Coupled Compositional Flow and Geomechanics Parallel Simulation

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Abstract

We present an iteratively coupled compositional flow and geomechanics model on parallel computer in this work. The model is designed to solve coupled physical problems involving multi-phase, multi-component flow and mechanical responses, e.g. stress and strain, of porous medium saturated by the fluids simultaneously on massive parallel computers. Mathematical description of the coupled problem is shown and the iterative coupling technique is presented. The model is implemented in our reservoir simulator, i.e. Integrated Parallel Accurate Reservoir Simulator (IPARS). Benchmark problems compared with Chevron's in-house reservoir simulator, i.e. Geo-mechanical Reservoir Simulator (GMRS) validates the convergence of our coupled model. We also show some numerical experiment results to illustrate the parallel efficiency of the model implemented in IPARS.

Motivation

- In reservoir simulation, problems such as hydrocarbon recovery, carbon dioxide sequestration, subsidence, and well stability require simulators to capture complicated interactions between fluids and solids
- Compositional flow model accurately depicts the multi-phase, multi-component nature of subsurface flow
- Linear elasticity model provides information of stress and strain responses of saturated solid medium
- Iterative coupling technique proves to be stable and efficient in coupling the fluid and solid models together
- Parallel computing makes solving large reservoir simulation problems in high resolution and short time feasible

Governing Equations

- Compositional Flow:

$$\frac{\partial(\phi N_i)}{\partial t} = -\nabla \bullet \left(\sum_\alpha \vec{J}_i^\alpha\right) + q_i$$

$$\vec{J}_i^\alpha = \rho_\alpha \xi_i^\alpha \vec{u}_\alpha - \phi \rho_\alpha S_\alpha \underline{D}_i^\alpha \nabla \xi_i^\alpha$$

$$\vec{u}_\alpha = -\frac{k_{r\alpha}}{\mu_\alpha} \underline{K} (\nabla p_\alpha - \rho_\alpha \vec{g})$$

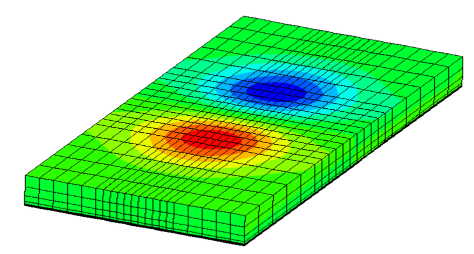
- Linear Elasticity:

$$-\nabla \bullet \underline{\sigma} = \vec{f}$$

$$\sigma_{ij} = \sigma_{ij}^0 + \lambda \varepsilon_{kk} \delta_{ij} + 2\mu \varepsilon_{ij} - \alpha(p - p^0)\delta_{ij},$$

$$\varepsilon_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$

Simulator Features



➢ Compositional flow model in IPARS:

- ✓Mixed Finite Element method on rectangular grids
- ✓Thermal, Chemistry
- ✓BCGS, GMRES, Multi-grid, LSOR
- ✓Parallel capable

➢ Linear Elasticity model in IPARS:

- ✓Galerkin Finite Element method on rectangular grids
- ✓AMG, GMRES, PCG from HYPRE
- ✓Parallel capable

Iterative Coupling Technique

- In compositional flow simulator:

$$\phi^* = \phi^0(1 + c_r(p - p^0))$$

$$\delta\phi^* = \phi^0 c_r \delta p$$

- In coupled compositional flow and geomechanics simulator:

$$\phi^* = \phi^0 + \alpha(\nabla \bullet \vec{u} - \varepsilon_v^0) + \frac{1}{M}(p - p^0)$$

$$\delta\phi^* = \alpha \nabla \bullet \delta\vec{u} + \frac{1}{M}\delta p$$

1.For horizontally unconfined problem, if $\delta\bar{\sigma}$ very small:

$$\delta\phi^* = \left(\frac{3\alpha^2}{3\lambda + 2\mu} + \frac{1}{M}\right)\delta p + \frac{3\alpha}{3\lambda + 2\mu}\delta\bar{\sigma} \approx \left(\frac{3\alpha^2}{3\lambda + 2\mu} + \frac{1}{M}\right)\delta p$$

$$\Rightarrow c_{er} = \frac{1}{\phi^0}\left(\frac{3\alpha^2}{3\lambda + 2\mu} + \frac{1}{M}\right)$$

