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Modelling Single Well Closed Loop for Dry Rock Geothermal System

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ABSTRACT

Deep dry rock geothermal resources provide an excellent source of low-carbon sustainable energy. However, a high level of capital investments in such projects often makes them low profitable. One of the large parts of the capital cost is related to the drilling of the wells and their completion. Using a single well closed-loop concept can significantly reduce the capital cost and makes the geothermal applications more profitable and attractive for investors. In this project, we design a numerical framework for predictive simulation and monitoring of single closed loop 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 which is constrained by the momentum balance equation. 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 simulation. This framework was tested for several complex physical kernels including thermal compositional multiphase flow and transport. The proposed model was validated using a comparison with analytic and numerical results.

1. INTRODUCTION

It is inevitable to overlook the role of well and borehole operations for successful management of any energy-related subsurface activities e.g., energy storage, geothermal energy production, carbon capture and sequestration, oil and gas production, wastewater disposal, thermal recovery processes. To maximize both the economy of the field and the reliability of the operations of the geothermal system, several advanced wellbore models have been introduced. A closed-loop system is one of the promising technologies in the geothermal industry. The major benefit of the closed-loop system is a limited environmental impact due to the closeness of the system. On the other hand, the poor thermal conductivity of geological formations requires a large surface area to harvest enough heat. Moreover, it is economically unfavorable since it is necessary to drill at least two wells.

Recently, a stand-alone closed loop well also known as closed co-axial wellbore has been proposed that combat the drawbacks of other geothermal systems while keeping all the benefits (Law, et al., 2014). In this system, the fluid flows either through the annulus and recirculated by natural convection through the inner tube at the bottom of the wellbore or reverse direction. since it is a closed loop, we exploit the environmental advantage of the closed system. It can further cut the plant cost by recirculating fluid in the downhole heat exchanger to drive a flash plant at the surface. Moreover, it can be combined with an enhanced geothermal system, that produces the greater surface area for heat exchange via fracturing the shale well.

There are multiple challenges with accurate modeling such wells. Firstly, capturing accurately the physics of flow through the wellbore is complex. The full momentum equation should be solved considering pressure losses due to friction, acceleration, and gravitational forces acting in the fluid. Coupling wellbore nonlinear governing equations to the reservoir due to the contrast in temporal and spatial scale may cause a set of stiff partial differential equations. Moreover, the model should be reliable enough to honor more sophisticated intelligent well topology.

Several coupled reservoirs and well models were proposed to simulate the complicated physics involved in the wellbore. The standard well model, which views well as a point source or sinks term in the perforated reservoir block, is the most prevalent approach for modeling well in reservoir simulation (Peaceman, 1990; Nolen 1990). However, the standard well model is blind to the actual physics in the wellbore. Moreover, it cannot capture the complex well network topology. To overcome this drawback, the multisegmented well (MS-well) model was proposed (J.A. Holmes, 1998; Jiang 2008). In MS-well model, wellbore is discretized into several segments with the fluid velocity, node pressure, and other properties simulated along with the wellbore geometry. The benefits of the general MS-well model are firstly, it can flexibly approximate the actual geometry of each wellbore and handle the complex well topology and controls in the pipeline network. Moreover, introducing velocity as an additional degree of freedom allows us to solve for pressure losses that approximate the steady-state momentum equation.

A few fully coupled numerical models with different strategies for thermal wellbore flow have been suggested (J.A. Holmes 1998; Jiang 2008). The hybrid semi-explicit formulation for the transient flow in the geothermal wellbore was proposed by Pan et al. (2012). However, for practical applications fully implicit coupling is more attractive option due to the unconditional stabilities.

In fully implicit approach we used Newton-Raphson method to linearize and solve set of nonlinear equations. Linearization of discrete mass and energy governing equations of multiphase multicomponent flow and transport is challenging due to the highly nonlinear coupling and complex thermodynamic phase behavior that needs to solve flash in each newton iteration to accurately evaluate the fluid/rock interactions in the molar formulation (Collins, 1992; Voskov 2012).

A new approach for the linearization of governing equations called operator-based linearization (OBL), was proposed by (Voskov, 2017). In this approach, the exact physics of the simulation model was approximated using abstract algebraic operators.). Later this technique was extended and implemented in the open-source Delft Advanced Research Terra Simulator (DARTS). DARTS is a scalable parallel modeling framework aims to accelerate the simulation performance while capturing multi-physics geo application phenomena such as Hydrocarbon (Khait and Voskov,2018; Lyu et al.,2021), geothermal (Wang et al.,2020) and CO_2 sequestration (Kala and Voskov, 2020, Lyu et al.,2021).

