New Insights into the THM Modeling of Three-dimensional Fractured Media

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1 Introduction

The recent technical progress made in geo-reservoir engineering in the last 30 years highlights the necessity of obtaining numerical models in thermo-hydro-mechanically (THM) coupled situations which are able to meet prediction needs ("what is the operating life of a reservoir ?") and planning needs ("where to drill a new well ?"). Overall, numerical simulations of fractured media with THM couplings still face two major obstacles (Franco and Vaccaro, 2014). The first is the realization of a mesh representing the fracture network. The problem which arises is to mesh objects with one and two dimensions that can be quite small compared to the sample size (e.g. fault zones of 50 to 100 m thick in a geothermal reservoir at the kilometer scale). In addition, the fracture network to mesh may, for example, be contained in a medium whose properties change from one location to another (e.g. if faults are embedded in different geological layers). The second obstacle is the CPU time required to perform a calculation because of the mesh's heaviness and also the filling degree of the tangent matrix to be inverted. In this contribution, the geometry of all fractures is assumed to be perfectly known (deterministic framework), and new perspectives are proposed about mesh refinement techniques in order to (i) represent a network of fractures or faults (ii) without leading to excessive growth of the underlying calculation time. The proposed strategy is based on the finite element method but exhibits similarities with meshfree methods since the mesh can be viewed as a set of nodes linked by single connections. At first, the main aspects of the approach are presented. Afterwards, we present an example of a calculation of a deep geothermal reservoir. As for the temperature field, the model anticipates that convection loops are initiated in two of the three faults present in the reservoir.

2 Numerical aspects

A new finite element has been implemented and validated in the French finite elements software *Code_Aster*. This element simply relies on a two-nodes segment embedded in a three dimensional space. A node, numbered j, has three coordinates x_{1j}, x_{2j}, x_{3j} and is associated with degrees of freedom (dof) of different kinds: mechanical dof (displacement $\boldsymbol{\xi}$), hydraulic dof (interstitial fluid pressure p_w) and thermal dof (temperature T). On a physical viewpoint, both nodes of the element tend to exchange extensive quantities (displacement in three directions, entropy, and fluid volume) in order to cancel the gradients of intensive quantities (force, temperature and pressure) inside the element. Figure 1 gives a schematic diagram of the finite element.

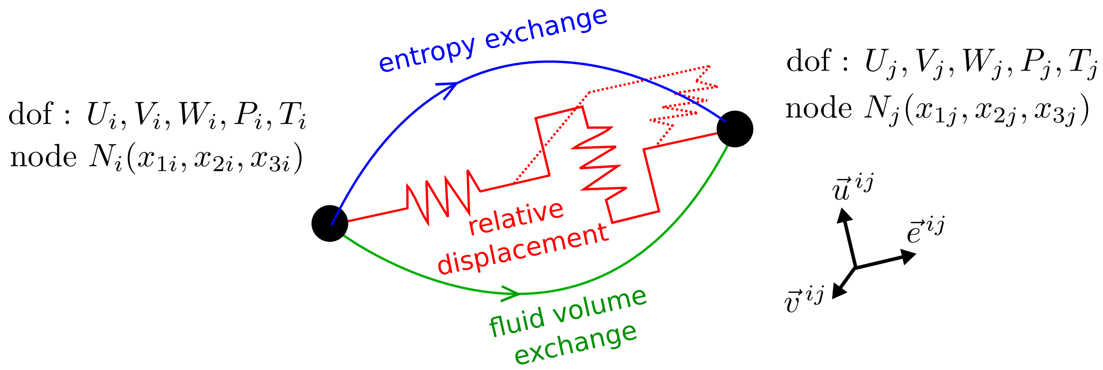

Figure 1: Schematic representation of the "THM-beam" finite element (i, j).