2.For horizontally confined problem, if $\varepsilon_{xx} + \varepsilon_{yy} \ll \varepsilon_{zz}$:

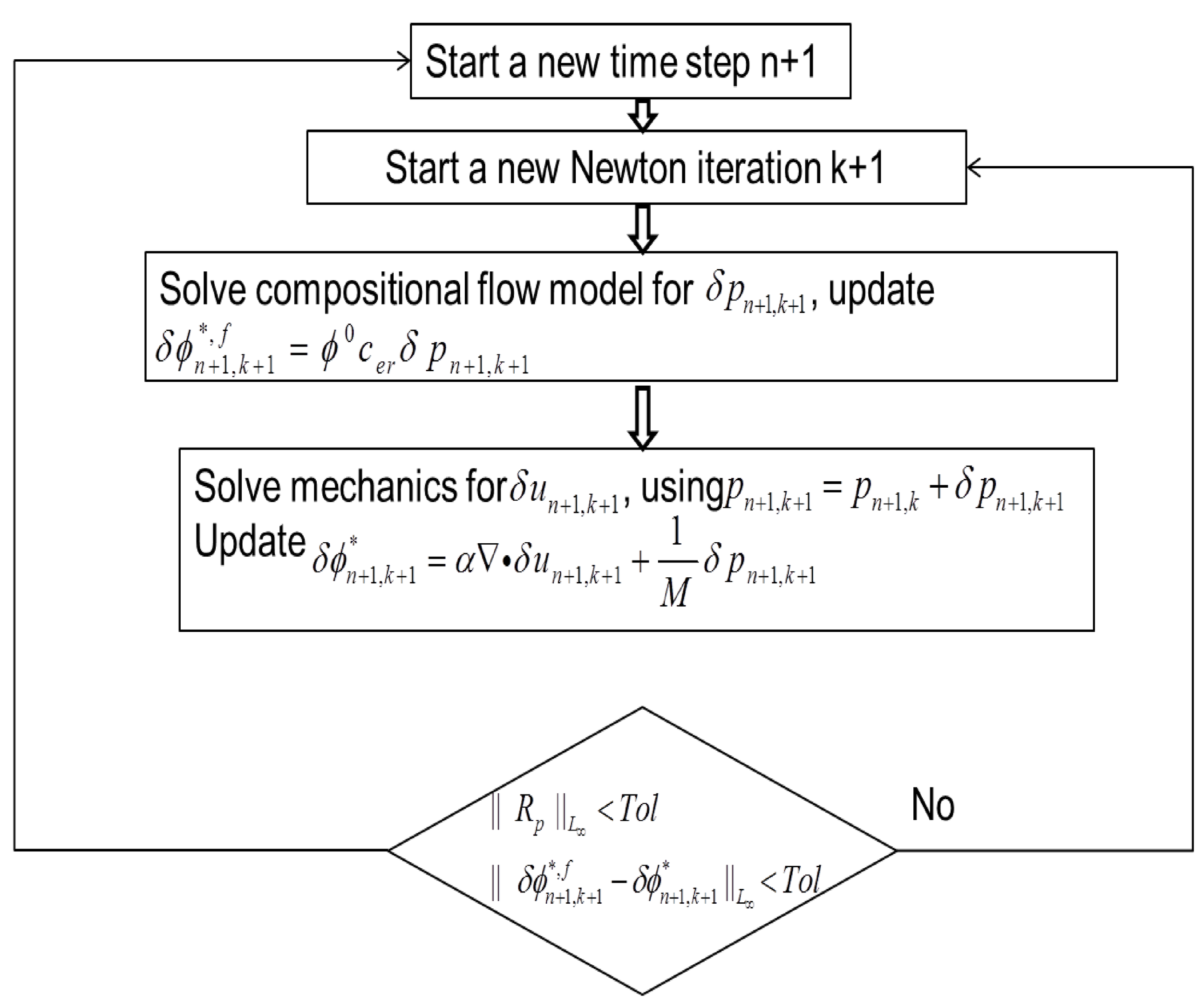
$$\delta\phi^* = \alpha(\delta\varepsilon_{xx} + \delta\varepsilon_{yy} + \delta\varepsilon_{zz}) + \frac{1}{M}\delta p$$