In this work, we develop a new computational framework in DARTS applying the general decoupled velocity formulation and extend OBL to couple well and reservoir model. Well and reservoir are both discretized similarly into nodes and connections following the general unstructured grid framework (connection-based method by Lim et al., 1995) using finite-volume scheme. Total velocity serves as an additional nonlinear unknown written at each interface (connection) on the total computational domain and bounded by the suitable momentum equation. Coupling mass and energy balance equations for multi-phase multi component system written on the center of each cell along with momentum balance equation on the cell-faces solves simultaneously. Moreover, transforming both reservoir and well nonlinear governing equations into an operator form benefits from OBL techniques and reduce further the computational cost of simulation.

The paper is organized as follows. First the governing equations describing thermal, multi-phase flow in the wellbore and the reservoir are presented in detail. Next, we explain our strategy for solving it. We then test the accuracy and consistency of the method through a set of benchmark tests. We further test the framework for more complex physical kernel considering thermal flow. Lastly, we present our well design for single-closed loop and investigate the impact of several parameters in heat recovery of this wellbore.

2. METHODOLOGY

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 momentum equation as shown in Table 1. Here, ξ is a space-dependent vector of parameters (like permeability), ω is state-dependent vector of parameters (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. Table.1 summarized the governing equations describing mass and energy and momentum transport for both reservoir and the wellbore domain.

Table 1. Mass, energy, and momentum balance equations

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)

2.1 OBL solution strategy with decouple velocity formulation

Unlike former DARTS formulation, in decoupled velocity formulation, velocity is an additional primary unknown of the problem written at each interface between two nodes. On each node, the following independent variables are defined:

- $\omega = [P_i(pressure), H_i(Enthalpy), Z_i(overall\ composition), \dots]$

Note that the above variables are all defined at the center of the node. On each connection, we define total velocity:

- $v_m, Total\ velocity$

Figure .1 illustrated the grid domain and the location of the primary unknowns:

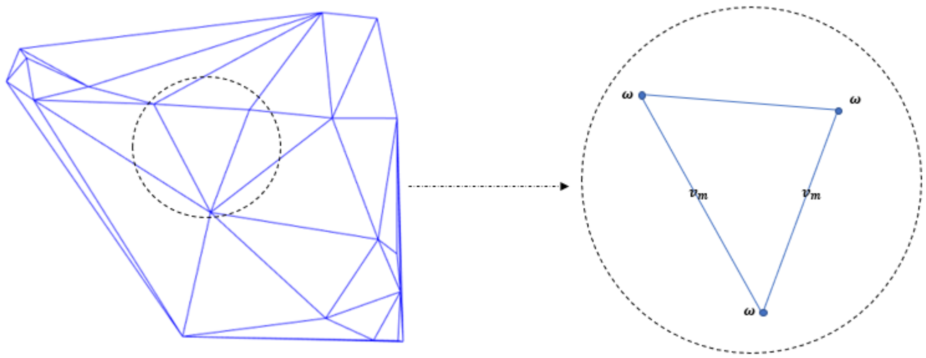


Figure 1 Location of the unknowns on general unstructured domain in decoupled velocity framework

After discretization Equation.1, using finite-volume scheme and backward Eular approximation in time, we transform the mass and energy residual equations into an operator form as follow:

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

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

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:

$$\boldsymbol{R}_c = \begin{cases} v_{mix} + T_c \lambda(\omega)(P_i - P_j), & \text{Reservoir connection} \\ P_i - P_j - \left(\Delta P_h(\omega, \xi) + \Delta P_f(\omega, \xi, v_m) + \Delta P_a(\omega, \xi, v_m)\right), & \text{Well connection} \end{cases} \tag{10}$$

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.

3. NUMERICAL RESULTS

3.1 MS-well validation

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 are 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.

