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Decoupled velocity formulation for geothermal well and reservoir simulation.

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Summary

The energy transition is inevitable since approximately two-third of the current global emission is due to energy production. Subsurface can provide a great opportunity for innovative low-carbon energy solutions such as geothermal energy production, hydrogen storage, carbon capture, and sequestration, etc. Well and borehole operations play an important role in all these applications. In order to operate wells intelligently, there must be a robust simulation technology that captures physics and the expected production scenario. We design a numerical framework for predictive simulation and monitoring of injection and production wells based on the general multi-segment well model. Our simulation model is based on the general unstructured grid framework in which the wells are segmented similar to finite-volume discretization of reservoir. Total velocity serves as an additional nonlinear unknown and it is constrained with the momentum equation. Moreover, transforming nonlinear governing equations for both reservoir and well into operator form benefits from operator-based linearization (OBL) techniques and reduce further the computational cost related to linearization. This framework was tested for several complex physical kernels including thermal compositional multiphase reactive flow and transport. The proposed model was validated using a comparison with analytic and numerical results.

Introduction

One of the critical factors for successful management of any energy-related subsurface activity (e.g. energy storage, geothermal, hydrocarbon production, wastewater disposal) is well and borehole operation. Recently, smart wells such as long deviated multi-lateral wells with sophisticated inflow control valves are being used to maximize both the economy of the field and the reliability of the operation. The design, prediction and optimization of all the processes of interest require accurate models for thermal multi-phase flow in the wellbore and surface facilities.

Several challenges for accurate modelling of such wells exist. Firstly, the thermal multiphase multi-component flow through the wellbore is complex. Moreover, chemical interactions between the wellbore and flowing fluids cannot be negligible in energy transition application. The coupling between the wellbore and reservoir introduces additional complications. The complexity stems from the fact that the flow-through wellbore should account for the full momentum equation with friction and acceleration terms, unlike the flow in reservoir which is following Darcy's law and directly substituted into the conservation equations. Coupling of nonlinear governing equations for wells and reservoir may cause a set of stiff partial differential equations due to the contrast in temporal and spatial scale. Moreover, the model should be flexible enough to honour sophisticated well topology.

To overcome these challenges, the Multi-Segmented well (MS-well) model was proposed (Holmes et al. 1998; Jiang, 2007). In the MS-well model, a wellbore is discretized into several segments with the fluid velocity, node pressure, and other properties simulated along with the wellbore geometry. The general MS-well can flexibly approximate the actual geometry of a wellbore and handle the complex well topology and controls in the pipeline network.

In this work, we develop a new modeling capabilities in Delft Advanced Research Terra Simulator (DARTS, 2019) applying the decoupled velocity formulation. In this formulation, total velocity acts as an additional nonlinear unknown written at each interface (connection) on the entire computational domain and bounded by the suitable momentum equation. Coupled mass and energy balance equations with momentum balance equations are solved in a fully implicit manner. Well and reservoir are both discretized similarly into nodes and connections following the general unstructured grid framework using finite-volume scheme. For the nonlinear solution, DARTS uses an Operator Based Linearization (OBL) approach (Voskov, 2017). In this work, we extend OBL technique to account for velocity formulation that can be served for a coupled well and reservoir modelling.

Method and/or Theory

For the investigated domain with volume Ω bounded by surface Γ, the mass and energy conservation can be expressed in a uniformly integral way along with the proper moment equation as shown in Table 1. Here, ξ is a space-dependent parameter (like porosity or permeability), ω is state-dependent parameter (like pressure, temperature or chemical composition), ϕ represents porosity, $x_{cj}(\omega)$ is the mole fraction of component c in phase j, $s_j(\omega)$ is phase saturation, $\rho_j(\omega)$ is phase molar density, $v_j(\xi,\omega)$ is phase velocity, $U_j(\omega)$ is phase internal energy, $h_j(\omega)$ is phase enthalpy, $U_r(\omega)$ is rock internal energy and k is thermal conduction.