$$\approx \alpha\delta\varepsilon_{zz} + \frac{1}{M}\delta p \approx \frac{\alpha}{\lambda + 2\mu}(\delta\sigma_{zz} + \alpha\delta p) + \frac{1}{M}\delta p$$

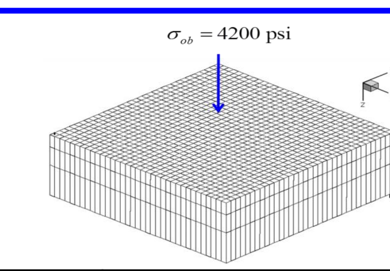
$$\approx \left(\frac{\alpha^2}{\lambda + 2\mu} + \frac{1}{M}\right)\delta p$$

$$\Rightarrow c_{er} = \frac{1}{\phi^0}\left(\frac{\alpha^2}{\lambda + 2\mu} + \frac{1}{M}\right)$$

Flow Chart of Iterative Coupling

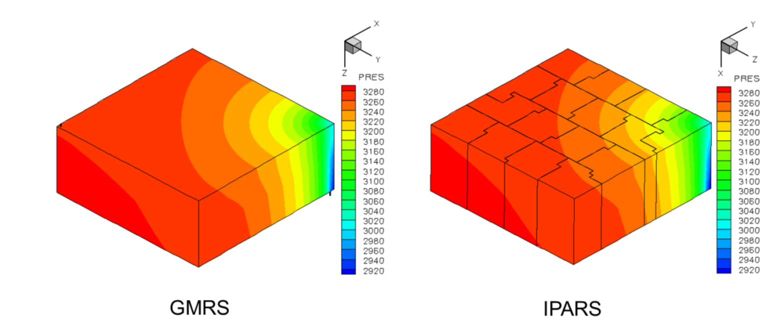


Benchmark Results

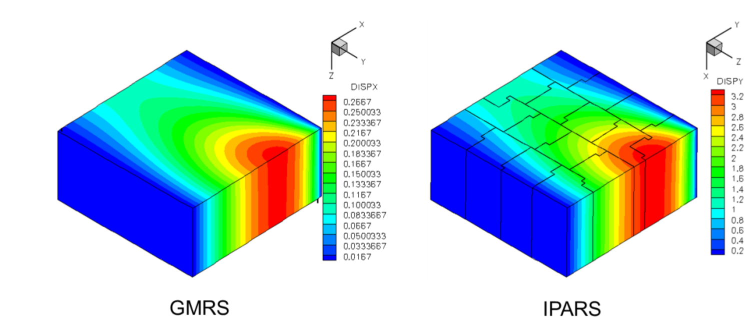


Dimension	3500 X 3500 X 100 (ft)
Grids	35 X 35 X 3
Components	C1, C3, C6, C10, C15, C20
Initial pressure (psi)	3984.3, 3990.3, 4000.0
Porosity	0.3
Oil production rate (STB/D)	12000
Initial water saturation	0.2
X, Y-perm (md)	500, 50, 200
Z-perm (md)	50, 5, 20
Young's modulus (psi)	1.E5
Poisson's ratio	0.3