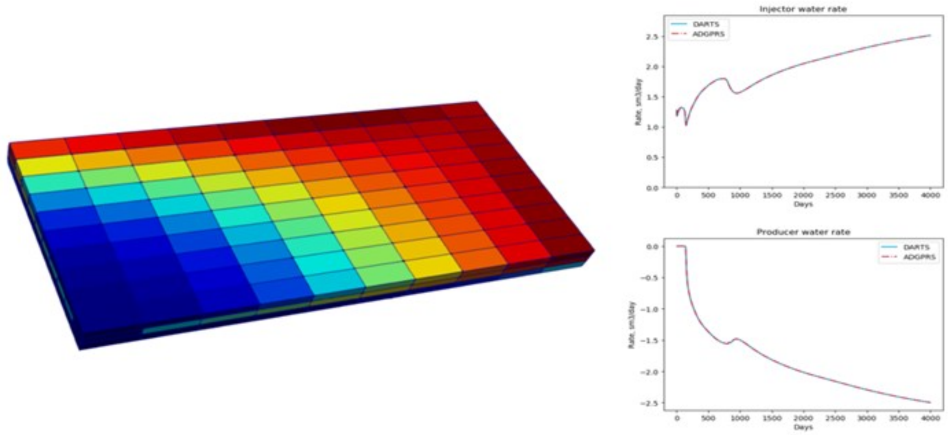


Figure 2. Benchmark with ADGPRS for SPE1 reservoir

3.2 2-D heterogeneous low enthalpy test case

In this test case, 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 10 illustrates the permeability and porosity distribution of the model. The initial pressure of the reservoir is200 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 11 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%

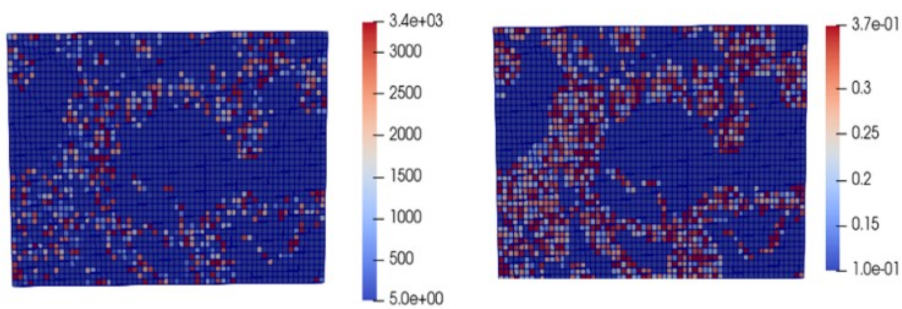
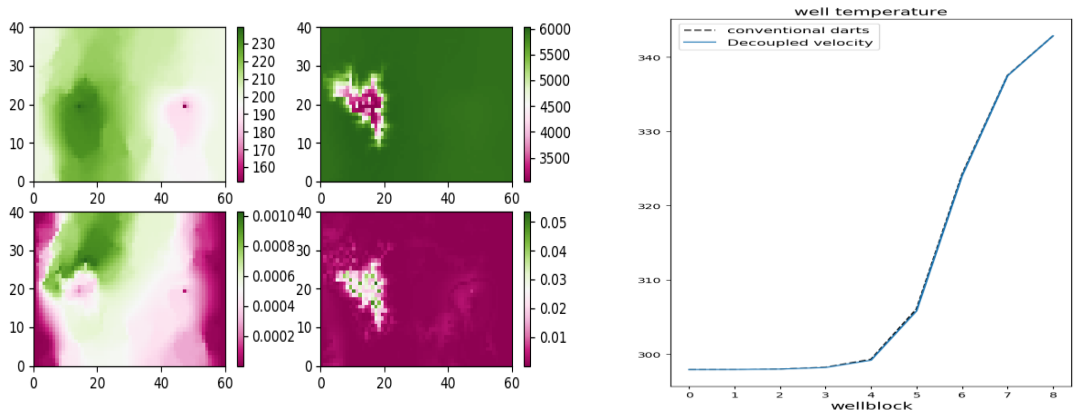


Figure 3. permeability (right figure) and porosity (left figure) distribution



(a) (b)

Figure 4. (a) Comparison 2-D heterogeneous low enthalpy with stand-alone velocity and conventional engine (b) Temperature profile along the wellbore for decouple and coupled velocity engine.

3.4 Single Well Closed Loop

Figure 5. illustrates single well closed loop schematically. In order to model such wells, the wellbore is discretized into nodes and connections as a similar fashion to reservoir using finite-volume scheme. Any well segment can be connected with an arbitrary number of reservoir control volumes, representing well perforations. Each segment of the MS-well pipeline is a separate object that can have different geometrical properties from other segments. Currently in DARTS there are two types of tube and annulus segments available which allows us to model coaxial wellbore. In order to model such well, we need to create a special connection list. Figure 6. illustrates the discretize wellbore and corresponding connection list for such wells.