Description	Equation	
Conservation of mass and energy	$\frac{\partial}{\partial t}\int_{\Omega} M^k d\Omega + \int_{\Gamma} F^K \cdot n d\Gamma = \int_{\Omega} q^k$	(1)
Mass accumulation	$M^k(\omega, v_m) = \phi \sum_{j=1}^{n_p} x_{cj}\rho_j s_j$	(2)
Energy accumulation	$M^{ke}(\omega, v_m) = \phi \sum_{j=1}^{n_p} x_{cj}\rho_j s_j\, U_j - (1-\phi)U_r$	(3)
Mass flux	$F^k(\xi, \omega, v_m) = \sum_{j=1}^{n_p} x_{cj}\rho_j v_j$	(4)
Energy flux	$F^k(\xi, \omega, v_m) = \sum_{j=1}^{n_p} x_{cj}\rho_j v_j\, h_j + k\nabla T$	(5)
Reservoir momentum equation	$v_j = \frac{\boldsymbol{K} k_{rj}}{\mu_j}(\nabla p_p - \rho_j g \nabla \mathrm{D})$	(6)
Well momentum equation	$\frac{\partial p^w}{\partial z} = \left(\frac{\partial p}{\partial z}\right)_h + \left(\frac{\partial p}{\partial z}\right)_f + \left(\frac{\partial p}{\partial z}\right)_a$	(7)

***Table 1**. Mass, energy, and momentum balance equations*

After discretizing conservation equations explained in Table 1, using finite-volume scheme and backward Euler approximation in time, the mass, energy and momentum residuals are written into an operator form. In this case, each term can be represented as a product space-dependent properties and of state-dependent operators (Khait et al., 2018):

$$R_{nm}(\omega, v) = V_n\phi\big(\alpha_c(\omega) - \alpha_c(\omega^n)\big) + \Delta \sum_l \beta_c^l(\omega) v_m^l(\xi, \omega) = 0 \tag{8}$$

$$\begin{aligned} R_{ne}(\omega, v) = {} & V_n\phi\left(\alpha_f(\omega) - \alpha_f(\omega^n)\right) \\ & + (1-\phi)V_n U_r\big(\alpha_{er}(\omega) - \alpha_{er}(\omega^n)\big) \\ & + \Delta t \sum_l \beta_e^l(\omega) v_m^l(\xi, \omega) \\ & + \Delta t \sum_l \Gamma^l\big(T_i - T_j\big)\left(\phi_0 \gamma_{ef}(\omega) + (1-\phi_0) k_r \alpha_{er}(\omega)\right) = 0 \end{aligned} \tag{9}$$

The nonlinear operators α, β, γ represent nonlinear operators based on governing properties of PDEs, see more details in (Lyu et al., 2021). Unlike former DARTS formulation, in the proposed extension, the total velocity v_m is an additional primary unknown of the problem written at each interface between two nodes. For each connection between node block *i* and *j*, we write a discrete momentum equation in residual form depending on a connection whether it is between wells or reservoir blocks, as follows:

$$\boldsymbol{R_c} = \begin{cases} v_{mix} + T_c \lambda(\omega)(P_i - P_j), & \text{reservoir connection,} \\ P_i - P_j - \big(\Delta P_h(\omega, \xi) + \Delta P_f(\omega, \xi, v_m) + \Delta P_a(\omega, \xi, v_m)\big), & \text{well connection.} \end{cases} \tag{10}$$

Here $\lambda(\omega)$ is total mobility operator and ΔP_h, ΔP_f and ΔP_a are pressure losses operators due to the hydrostatic, friction and acceleration respectively. Newton's method is applied to the entire coupled system, and it will be solved until reaching the global convergence criteria. During the simulation, operator interpolation accelerated the Jacobian assembly since it is replaced by the repetitive and time-consuming evaluation of the physical properties.

Examples

Here we demonstrate the capabilities of decoupled velocity formulation for several physical kernels. To begin, we make simple benchmark with AD-GPRS (Garipov et al, 2018) to see the accuracy of the MS-well model for non-isothermal case. In this test case the reservoir dimensions is 3 × 10 × 10 with the grid size 6.096m × 3.048m × 6.096m with lateral permeabilities of $K_{xy} = 100$, and 500 mD, while the vertical permeability was set as $K_z = \frac{K_{xy}}{100}$ mD. Two vertical multi-segmented wells with 4 segments each are placed at the opposite sides of the model. Each segment is connected to the corresponding layer with different well indices 10, 20, and 30. Initially reservoir is saturated with oil and pressure 400 bar. We inject water to the injection MS-well at 405 bar and produce at 395 bars at the production MS-well. We run the simulation for 4000 days. The comparison between DARTS and AD-GPRS with MS-well model is shown in Figures.1, From this graph we can observe that there is a perfect match between both DARTS and AD-GPRS for this model.