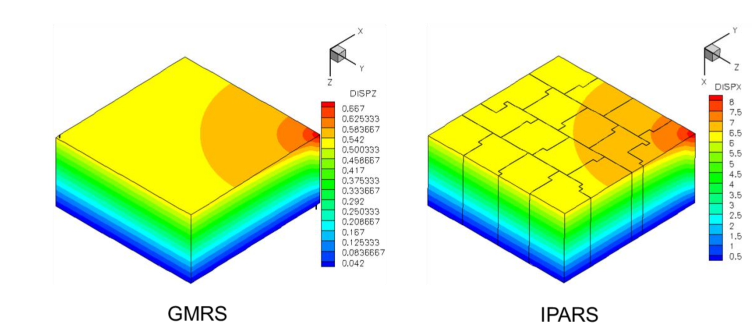
- Pressure @ 120 days



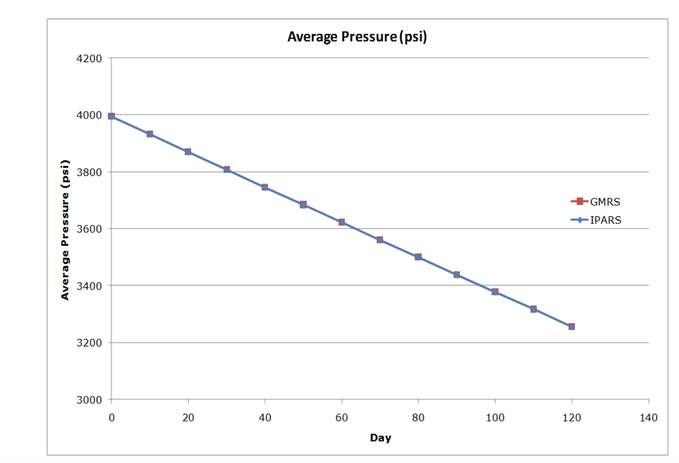
- Horizontal Displacement @ 120 days



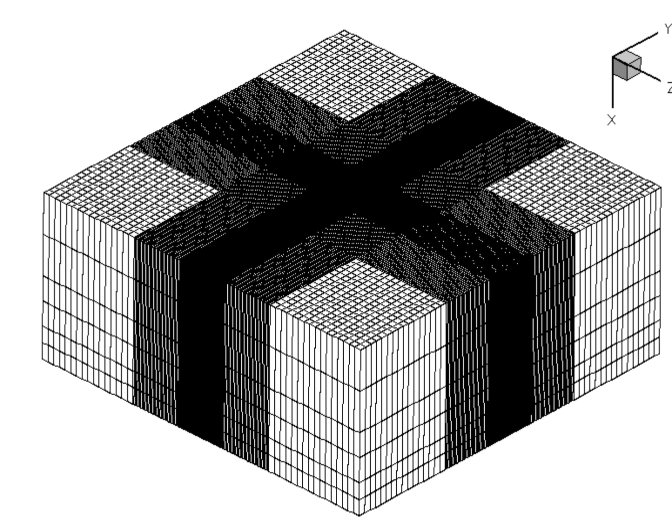
- Vertical Displacement @ 120 days



- Average Pressure History

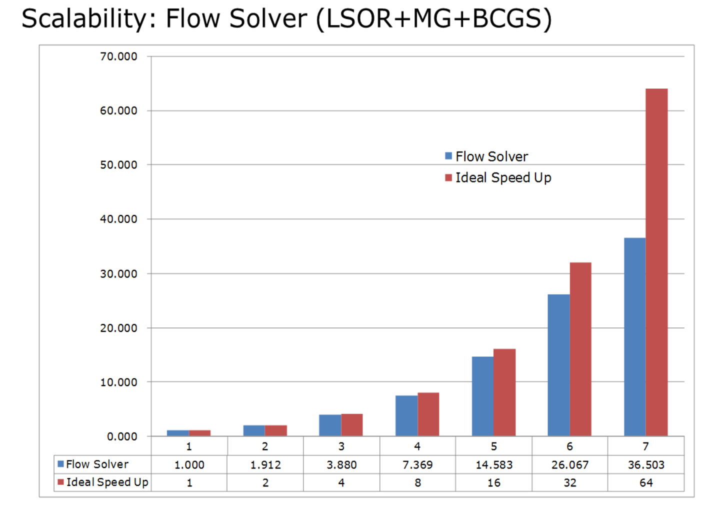


Parallel Scalability: A CO2 Injection Example



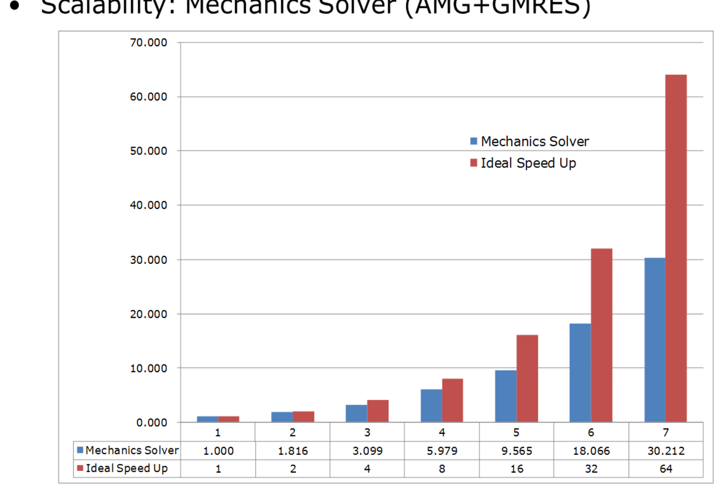
Dimension	100 X 3500 X 3500
Grids	6 X 192 X 192
Number of elements	221184
Number of unknowns for mechanics	782229

- Scalability: Flow Solver (LSOR+MG+BCGS)



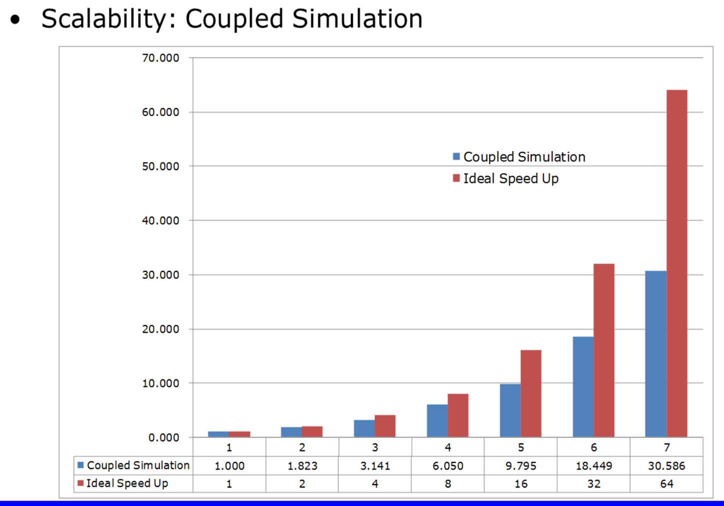
	1	2	3	4	5	6	7
Flow Solver	1.000	1.912	3.680	7.368	14.583	26.067	36.903
Ideal Speed Up	1	2	4	8	16	32	64

- Scalability: Mechanics Solver (AMG+GMRES)



	1	2	3	4	5	6	7
Mechanics Solver	1.000	1.816	3.099	5.979	9.565	18.066	30.212
Ideal Speed Up	1	2	4	8	16	32	64

- Scalability: Coupled Simulation



	1	2	3	4	5	6	7
Coupled Simulation	1.000	1.823	3.141	6.050	9.795	18.449	30.586
Ideal Speed Up	1	2	4	8	16	32	64

Conclusions

- Iteratively coupled compositional flow and linear elasticity in IPARS converges and matches implicit coupling result from GMRS
- Scalability of compositional flow in IPARS is good, room to improve scalability of geomechanics in IPARS
- Mechanics calculation costs more than flow calculation, thus determines efficiency of coupled simulation

Future work

- Further tune HYPRE solvers to achieve better scalability for geomechanics
- Incorporate plasticity model for geomechanics in IPARS
- Use multi-scale method for domain decomposition for geomechanics on non-matching hexahedra grids
- Develop 3D fracture model to further enable the compositional/geomechanics model to simulate hydraulic fracturing