We write control equation either as a pressure control also known as BHP control for the ghost cell or we write it as rate control and solve it for the first connection as follow.

$$\begin{cases} R_1^{seg} = \omega_1^{seg} - \omega_{target} & \text{BHP control} \\ R_1^{conn} = \frac{v_j^{sj}}{\rho_j^{sc}}\left(\sum_c \sum_p \rho_p Q_p x_{x,p}\right) - Q_j^{target} & \text{Rate control} \end{cases} \tag{11}$$

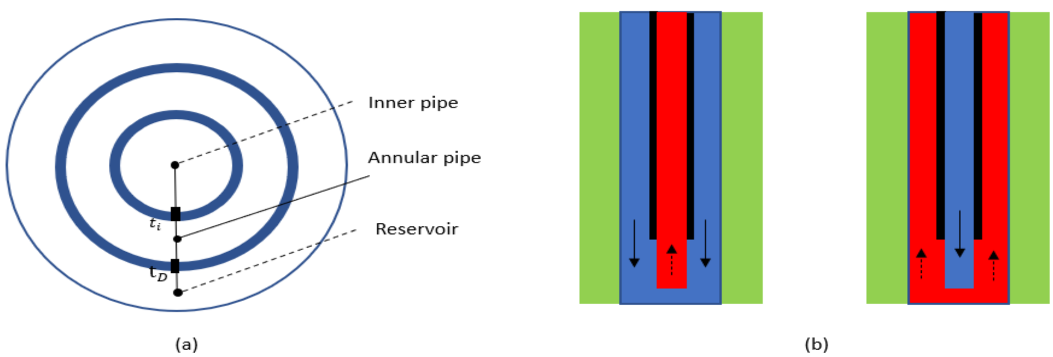


Figure 5 (a) Cross section of a pipe-in-pipe single closed-loop wellbore (b) schematic diagram of Single Well Closed Loop for different flow direction

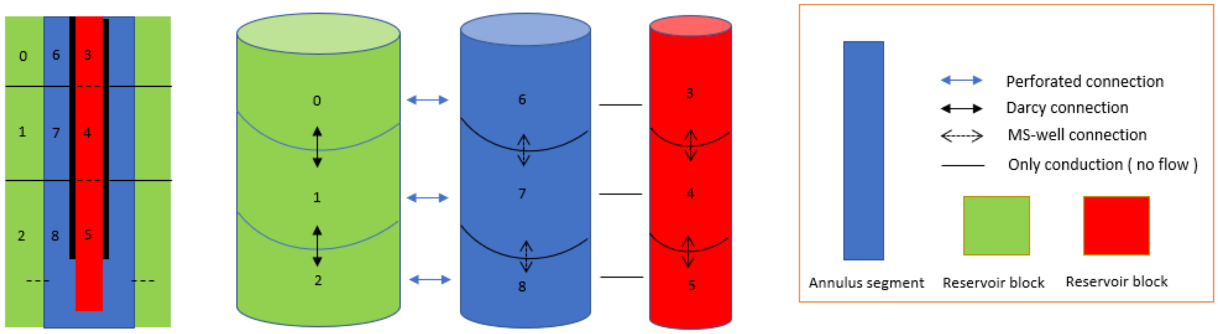


Figure 6. Co-axial MS Well-reservoir discretized network scheme

We made two different scenarios for two different flow direction and investigate the effect of the heat conduction (different resistance) between the annulus and the reservoir part. In this test case, the reservoir dimensions are 1 × 1 × 100 with the grid size 0.30m × 30m × 6.96m with impermeable layers. The stand-alone Ms-well with 100 grid blocks for each annulus and the inner tube and the annulus is fully connected through the reservoir. We ran the test case for 2.4h considering different conductive heat transfer coefficient, t_d between the annulus and the reservoir. In this test case, we also assume a perfect isolation between the annulus and the inner tube ($t_i \approx 0$). In Figure 4. We can see the temperature profile along the annulus and the inner tube while we inject from annulus and produce from the inner tube. We can see that by increasing the t_d the temperature profile goes slightly upward, meaning lower resistance between annulus and the reservoir and thus more heat conduction. Figure 5 corresponds to the reverse flow direction in which we inject from inner tube and produce from the annulus. As we can see the effect of the t_d on the injection well is null as there is no contact between the inner tube and the reservoir. On the other hand, the temperature profile along the annulus is nonlinear and temperature increases by increasing conductivity between the annulus and the reservoir.