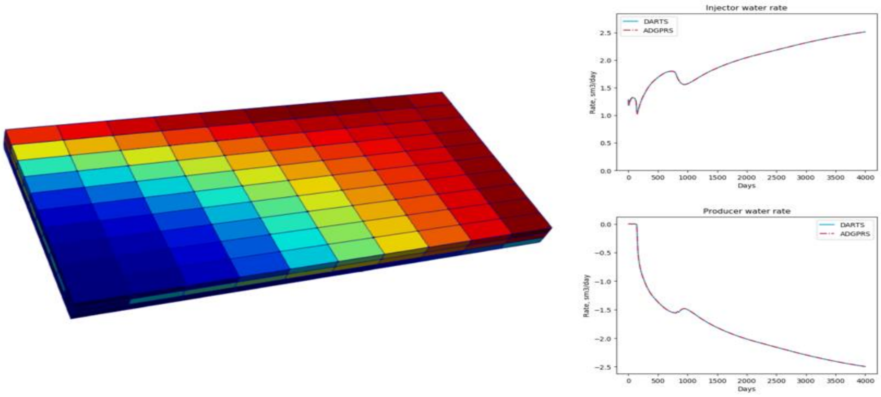

Figure 1. *Benchmark with ADGPRS for SPE1 reservoir*

Next example, we show the capabilities of the decoupled velocity engine for simulation of geothermal reservoir with heterogenous properties. a one-layer model extracted from a synthetic geological model from the West Netherlands Basin - WNB (Wang et al., 2020). is chosen for the two-dimensional comparison. Figure. 2 illustrates the permeability and porosity distribution of the model. The initial pressure of the reservoir is 200 bar, temperature 348.15 K. We inject water at 308.15 K with constant pressure 250 bar and produce with BHP control at 125 bar. Figure 3. shows the pressure and enthalpy distribution after 3650 days and comparing it with the conventional DARTS engine. As we can see we obtained a good match with conventional DARTS engine and the error is less than 0.05 %.

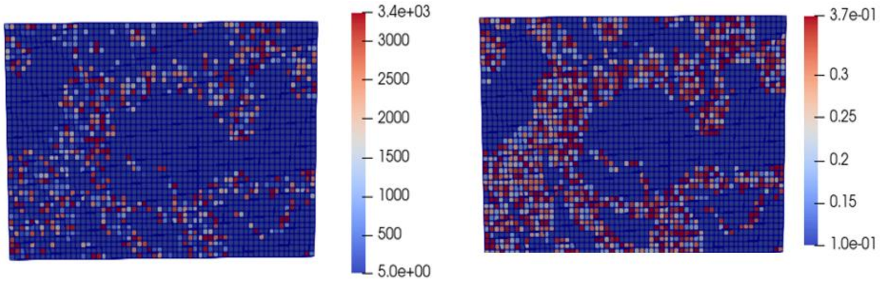

Figure 2*. permeability (right figure) and porosity (left figure) distribution*

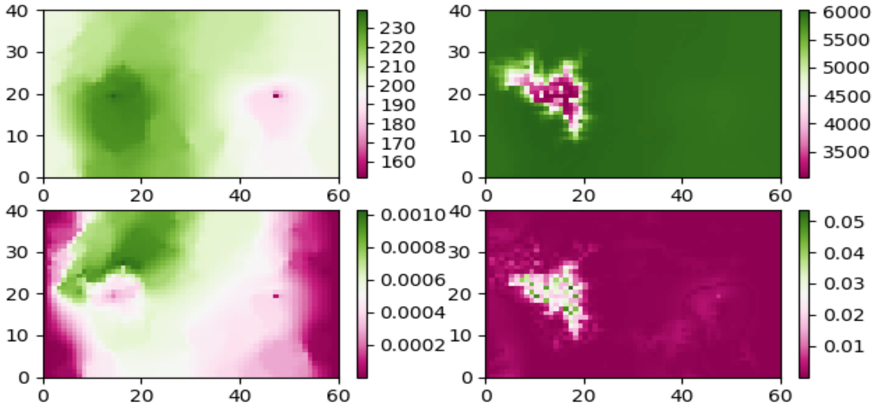

***Figure 3**. Comparison 2-D heterogeneous low enthalpy with stand-alone velocity and conventional engine*

Conclusions

We have developed a new computational framework that can simulate thermal multiphase, multi component flow in both wellbore and reservoir. The advantage of this new framework is that it allows to write the suitable momentum equations for a part of the domain that deviates from Darcy's laws such as wellbore or the region which need Reynolds number is high that Darcy velocity is not accurate assumption. We verify the ms-well accuracy of the model comparing a solution for thermal-compositional physics with AD-GPRS. Next, we test the decoupled velocity engine for several physical kernels including low enthalpy geothermal reservoir with heterogeneous structure.

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