The meshing strategy is iterative and runs, globally, as follows: one begins by defining an assembly of finite elements that will be used as a "pattern cell" for generating the full mesh. Secondly, this pattern is repeated by translation in three spatial directions in order to generate a representation of the whole sample, regardless of fractures. Thirdly, the cells are cut by matching a certain criterion of proximity with fractures. Without loss of generality, we have implemented the refinement procedure for elliptic fractures. Figure 2 illustrates the proposed strategy in two dimensions.

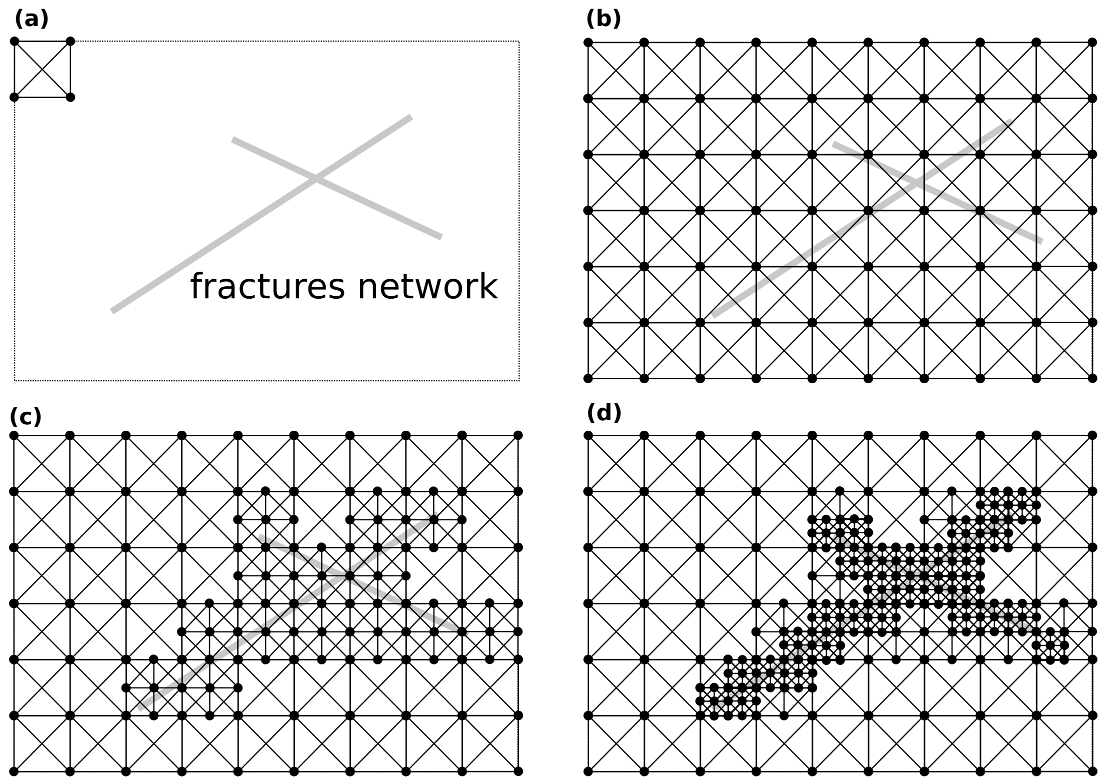

Figure 2: Meshing strategy: (a) choice of a pattern cell (made of six THM-beam elements in this example) (b) generation of the initial mesh by translation of the pattern cell (c) first cells refinement in the vicinity of fractures (d) second refinement step.

Once the simulation is finished, we proceed to an estimation of generalized strains (linear strain, pressure and temperature gradients) at the nodes of the mesh. To achieve this goal for a given node i, one seeks the equation of the plane fitting (least square method) the values of generalized displacements ($X \equiv \xi_x$, ξ_y, ξ_z, p_w, T) in the vicinity of the considered node. Afterwards, the generalized stresses can be calculated for each time increment from the generalized strains.