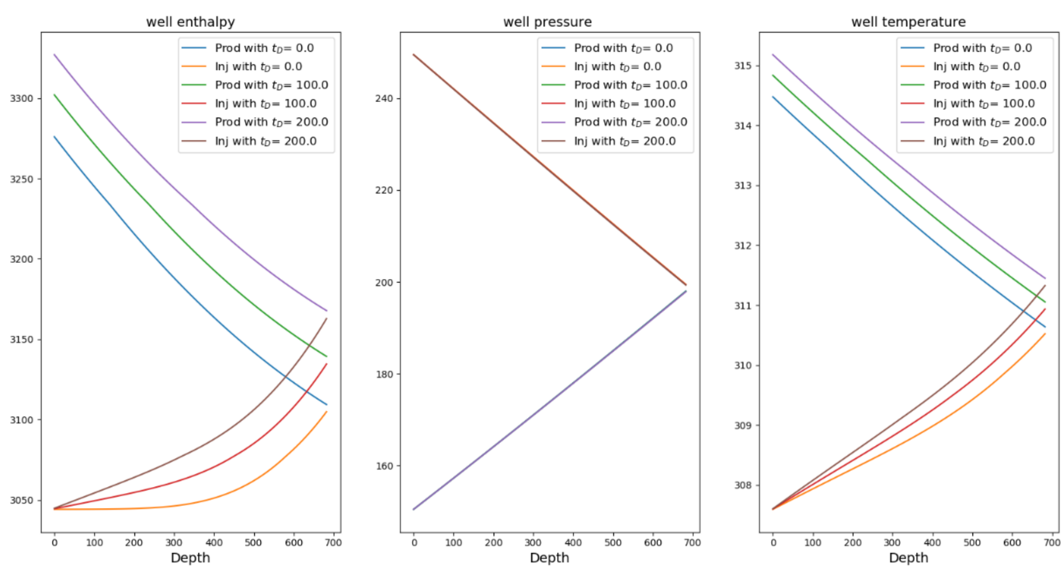


Figure 7. Comparison of water temperature profile under different thermal conductivity between annulous and reservoir while injecting from annulus pipe

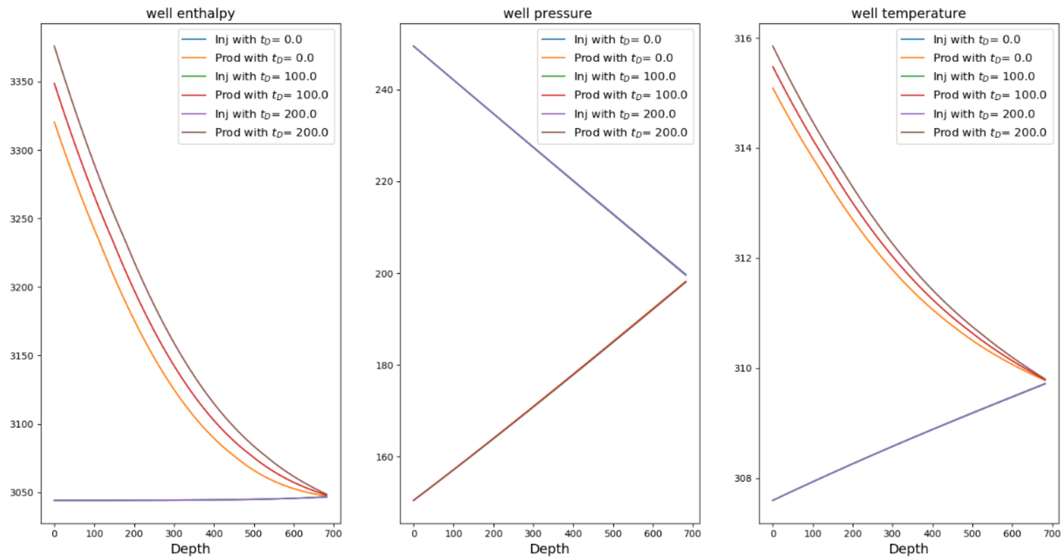


Figure 8. Comparison of water temperature profile under different thermal conductivity between annulus and reservoir while injecting from inner pipe

4. CONCLUSION

We have developed a new computational framework that can simulate thermal multiphase, multi-component flow both in the wellbore and the reservoir. We extend this model to be capable to model the coaxial wellbore model. First, we verify the MS-well accuracy of the model comparing a solution for non-isothermal-compositional physics with AD-GPRS. We further test the framework for more complex Physical kernel considering thermal effect. Finally, we validated the framework for a single closed loop wellbore and ran multiple numerical experiments and sensitivity analyses on various factors that affect heat extraction from the co-axial wellbore.

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