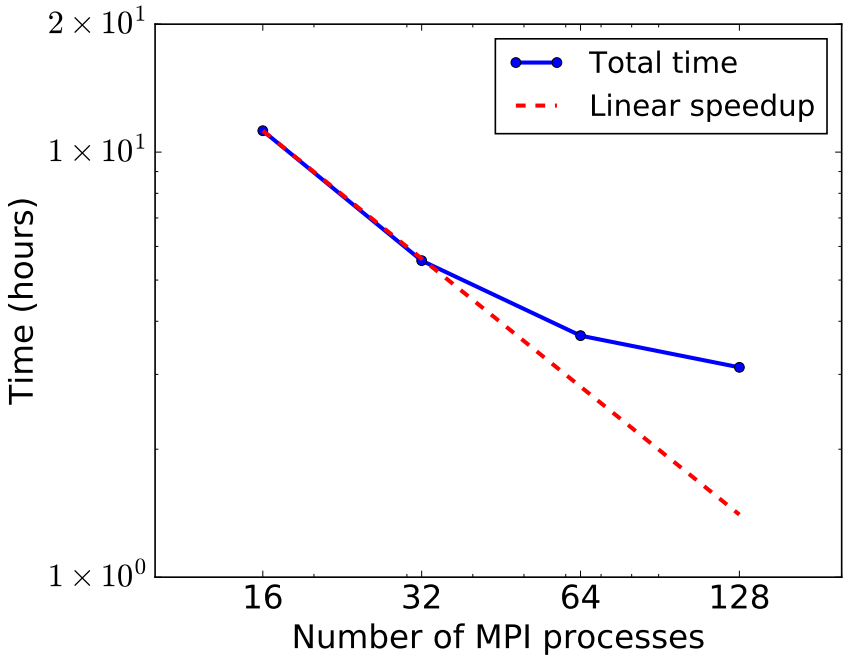


Numerical test 2 - Black oil

Oil saturation in the matrix and in the fracture network

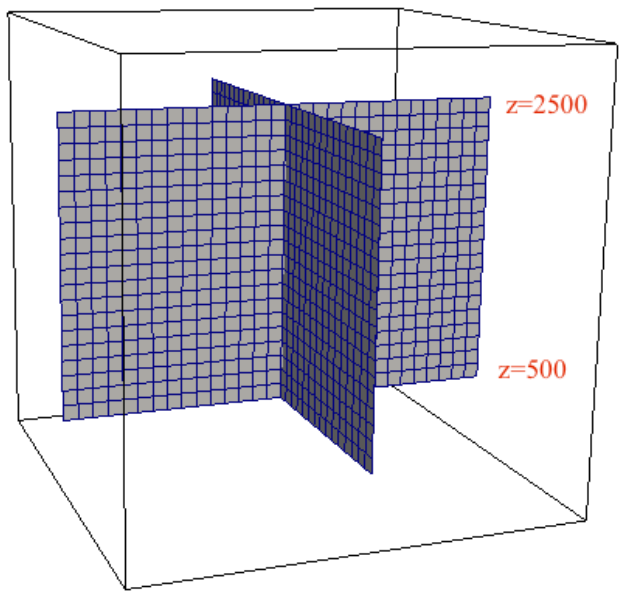
Molar fraction of HC in the water phase in the matrix and in the fracture network

Numerical test 2 - Black oil



Numerical test 3 - Thermal convection

- Gas liquid thermal model with a single component H_2O.
- Reservoir of size $3km \times 3km \times 3km$ initially at hydrostatic pressure and 293 K (liquid phase).
- Temperature fixed to be 623 K at the bottom boundary (liquid phase) and to be 293 K at the top boundary.
- Homogeneous matrix of permeability 1 mDarcy with four fractures of width 1 m and permeability 1 Darcy.
- 3D Cartesian mesh of size $240 \times 240 \times 240$ ($\approx 14M$).
- 2×10^7 days of simulation.



Numerical test 3 - Thermal convection

Temperature

Saturation of Gas

We focus on thermal well integration, which is a central feature of geothermal exploitation and it is not implemented in the current version.

The code will be brought to a level where operational use is possible and real geothermal cases can be considered.

Member:

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BRGM, INRIA, Storengy, CEA

Brief working topics

- Thermal well model (Bibliography).
- Geometry of wells.
- Peaceman numerical indices with VAG scheme.
- Jacobian system with wells.
- Solver and preconditioner adaptation.
- Validation tests.
- .....

Ongoing works

- Physics
  - ◇ Wells (CEMRACS 2016)
- Applications
  - ◇ Real case studies, geothermal reservoir simulation in Guadeloupe
- Code
  - ◇ Optimization
  - ◇ User-friendly interface

Thanks

Thanks for your attention!

MORE → http://compass.gforge.inria.fr