3 Example of simulation

A realistic application of the proposed strategy is presented here. The chosen example is a deep geothermal reservoir crossed by several kilometer-scale faults. It does not correspond to any real reservoir but is inspired by the Soultz-sous-Forêts site (Genter et al., 2010). One must therefore consider a rectangular reservoir of 15 km in width and 7.5 km in height, crossed by three elliptic fractures. The material parameters used for the simulation are assumed to be constant with respect to pressure and temperature although the proposed approach does not constrain us to this assumption. In this example, only the permeability is a piecewise function with respect to space variables, as it is 1000 times greater in faults than in the rock matrix. The mesh used for the simulation is shown in Figure 3.

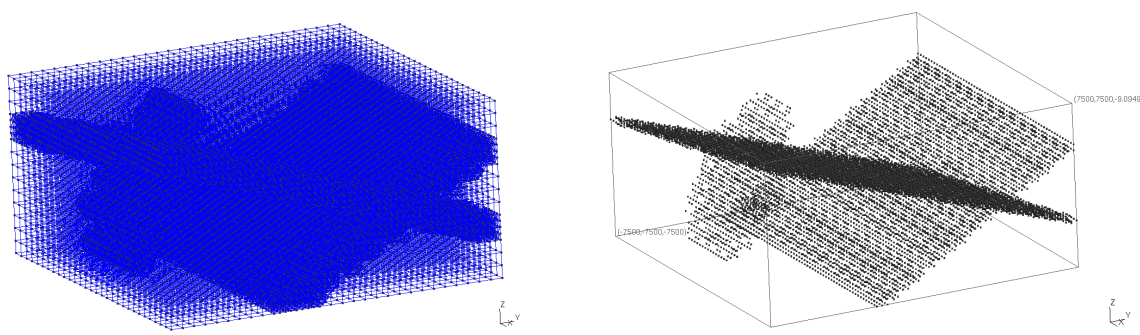

Figure 3: Mesh used for the present simulation (left: entire mesh, right: nodes belonging to faults)

At $t = 0$, temperature and pore pressure are assumed to be homogenous in the reservoir. Gravity (vertical direction $\boldsymbol{x}_3$) is taken into account but progressively applied between $t = 0$ and $t = t_1$ with $t_1 = 1\,\text{Ma}$. Regarding boundary conditions, two lateral facets ($x_1 = 0$, $x_2 = 0$) are symmetry planes. On the other two lateral facets, a normal negative displacement equal to $-100\,\text{m}$ in the direction of $\boldsymbol{x}_1$ and $-200\,\text{m}$ in the direction of $\boldsymbol{x}_2$ are gradually applied in the time interval $[t_1, t_2]$ ($t_2 = 2\,\text{Ma}$). Hydraulic and heat flows are zero on these facets. On the lower boundary, the normal displacement and the hydraulic flow are assumed to be zero while the temperature increases linearly from 300 K to 600 K on the time interval $[t_1; t_2]$. On the upper boundary, the temperature and pressure are maintained at their initial values. When gravity and temperature on the lower boundary reach their maximal values (at time t_2), the simulation is continued at constant sollicitation on the time interval $[t_2; t_3]$ with $t_3 = 10\,\text{Ma}$. In total, the linear system to be solved in a time increment (search of nodal values and dualization of boundary conditions) contains 413,845 equations. Regarding the running of the calculation itself, a parallel version (MPI) of *Code_Aster* has been used on twelve cores of an HP-Z820 machine containing 256 Go of RAM. The simulation takes approximately 3 hours and 56 minutes for 120 time increments of 50,000 years (time interval $[t_1; t_2]$) and 100,000 years (time interval $[t_2, t_3]$). The post-processing of nodal generalized stresses takes about 42 minutes. Figure 4 shows the

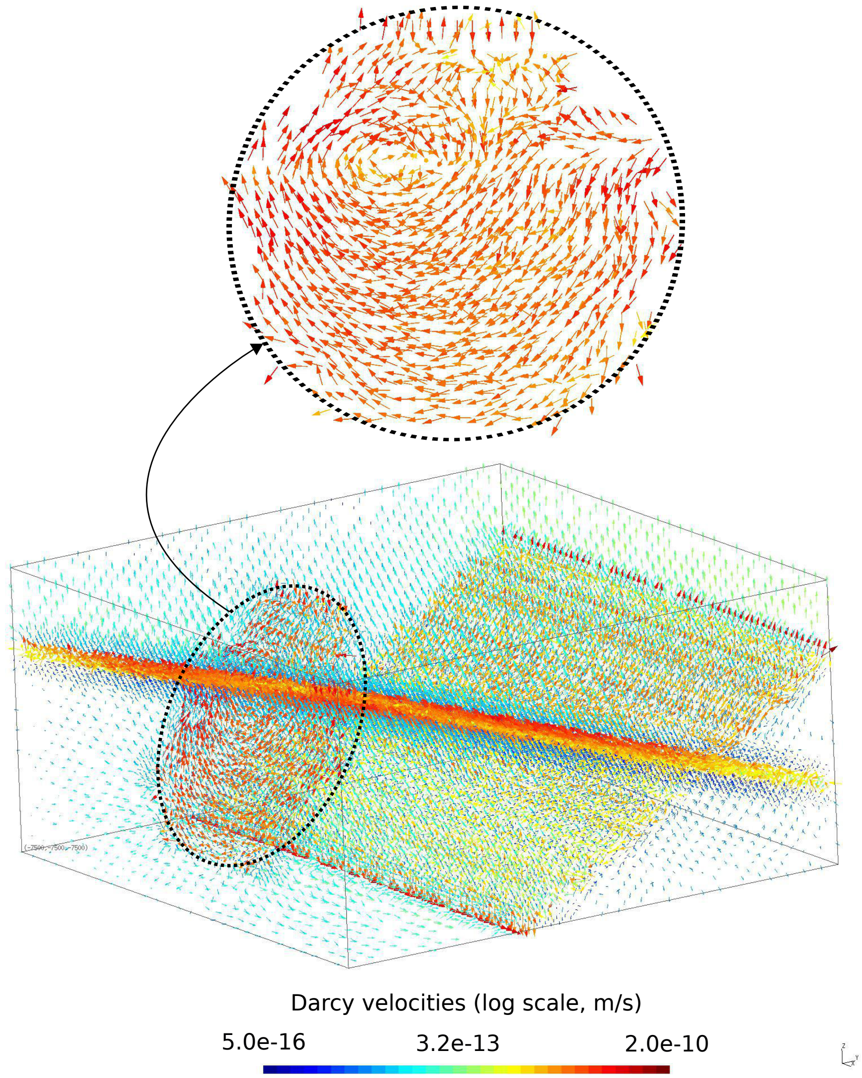

Figure 4: Darcy velocities as predicted by the model.

Darcy velocities at the end of the simulation. Qualitatively, these first results seem physically reasonable and encouraging. As for the temperature field, the model anticipates that convection loops are initiated in two of three faults present in the reservoir. Figure 4 exhibits a strong gradient of Darcy velocities in the direction perpendicular to faults in accordance with the fact that faults have a stronger permeability than their vicinity.

4 Conclusion/Outlooks

A numerical approach to solve THM constitutive equations in fluid-saturated fractured media has been proposed. The benefit of this approach is its ability to take into account the presence of several fractures in the medium, whatever their geometrical arrangement, but without notable difficulty to generate the mesh. The potential of the approach seems to be emphasized since we have shown on an example that several fields can already be exported. However, several issues remain unresolved like the implementation of a more specific mechanical behavior of fractures.

Several studies are currently in progress to address these issues and implement the approach in a more realistic manner.

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